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**Environmental Energy
Technologies Division**

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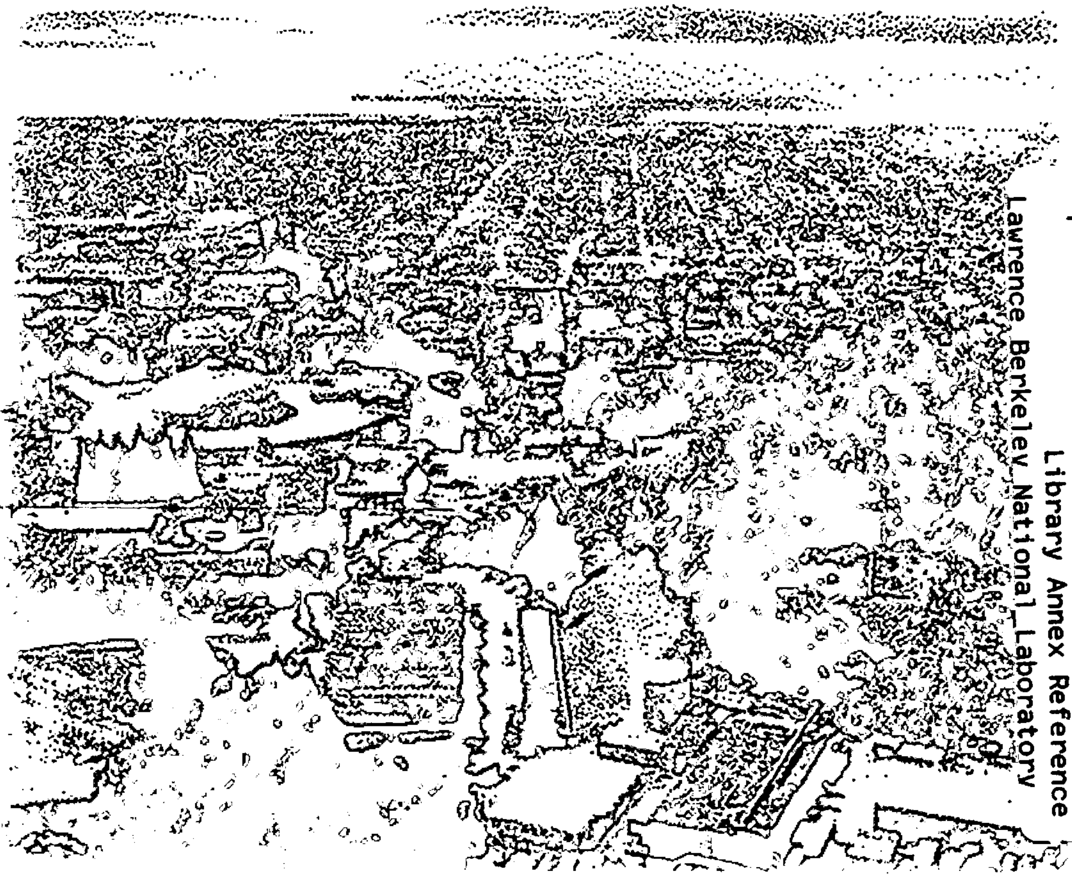

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# EXECUTIVE SUMMARY

## The Overall Benefit of Commissioning California's Houses

Commissioning California's houses can result in better performing systems and houses. In turn, this will result in more efficient use of energy, carbon emission reductions, and improved occupant comfort. In particular, commissioning houses can save a significant amount of HVAC-related energy (15 to 30% in existing houses, 10 to 20% in new conventional houses, and up to 8% in advanced energy efficiency houses). The process that we considered includes corrective measures that could be implemented together during construction or during a single site visit (e.g., air tightening, duct sealing, and refrigerant and air handler airflow corrections in a new or existing house). Taking advantage of additional, more complex opportunities (e.g., installing new windows in an existing house, replacing the heating and air conditioning system in a new or existing house) can result in additional HVAC-related energy savings (60 to 75% in existing houses, and 50 to 60% in new conventional houses).

The commissioning-related system and house performance improvements and energy savings translate to additional benefits throughout California and beyond. By applying commissioning principles to their work, the building community (builders and contractors) benefit from reduced callbacks and lower warranty costs. HERS raters and inspectors will have access to an expanded market sector. As the commissioning process rectifies construction defects and code problems, building code officials benefit from better compliance with codes. The utilities benefit from reduced peak demand, which can translate into lower energy acquisition costs. As houses perform closer to expectations, governmental bodies (e.g., the California Energy Commission and the Air Resources Board) benefit from greater assurance that actual energy consumption and carbon emissions are closer to the levels mandated in codes and standards, resulting in better achievement of state energy conservation and environmental goals. California residents' quality of life is improved through better indoor environmental comfort and lower energy bills. Lower energy bills free up money for residents to spend on other needs or goals, such as additional education and health and welfare. With an expansion of existing industries and the development of new commissioning-related industries, related jobs and tax revenues will increase, further increasing the quality of life for California.

## Background

Significant opportunities to improve energy efficiency and comfort exist in California houses. The California Energy Commission is evaluating ways to expand and accelerate the implementation of these opportunities.

Residential commissioning is a means to achieve this goal. In addition to improving system and equipment efficiency on a component-by-component basis, commissioning considers the house as a system and takes advantage of the interactions between systems and components. It combines auditing, testing, and implementing energy efficiency and comfort improvements to enhance component and system performance. By doing so, it is possible to leverage capital and operating cost savings to fund measures that are more expensive. Such an integrated approach allows energy-efficiency measures that make little sense individually (e.g., windows) to be cost-effective and attractive together within the whole system, due to concurrent benefits such as reduced equipment size and improved comfort (RMI 1997).

There is a broad spectrum of potential energy and non-energy benefits for various stakeholders such as builders, consumers, code officials, utilities, state agencies, and energy planners. For example, builders and/or commissioning agents will be able to improve system performance and reduce consumer costs associated with building energy use. Consumers will be more likely to get what they paid for and builders can show they delivered what was expected in terms of improved indoor environmental quality, housing durability, and resale value. Also, code officials will be better able to enforce existing and future energy codes. As energy reduction measures are more effectively incorporated into the housing stock, utilities and energy planners will benefit through greater confidence in predicting demand and greater assurance that demand reductions will actually occur. Performance improvements will also reduce emissions from electricity generating plants and residential combustion equipment, which will benefit the environment as a whole.

The work reported here is the third step in a larger project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. This report describes our assessment of the potential quantitative and qualitative benefits one can realistically expect from commissioning prototypical new and existing California houses. Our assessment expands upon our recent literature review and annotated bibliography (Wray et al. 2000), which facilitates access to 469 documents related to residential commissioning published over the past 20 years. It also expands upon our assessment of 117 diagnostic tools for evaluating residential commissioning metrics (Wray et al. 2001).

We will use the results of these efforts to prepare a separate commissioning guide that describes how typical contractors and service providers could achieve the benefits that we identify. That guide will contain specific recommendations on what diagnostics to use and how to use them to commission new and existing houses. The guide will also explain the potential benefits of using these diagnostics.

## Report Structure

Quantitatively, this report focuses on the energy and operating cost benefits related to commissioning houses in California. It also qualitatively discusses related non-energy benefits. Within the report introduction, we first describe the need for commissioning and how it fits into the life cycle of a house. Next, we briefly identify the benefit types, the stakeholders, and who may place value on a particular benefit. Our intent here is to set the context for our analyses and discussions.

Following the introduction, we have divided the report into the following eight sections:

- “Analysis Framework – Modeling Tools and Methodology”, which provides an overview and flowchart of the modeling structure that we used to quantify the energy performance benefits.
- “Analysis Framework – Building and Climate Characteristics”, which provides our analytical assumptions, summarizes the pre-commissioned house cases that we considered, and discusses the commissioning and opportunity measures that we modeled.

- "Energy Performance Benefits", which discusses the modeled energy consumption, and operating cost savings in terms of specific components and the house as a whole.
- "Non-Energy Benefits", which discusses other commissioning benefits, such as house durability, indoor environmental comfort, the environment, and the economy.
- "Conclusions", which summarizes our results regarding the impact of commissioning on California's residents, businesses, and the state as a whole.
- "Appendix A: Analysis Assumptions", which provides additional details regarding our analytical approach, assumptions, and climate/case specific findings.
- "Appendix B: Peak Demand", which discusses peak demand impacts, as determined from the DOE-2 peak consumption outputs.
- "Appendix C: Comfort Call Cases", which discusses the potential benefit of commissioning houses where comfort calls may occur due to the existing HVAC systems.

**Analysis Overview**

In evaluating the commissioning-related benefits (component and system efficiency improvements and energy and cost savings), we have quantitatively considered how several envelope and HVAC-related measures work together synergistically to improve energy utilization efficiency, energy consumption, operating costs, comfort, ventilation, and environmental effects. We have also briefly considered some non-energy benefits involving durability, indoor environmental quality, the environment, and the economy.

We determined benefits relating to commissioning California's houses using 128 hour-by-hour simulations with data derived from our field and laboratory studies to evaluate commissioning diagnostics (Wray et al. 2001) and from other sources referenced in the commissioning literature study (Wray et al. 2000). In particular, we determined building performance (e.g., ventilation rates, energy consumption and operating costs) using simulation programs (DOE-2, RESVENT [Sherman and Matson 1993, 1997]) and the requirements of codes and standards (Title 24, ASHRAE Standards 62.2P and 152P [ASHRAE 1999]). We conducted our evaluations using combinations of three commissioning phases (audit, commissioning, and opportunity), three house prototypes (existing, new and advanced), two housing quality analysis sets (typical and poor) and four climate zones (two coastal climates and two inland valley climates). The following summarizes the characteristics of these simulation elements. Details are contained in the body of the report and in Appendix A.

**Commissioning Phases**. The three commissioning phases that we considered include:

- the audit phase, when the current conditions and performance of the house are evaluated;
- the commissioning phase, when systems and materials are tuned and tweaked to improve efficiency and to perform better; and
- the opportunity phase, which identifies additional energy-efficiency measures that could be installed and implemented.

The commissioning phase includes measures that could be implemented during the commissioning visit or as part of the correction of construction defects (e.g., air tightening, duct sealing, and refrigerant and air handler airflow corrections in new and existing houses; improved insulation installation quality in new houses; installation of correct windows in new houses). If commissioning takes place during construction, implementation is more cost-effective than after completion.

The opportunity phase includes additional energy efficiency measures and improvements that cannot be implemented easily during a commissioning visit. These measures would require additional funds and decisions regarding overall cost-benefits (e.g., improved insulation and windows in existing houses; more efficient HVAC equipment in new and existing houses).

**House Prototypes**. The three house prototypes that we modeled include:

- An existing house, representing the existing housing stock built before Title 24;
- a new house, representing the current Title 24 requirements; and
- an advanced house, representing the level of energy-efficiency construction currently being built in advanced energy efficiency programs, such as Building America.

**Typical and Poor Construction Cases.** In order to evaluate the impact of commissioning a typical California house versus a "worst case" California house, we modeled typical and poor condition cases.

- The typical cases represent the California housing stock and our assessment of the penetration of individual energy efficiency measures within it. These measures are the same measures implemented or improved upon in the commissioning and opportunity case models. The measures include improved insulation installation quality, correct windows (low-E glass when specified), envelope and duct air leakage reduction, air handler airflow corrections, and refrigerant charge corrections.
- The poor cases represent "worst case" California houses where none of these measures are installed or where they are all operating in an inefficient and deficient manner.

### Energy and Operating Cost Savings from Commissioning

Table I summarizes the range of electricity consumption, natural gas consumption, and operating cost savings that we calculated for the commissioning and opportunity cases for our three house types in four climate zones. All savings are presented as savings over the unimproved audit case. No opportunity cases are listed for the advanced houses, because they are already engineered and designed to be energy efficient.

Annual operating cost savings are based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of \$0.1071/kWh (EIA 2000) and \$0.634/therm (EIA 2001). Energy price increases and price volatility will further enhance the attractiveness of commissioning California's houses.

The following summary compares the data in Table I on a house-by-house type basis for each benefit type.

*Existing Houses*

*Electricity.* Commissioning the existing house results in electricity savings ranging from 14 to 18% (typical) and 20 to 28% (poor). In the opportunity phase, adding insulation, low-e double-pane windows, and equipment with a thermostatic expansion valve (TXV) and an electronically commutated motor (ECM), results in substantial savings compared to the audit case. Within this phase, the overall electricity saving range from 61 to 74% for the typical cases and from 71 to 80% for the poor cases.

*Natural Gas.* Natural gas savings are from 18 to 21% for the typical cases and from 33 to 36% for the poor cases. Implementing the opportunity phase improvements substantially increases natural gas savings to 44 to 54% for the typical cases and from 59 to 67% for the poor cases.

*Operating Costs.* Operating cost savings in the commissioning phase range from 15 to 18% (typical) and 25 to 30% (poor). Implementing the opportunity phase measures substantially increases the operating cost savings to 59 to 64% (typical) and from 69 to 73% (poor).

Table I: Commissioning-Related Energy and Operating Cost Savings

| | | Electricity Consumption Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 14 to 18% | 20 to 28% |
| | Opportunity | 61 to 74% | 71 to 80% |
| New | Commissioning | 7 to 11% | 55 to 71% |
| | Opportunity | 8 to 12% | 62 to 72% |
| Advanced | Commissioning | 7 to 10% | 52 to 73% |

| | | Natural Gas Consumption Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 18 to 21% | 33 to 36% |
| | Opportunity | 44 to 54% | 59 to 67% |
| New | Commissioning | 24 to 25% | 18 to 35% |
| | Opportunity | 28 to 31% | 22 to 41% |
| Advanced | Commissioning | 2 to 3% | -19 to -10% |

| | | Energy Operating Cost Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 15 to 18% | 25 to 30% |
| | Opportunity | 59 to 64% | 69 to 73% |
| New | Commissioning | 12 to 17% | 50 to 62% |
| | Opportunity | 17 to 22% | 51 to 63% |
| Advanced | Commissioning | 6 to 8% | 45 to 66% |

*New Houses*

*Electricity.* The electricity savings in the commissioning phase range from 7 to 11% (typical) and 55 to 71% (poor). In the opportunity phase, adding equipment with a TXV and an ECM increases savings only slightly (one to seven percentage points more).

*Natural Gas.* Natural gas savings in the commissioning phase are about 25% for the typical cases and from 18 to 35% for the poor cases. In the opportunity phase, installing a higher efficiency furnace (90% instead of 80%) increases natural gas savings slightly to about 30% for the typical cases and from 22 to 41% for the poor cases.

*Operating Costs.* Operating cost savings in the commissioning phase range from 12 to 17% (typical) and from 50 to 62% (poor). In the opportunity phase, installing the HVAC equipment with a TXV, an ECM, and higher furnace efficiency increases the operating cost savings to 17 to 22% (typical) and from 51 to 63% (poor).

*Advanced Houses*

Because the advanced houses are already engineered and designed to be energy efficient, relative savings for the typical cases are lower than those for the typical existing and new houses. For the advanced houses, the primary difference between the typical and the poor cases is the incorrect installation of clear glazing in place of low-e glazing. Correcting this problem in the poor cases drives the energy consumption and savings closer to the levels seen with the new houses.

*Electricity.* The commissioning phase electricity saving range from 7 to 10% (typical) and from 52 to 73% (poor).

*Natural Gas.* Natural gas savings range from 2 to 3% for the typical cases. Due to a reduction in solar gains when the incorrect clear double-pane windows are replaced with low-e double-pane windows, the poor advanced commissioning cases have higher gas consumption, resulting in negative gas savings, from –19 to –10%.

*Operating Costs.* The typical case operating cost savings range from 6 to 8%. The operating cost savings for the poor case are higher, ranging from 45 to 66%.

### Other Commissioning Benefits

Qualitatively, we expect that commissioning will provide benefits beyond the occupant's reduced energy bills and increased satisfaction with the operation of their home. For example, decreased electrical demand will provide greater system reliability for utilities. Reduced electricity and gas consumption translates directly into reduced carbon emissions. Commissioning can result in space conditioning related carbon emission savings of about 20% for typical existing and new houses, and about 4% for the typical advanced houses. Implementing additional opportunities can result in an additional 40% reduction in typical existing houses and an additional 10% in typical new houses. Greater carbon emission reductions can be realized in houses where significant improvements can be made. Commissioning poor condition existing and new houses can result in about 40% carbon emission reductions. Additional opportunities can provide an additional 30% carbon emission reduction in these poor condition existing houses and 10% in poor condition new houses. Improved building performance and better indoor environmental comfort helps improve the quality of life for occupants. We also expect greater envelope durability and longer HVAC equipment life by improving the building and its systems (e.g., adding insulation, reducing duct leakage, and correcting charge and airflow). This will reduce callbacks and warranty costs, which will provide the business community with increased profits. As the commissioning industry expands, we expect that the building industry will find an increased role that may require a larger workforce and lead to new jobs. This will benefit the state and the economy.

### Cost of Commissioning

The focus of this report is to evaluate the potential benefits from commissioning California houses. Ultimately, however, it is unlikely that stakeholders will adopt commissioning unless the anticipated benefits outweigh the anticipated costs, so it is important to address the issue of cost at some level.

The cost of commissioning will be highly variable. It will depend on the specific implementation of a commissioning program and will depend on how commissioning is folded in with other programs. It will depend on the training of the personnel and level of commissioning chosen. Commissioning could be a loss leader, a built-in cost, a profit center, or part of a public purpose program or regulation.

Because of all this variability, dollar-cost estimates for commissioning are not terribly useful. However, we can indicate some ranges of required resources. Testing a house as part of the commissioning described in this study should take a trained crew from 4 to 6 person-hours, excluding tuning and tweaking of the building and its systems. The amount of special-purpose equipment required for the tests would cost between $6,000 and $15,000. The biggest variation in the total cost comes from using additional equipment to automatically control duct leakage and grille airflow tests. Together, a data acquisition system and computer for this control cost about $3,000 to $5,000. Automatic control is not necessary to carry out these tests, but tests without it will take about 50% longer (6 hours rather than 4 hours). With automatic control, it is likely that a two-person commissioning team could test two houses a day, excluding travel time. Computerized systems can also be used to generate reports (and advice) on-site and can be a useful marketing tool. Another large variation in the total cost is the price of blower doors: they currently cost about $1,600 to $3,500.

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# INTRODUCTION

## The Need for Commissioning

The State of California has made long-standing efforts to reduce the residential building sector's energy consumption through codes and standards for new houses and through retrofit activities and rebate programs for existing houses. In spite of these efforts, houses still do not perform optimally, or as predicted in forecasts based on codes and expectations.

Studies have found that 50% of the heating-related and 30% of the cooling-related energy consumption could be reduced in new houses (Edminster 2000). In existing houses, even greater savings are possible. Through analyses of existing programs, researchers have found that codes and standards have been helpful in reducing California's per-house energy consumption. However, predicted savings based on required Title 24 components are not as high as expected.

A substantial reason for these differences is that few houses are now built or retrofitted using formal design procedures; most are field assembled from a large number of components and there is no consistent process to identify problems or to correct them. For example, Walker et al. (1998a) found large variations in duct leakage, even between side-by-side houses with the same system design and installation crew. This has resulted in as much as a factor of two variation in thermal distribution system efficiency for these houses. This and other studies (e.g., Jump et al. 1996) indicate that duct leakage testing and sealing can readily improve thermal distribution system efficiency and achieve a 25 to 30% reduction in energy consumption.

As another example, consider that for at least 20 years the building industry has recognized the substantial impact of envelope airtightness on thermal loads, energy use, comfort, and indoor air quality. However, Walker et al. (1998a) found 50% variances in airtightness for houses with the same design and construction crews, within the same subdivision.

In recognition of these problems, the California Energy Commission is considering approaches to improve building performance. One way to meet this goal is to apply appropriate and agreed upon field measurement and verification procedures to the residential building sector. These procedures would ensure that the components, materials, and systems of California's houses are installed as specified, and can operate closer to expectations, within the Title 24 requirements, and as well as possible. These procedures also can be used to point out additional energy savings improvements.

Such a practice has already begun in the commercial building sector, usually to tune component and system performance and verify savings related to energy savings performance contracts. The California building industry is also implementing various residential commissioning elements, but only on a component-by-component basis (e.g., testing and correcting building and duct airtightness, air handler airflow, and refrigerant charge problems).

The work reported here is the third step in a larger project that is laying the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. This report describes our assessment of the potential quantitative and qualitative benefits one can realistically expect from commissioning prototypical new and existing California houses. Our assessment expands upon our recent literature review and annotated bibliography (Wray et al. 2000), which facilitates access to 469 documents related to residential commissioning published over the past 20 years. It also expands upon our assessment of 117 diagnostic tools for evaluating residential commissioning metrics (Wray et al. 2001).

We will use the results of these efforts to prepare a separate commissioning guide that describes how non-experts could achieve the benefits that we identify. That guide will contain specific recommendations on what diagnostics to use and how to use them to commission new and existing houses. The guide will also explain the potential benefits of using these diagnostics.

The CEC is currently looking at how to combine and enhance these practices for use by a residential commissioning industry. This project looks at test methods and protocols that can be used towards this goal. The purpose of this benefits study is to determine the energy and non-energy benefits of commissioning California's houses.

## Commissioning within the House Life Cycle

The types of opportunities and the amount of implementation possible will depend on where a given house is in its life cycle: whether it is being built, has just been completed, is fully occupied, or is built based on older construction practices. In new construction, there are two possible times at which changes pointed out in the commissioning process can be implemented: during and/or after the construction process.

Correcting problems during the construction process, while the building framework and surfaces are still open, is often more first-cost effective and could result in significant savings. At this stage in the building life cycle, construction defects can be more easily rectified and system and component efficiencies can be improved. This can reduce the builder's costs, reduce callbacks, and reduce impacts on the environment, while providing better comfort and house performance for the occupants.

At the time of completion, a new house is similar to an existing house: it is difficult to improve insulation installation problems without the expensive process of taking apart and rebuilding part of the house. However, it is still relatively easy to tune and tweak component and system performance to what is intended or expected (e.g., reduce envelope and duct leakage, correct air handler airflow, or correct refrigerant charge). Opportunities to replace existing equipment and materials with more efficient or better performing components can be identified. An example is replacing HVAC equipment with more-efficient, equipment; another is improving insulation levels and upgrading windows.

## Benefit Types and Stakeholders

In evaluating the potential benefits of commissioning California houses, we considered several benefit types and several stakeholders who could be influenced by commissioning activities. This section briefly identifies the benefit types, the stakeholders, and who may place value on which particular benefit.

Stakeholders who may be affected by, and receive benefits from, residential commissioning include occupants (tenants and homeowners), builders and the building community, utilities, governmental agencies and bodies, insurance and banking industries, and the State (the public-at-large). Table 1 provides an overview of the types of benefits that may interest each stakeholder. For each benefit type and each stakeholder, we evaluated whether there is a perceived direct value now to the commissioning user relating to each of the commissioning benefits. The diamonds signify that a given stakeholder may see value now in the benefit listed. The term "warranty" signifies that the builders could expect reduced callbacks and reduced warranty costs related to these benefits.

Table 1: Benefits Framework
"Is there a perceived direct value now to the commissioning user relating to:"

| | Tenants | Owner Occupants | Builders | Utilities | CEC & Code Authorities | Insurance & Banking Industries |
|---|---|---|---|---|---|---|
| Energy Consumption | ◆ | ◆ | | ◆ | ◆ | |
| Energy Operating Cost | ◆ | ◆ | | ◆ | ◆ | ◆ |
| Peak Electrical Demand | ◆ | ◆ | | ◆ | ◆ | |
| Durability / Maintenance / Replacement | | ◆ | ◆<br>warranty | | | |
| House Resale Value | | ◆ | | | | ◆ |
| Thermal Comfort | ◆ | ◆ | ◆<br>warranty | | | |
| Indoor Air Quality | ◆ | ◆ | ◆<br>warranty | | ◆ | ◆ |
| Environmental Protection | ◆ | ◆ | | ◆ | ◆ | |
| Economic Benefits | ◆ | ◆ | ◆ | ◆ | ◆ | |

*The Benefits*

*Energy Consumption, Energy Operating Cost, and Peak Electrical Demand.* A primary goal of commissioning is to improve the energy efficiency of building systems and components. This will reduce energy consumption, peak demand, and operating costs while ensuring sufficient space conditioning and ventilation to maintain acceptable thermal comfort and indoor air quality.

*Durability, Maintenance, Material Replacement, and House Resale Value.* Through commissioning, building envelope and equipment durability is improved and maintenance and material replacement activities and costs are reduced. Increased energy savings can increase house resale values (Nevin and Watson 1998).

*Thermal Comfort and Indoor Air Quality.* Commissioning to reduce uncontrolled air infiltration, to provide appropriate ventilation capacity, and to achieve more consistent surface temperatures through better-installed insulation can help reduce moisture and comfort problems. It will also help ensure that the intended space conditioning systems can deliver the expected amount of space conditioning capacity.

*Environmental Protection.* Improvements in system and component performance (e.g., capacity and efficiency) reduce energy consumption, which translates into a reduction in carbon emissions. Longer equipment life and improved durability reduces the amount of additional materials needed to replace existing equipment and maintain an existing house, thus reducing embodied energy and reducing waste disposal into the environment.

*Improving the Economy.* The economy benefits from reduced energy costs, increased business opportunities and related jobs, and a better quality of life resulting in greater available household funds.

*The Stakeholders*

*Occupants.* The occupants of California's houses, whether tenants or homeowners, are the direct recipients of commissioning benefits. Through commissioning, occupants will benefit from improved quality assurance of their homes, improved interactions between house elements, improved comfort, more efficient use of energy, reduced peak demand and reduced utility bills.

*The Building Community.* The building and contracting industries (e.g., homebuilders, contractors, HERS raters, home inspectors, and energy professionals) may implement commissioning activities in California's houses. As such, the building community will benefit economically by an expansion and increase in business activity, decreased warranty and callback expenses, and improved recognition for quality work. The building community will also benefit from streamlined methods for validating and improving the performance of houses and their systems.

*Utilities.* The utilities and energy service providers benefit from reduced demand from the grid due to increased efficiency and reduced equipment power consumption from downsizing equipment and, correspondingly, avoided capital expense related to building new generation facilities and reduced risk of exposure to high energy prices.

*Governmental Agencies and Bodies.* State agencies such as the CEC will find better agreement between projected and actual energy consumption of California's houses. Code authorities and officials will see better compliance with building codes as the commissioning process identifies and corrects code violations.

*Insurance and Banking Industries.* The insurance industry is interested in reducing their liability due to building defect claims, whether it is part of a natural disaster claim or a standard homeowner claim. As such, the insurance industry will benefit when the commissioning process improves the construction quality and corrects construction defects that could have led to insurance claims. The banking industry will benefit from increased home loan profits, increased investments, increased resale values, and increased monies available for other activities.

*The State (Public-at-Large).* The State, which is a surrogate for the public-at-large, will benefit from increased electricity reliability, due to reduced demands, and reduced energy operating costs, which frees up household dollars to use for other purposes, such as education, leisure, health, and well-being. The expansion of the building community to include commissioning activities will result in additional jobs from the technician to executive level. The increase in business revenues will increase the related tax revenues for the state.

## Sizing: Peak Load and Comfort

The focus of this report is to look at the direct energy benefits of commissioning. As such the body of the report does not address issues related to sizing or peak loads. With the recent electricity crisis in California, however, issues relating to peak demand are much more important than when the study was begun. We have used the information available from our analysis to draw some conclusions about the impacts of commissioning on peak loads and have summarized them in Appendix B, but a thorough analysis of the peak load impacts requires a more extensive effort than can be done in the current context.

Proper sizing of the HVAC system requires understanding both the operating strategy of the occupants and an acceptable amount of discomfort in the form of temperature exceedence. If the system fails to meet the load during some hours of the year, then the impact of commissioning will be to improve house performance, which increases comfort rather than decreases energy consumption for those periods.

Because determination of optimal sizing is not part of this effort, we have made the assumption that the HVAC system can meet the load during each hour of the year. Thus, all the benefits of commissioning appear as consumption reductions. In many real houses, especially those in poor condition, the system may not be able to provide comfort (or the occupants may not wish to pay for it to provide comfort) all the time. In such cases, the energy savings will be reduced as occupants "take back" the savings in the form of increased comfort.

To give some indication of how capacity limitations might impact our analysis of energy savings, we have included cases in Appendix C in which the cooling system is not able to meet load during a significant number of hours during the summer. While not statistically representative, those results are indicative of how the California stock would operate.

## ANALYSIS FRAMEWORK – MODELING TOOLS AND METHODOLOGY

We conducted our quantitative analyses using a combination of simulation tools. Specifically, we used hour-by-hour DOE 2.1E simulations (SRG 1976-2001) to determine annual space conditioning energy consumption. A number of other simulation tools, standards, and data sources were used to determine inputs for DOE-2.1E. These inputs include house characteristics, hourly combined infiltration / ventilation airflow rates, duct system efficiency, and the effect of refrigerant charge and system airflow on air conditioning system performance. Figure 1 illustrates the main analysis components. Appendix A provides a more detailed discussion of each of these analyses.

The *background data* (Title 24 (CEC 2001), DOE/EIA Residential Energy Characteristics Survey (EIA 1999), the Building America Program (Ueno 2000), the Richard Heath Associates 100 House Study (Heath 2000), the LBNL Leakage Database (Sherman and Dickerhoff 1998)) were used to develop the house and system characteristics and various inputs to the DOE2.1E model for each of the cases.

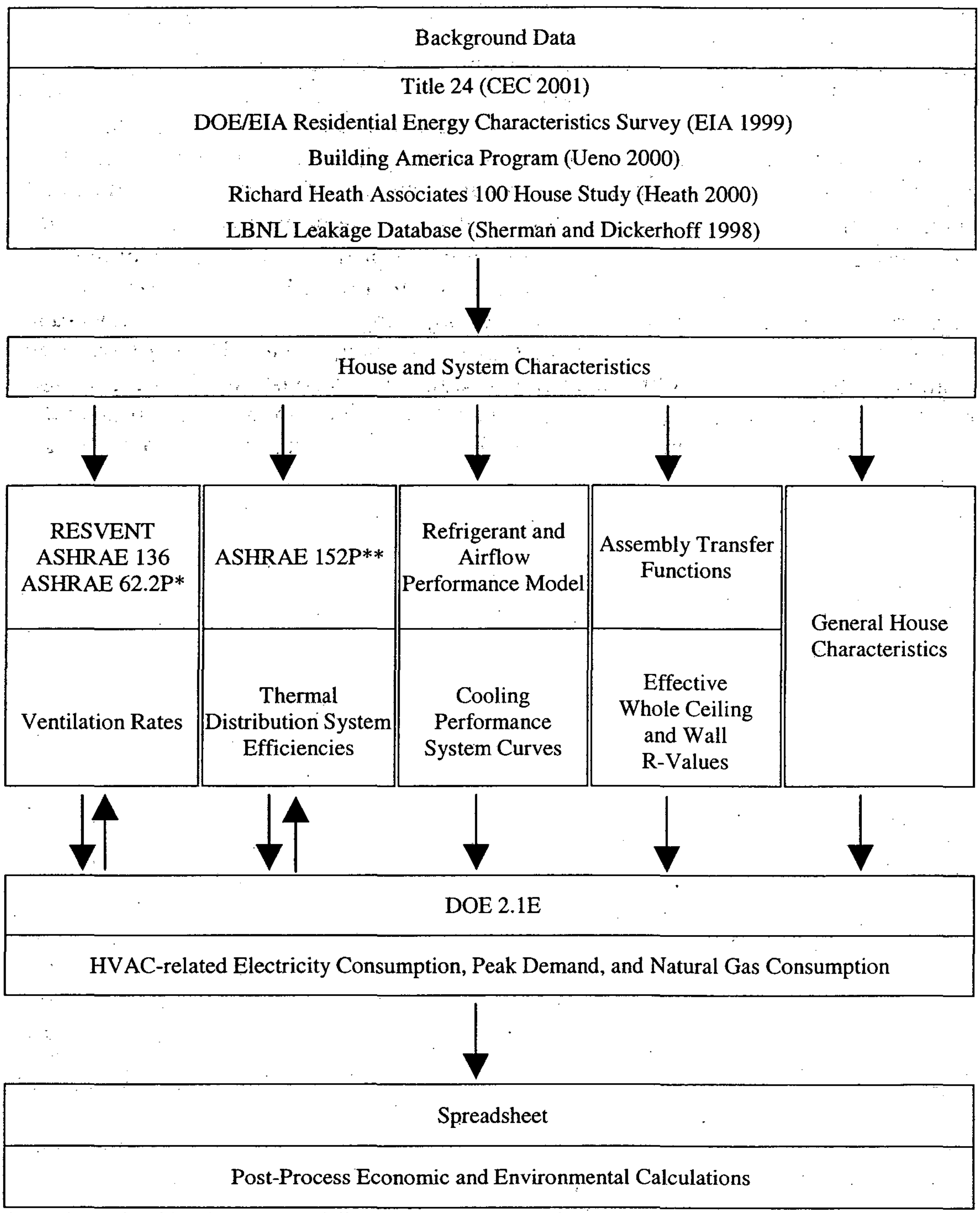
To determine hourly ventilation rates, we used the *RESVENT* computer program developed by Sherman and Matson (1993, 1997). This program uses the LBL infiltration model (Sherman and Modera 1984) to calculate infiltration and then combines it with intermittent and continuous mechanical ventilation. An extra step was required for the advanced houses, because their ventilation systems are integrated with the central HVAC systems. In these cases, we used DOE 2.1E to determine the HVAC hourly part load ratios (the fraction that the central HVAC system operates per hour) and then used these values in RESVENT to schedule intermittent mechanical ventilation when calculating the ventilation rates for these houses. Further details on the integrated supply ventilation system modeling are provided in Appendix A.

*ASHRAE Standard 152P – Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems* (ASHRAE 1999) was used to determine the heating and cooling seasonal duct efficiencies for each case. Because the HVAC equipment capacities and airflows are inputs to this method, DOE 2.1E and the 152P models were run iteratively to determine equipment sizes and duct efficiencies. For each analysis case, the average of the heating and cooling seasonal duct efficiencies was used as an input to DOE 2.1E.

The *Refrigerant and Airflow Performance Model* is used to determine the effect of refrigerant charge and system airflow deficiencies on air conditioning system capacity and efficiency. This model uses the charge and airflow degradation algorithms included in the REGCAP model (Siegel 2001), which were originally developed by Proctor Engineering Group (Proctor 2001). The resulting system capacities and efficiencies were used to develop corresponding cooling system performance curves for use in DOE 2.1E.

An LBNL procedure, called WALFERF, for determining DOE 2.1E thermal *assembly transfer functions* was used to evaluate the effect of insulation installation quality issues on overall ceiling and wall R-values. This procedure builds the ceiling or wall assembly in adjacent layers from defined materials with specified thermal variables (conductance, specific heat and density). It uses a finite difference calculation of two-dimensional heat transfer to determine heat transfer through the overall assembly and which allows the modeling of framing factors, concrete blocks, and other construction not integral to DOE-2.1E.

The *general house characteristics* are the dimensional, material, and HVAC system characteristics used in the DOE 2.1E model. To insure that the heating and cooling hourly loads are met by the HVAC systems for each of the analysis cases, we first sized the HVAC systems based on DOE 2.1E's recommended equipment capacities. DOE2.1E uses the peak loads and the equipment performance curves to determine the heating and cooling equipment at standard conditions (47°F dry-bulb for heating and 95°F dry-bulb / 67°F entering wet-bulb for cooling). The pre-commissioned low distribution system efficiencies and degraded equipment efficiencies due to low air handler airflow and refrigerant charge were taken into account when adjusting the total capacities upward to insure adequate cooling during the cooling season. We then selected the next larger size of commercially available cooling and heating equipment. A constraint on the gas furnace selection was that they have sufficient airflow for the cooling mode (based on a nominal 400 cfm per ton of air conditioning). This constraint usually leads to oversized furnaces.



*Iterative DOE-2/RESVENT modeling to determine central system contribution to ventilation rates (advanced houses).

**Iterative DOE-2/152P modeling to calculate overall system effect on thermal distribution system efficiencies.

Figure 1: Modeling Structure.

## ANALYSIS FRAMEWORK – BUILDING AND CLIMATE CHARACTERISTICS

Our analysis is based on three commissioning phases (audit, commissioning, and opportunity), three house prototypes (existing, new, and advanced), two housing quality analysis sets (typical and poor), and four climate zones (two coastal climates and two inland valley climates).

### The Commissioning Phases

The residential commissioning process can be split into three distinct phases – audit and diagnostic (audit phase), tuning and tweaking (commissioning phase), and opportunity identification (opportunity phase). To evaluate the potential energy and cost benefits associated with commissioning-related house improvements, we modeled these three phases in our prototypical houses.

The "audit" phase represents the pre-commissioned houses and is based on what could be found in the houses during the audit and diagnostic phase. This case defines the conditions and possible problems that might be found when commissioning houses in California.

*Commissioning and Opportunity Phases – Measures Implemented*

Table 2 summarizes the improvements modeled for the commissioning and opportunity phases. The "commissioning" phase includes all measures and improvements that were judged to be within the scope of a normal commissioning visit and resulting from tuning and tweaking the existing structures, components, and systems. For the new houses, we include correcting construction defects (insulation installation quality and incorrect window installation), improving the building envelope and duct system air tightness, and correcting the HVAC system's air handler airflow and refrigerant charge. In the existing houses, the list of commissioning improvements includes envelope and duct air tightening, insulating the ducts, and correcting air handler airflow and refrigerant charge.

The "opportunity" phase includes all measures and improvements implemented in the commissioning case plus any measures and improvements that are more extensive and that would require cost-benefit decision-making and additional owner buy-in and costs. The opportunity case for the existing houses includes insulation installation, improved windows, and the installation of HVAC equipment with a thermostatic expansion valve (TXV), an electronically commutated fan motor (ECM), and higher furnace efficiency (90% AFUE). For the new houses, HVAC equipment with a TXV, an ECM, and 90% AFUE furnace is installed. As the advanced houses already have these improvements, no further opportunities are evaluated for these houses.

Table 2: Commissioning and Opportunity Improvements Modeled

| | Commissioning Improvements | Opportunity Improvements |
|---|---|---|
| Existing House | - Envelope Air Tightening<br>- Duct Leakage Reduction<br>- Duct Insulation<br>- Air Handler Airflow<br>- Refrigerant Charge | - Insulation Installation<br>- Upgraded windows<br>- HVAC with:<br>TXV<br>ECM Motor<br>90% AFUE furnace |
| New House | - Insulation Installation Quality Improvements<br>- Correct Windows Installed<br>- Envelope Air Tightening<br>- Duct Leakage Reduction<br>- Air Handler Airflow<br>- Refrigerant Charge | - HVAC with:<br>TXV<br>ECM Motor<br>90% AFUE furnace |
| Advanced House | - Correct Windows Installed<br>- Envelope Air Tightening<br>- Duct Leakage Reduction<br>- Air Handler Airflow<br>- Refrigerant Charge | - No opportunity phase improvements |

The following paragraphs summarize the issues addressed in this analysis. As discussed later, we assume that all of these conditions occur in the poor case and to a lesser extent in the typical case.

*Insulation Installation Quality*. Several studies have found that insulation installation quality varies widely, often with missing, compressed, or improperly installed insulation. In a CEC-funded study, Davis Energy Group found that due to missing or compressed insulation, fiberglass wall insulation performed at 70% of its nominal value, affecting 8.3% of the net wall area (CEC 2000c). Christian et al. (1998) indicate that insulation deficiencies can increase whole-wall heat transfer by about 14%, increasing energy consumption and reducing comfort. Uniacke (2000) found that typically five percent of the attic floor area has no insulation at all, while the rest of the attic is 20% under-insulated due to over-fluffing. Based on the Davis Energy Group and Oak Ridge studies, we assumed a 15 to 16% net reduction in wall assembly insulation effectiveness. For the attics, we assumed that 2.5% of the insulation was missing and that the attic insulation was reduced by 20% due to over-fluffing. Building Science Corporation (Ueno 2001) specifies cocooned insulation methods and blown in cellulose for Building America houses, which eliminates insulation voids or over-fluffing. As such, we assume that the advanced houses do not have any insulation quality degradation.

*Correct Windows.* The primary purpose of windows is to allow occupants to see outdoors. They also serve as a light source, as an aperture for solar heat gains (desirable during the heating season, but undesirable during the cooling season), and as openings (if operable) for ventilation and free cooling. With the exception of some advanced windows that are not commonly installed, window thermal resistance is much lower than that of opaque elements. Because of these characteristics, windows can be one of the largest contributors to heating and cooling loads in a house. In addition, during the heating season, the use of an inappropriate window can lead to low temperatures on the window's interior surfaces, which in turn can cause thermal comfort and indoor air quality problems (e.g., increased radiative heat loss from occupants to nearby cool window surfaces, biological growth due to condensation on windows). As a result, having an appropriate window type installed correctly is important.

For example, Carmody et al. (2000) indicate that the thermal conductance and solar heat gain coefficient (SHGC) for a double-glazed window can each be reduced about 60% by using a low solar-gain low-emittance (low-e) coating and a vinyl frame, compared to using clear glazing and an aluminum frame. The spectral selectivity of the low-e coating allows the window to block out much of the sun's heat while transmitting substantial daylight. In turn, this can reduce the peak-cooling load for a typical southern-climate house by about 25%. Glazing emittance and the location of the low-e coating (on the inside surface of the outer pane) are the most important contributors to this difference.

In spite of the importance of these factors, mislabeled windows are still installed in some new California houses. A recent survey involving about 110 houses (approximately 2,800 windows) found on average that 3% of the windows are mislabeled (ConSol 2000). In two of the houses, as many as 17% of their windows were mislabeled. The mislabeling occurs during window manufacturing and is related to placing the virtually invisible low-e coating on the wrong pane (increases SHGC by about 20%) or the window having clear glazing instead of low-solar gain low-e glazing.

The installation of mislabeled windows with the low-e coating missing or located on the wrong pane can increase the solar heat gain coefficient (SHGC) by up to 45% (ASHRAE 1997), increasing window-related space conditioning loads. We assume that all of the poor and 3% of the typical new and advanced houses have clear double-pane windows rather than low-e double pane windows. The existing houses have single-pane windows.

*Envelope Air Tightening.* Infiltration, or uncontrolled air leakage through the building envelope, can account for up to half of a house's space conditioning loads (Liddament 1996). It is advantageous to reduce infiltration-related space conditioning loads, while still providing sufficient ventilation for indoor air quality purposes. The building envelope leakage values used in this analysis were selected so that they would represent the existing building stock and current new construction practices in California. Sherman and Matson (1997) have used measured building envelope leakage areas to determine a representative range of normalized leakage areas (NL) for existing U.S. housing. Our field measurements found an average normalized leakage of 0.25 for four Las Vegas Building America houses. The Las Vegas houses have construction similar to that found in the Tracy, California Building America houses. These two sets of data were used to estimate normalized leakage values for the analysis cases. For our audit cases, we assumed that the normalized leakage of:

- the existing houses would be equal to that of the existing U.S. housing stock (NL=1.2) for the typical houses and one standard deviation greater for the poor houses (NL = 1.4)
- the new houses would be equal to that of the new California houses built since 1990 in the database (NL = 0.75) for the typical houses and one standard deviation greater for the poor houses (NL = 1.0), and

- the advanced houses would be equal to that found in the Las Vegas Building America houses (NL = 0.25).

Note that Title 24 (CEC 2001b) specifies a default envelope leakage area of 0.49 (SLA=4.9) for new houses.

*Duct Leakage Reduction and Duct Insulation.* Space conditioning duct systems in unretrofitted existing houses have typically had, on average, 28% total duct leakage to outside (Jump et al. 1996). For new California houses, Title 24 assumes a default of 22% total duct leakage to outside (CEC 2001). LBNL field measurements in the Las Vegas Building America houses have found an 11% total duct leakage rate to outside. We assigned these values, respectively, to the existing, new, and advanced houses. These values are all higher than the 6% maximum duct leakage required for the Title 24 tight duct credit. In all cases, we are assuming that the duct leakage is split evenly between the supply and return ductwork.

*Air Handler Airflow and Refrigerant Charge.* Even in new houses, air conditioning systems rarely perform as intended (Sherman et al. 1987). Ensuring good delivery effectiveness and room-by-room distribution efficiency of thermal and ventilation distribution systems depends on maintaining proper airflow across the evaporator coil and through the duct system. Refrigerant charge also has an important impact on the capacity and efficiency of cooling equipment without a thermostatic expansion valve (TXV). For example, laboratory test data from Farzad and O'Neal (1988) for capillary-tube-controlled equipment indicate that a common charge deficiency of 15% can reduce cooling capacity by 8 to 22% and the energy efficiency ratio (EER) by 4 to 16%, depending on outdoor conditions. Typically, 15% under charge and 15% low evaporator airflow has been seen in residential field studies (Wray 2001). Note that while short-tube orifices are more common than capillary tube orifices, they perform similarly at the 15% under-charge and low flow conditions modeled.

*More Efficient HVAC Equipment.* Implementing commissioning and opportunity measures will result in lower building space conditioning loads. In existing houses, replacing older HVAC equipment with more efficient equipment having TXVs, ECM motors, and higher gas furnace efficiencies can result in better comfort and lower relative energy costs. Thermostatic expansion valves are less sensitive to variations in refrigerant charge and system airflow than capillary tubes, and are required to avoid air handler flow and refrigerant charge tests in the AB970 modifications to Title 24 (CEC 2001). As such, we have modeled the replacement of capillary tubes with TXV controls. Additional savings can be realized by changing out existing furnace and air handler motors with ECM motors. Extensive field studies (Phillips 1998) have shown that air handler fan motors typically use 0.5 watts per cfm. Phillip's research indicates that using an ECM motor can reduce this fan energy by 20% at high cooling speeds and by 75% at low heating speeds. We took this into account when determining space conditioning-related fan energy.

### *House Prototypes*

Table 3 summarizes the general house characteristics of the three prototypes modeled (existing, new, and advanced). The characteristics of the *existing* houses are based on California and Pacific Region house characteristics derived from the DOE/EIA

Residential Energy Consumption Survey (EIA 1999) and the PG&E 100 house duct study (Richard Heath and Associates 2000).

The characteristics of the new construction houses are based on the Building America houses currently being built by Pulte Homes in Tracy, CA. Building Science Corporation supplied us with the house characteristics (construction, insulation levels, equipment efficiencies, air tightness) for the Pulte control and optimized Building America houses (Ueno 2000). We used the Pulte control house characteristics and the AB970-revised CEC Title 24 Prescriptive Package D requirements (CEC 2000) to develop the *new* houses. Likewise, the characteristics of the *advanced* house were based on the Pulte Building America houses currently being built in Tracy, California.

Table 3: Analysis Prototypes: General House Characteristics

| | Existing | New | Advanced |
|---|---|---|---|
| Floor Area (ft$^2$) | 1,455 | 2,500 | 2,500 |
| Stories | 1 | 2 | 2 |
| Bedrooms | 3 | 4 | 4 |
| Glazing (% of Floor Area) | 20% (Coastal)<br>16% (Inland Valley) | 20% (Coastal)<br>16% (Inland Valley) | 20% (Coastal)<br>16% (Inland Valley) |
| Foundation | Slab on grade | Slab on grade | Slab on grade |
| Attic | Outside conditioned space | Outside conditioned space | Inside conditioned space |
| Duct Location | Attic | Attic | Inside conditioned space |

*Coastal climates are El Toro (CEC climate zone 8) and Pasadena (CEC climate zone 9). Inland Valley climates are Sacramento (CEC climate zone 12) and Fresno (CEC climate zone 13).

### *"Poor" and "Typical" Construction Cases*

To provide bounds on our analysis, we have evaluated two construction cases. The "typical" construction case represents our best assumption based on information available today of the mix and penetration of energy efficiency improvements typically found in the California residential building stock. To define the typical construction case any finer would require large-scale stock characteristic analyses, which is beyond the scope of this project. The "poor" construction case represents a worst-case scenario in which the building materials and systems are not optimized and only minimal energy efficiency improvements have been made. The typical cases provide an average level of energy savings and benefits while the poor case defines a much higher level of energy savings and benefits.

*Poor Construction Case.* Table 4 summarizes the "poor" case characteristics for the three house prototypes. In terms of commissioning benefits, all of the commissioning and opportunity phase improvements included in this analysis are realized to the largest extent in the poor case.

*Typical Construction Case*. Table 5 summarizes the weighting used to develop the typical house prototypes. The weighting, or the percent of the stock estimated to have a certain characteristic, are based on data from RECS (EIA 1999), the LBNL Leakage Data base (Sherman and Dickerhoff 1998), and field observations (Wray 2001). Eighty separate analyses were conducted, taking into account all of the combinations of improvements (insulation, windows, envelope air tightness, duct air tightness, airflow and refrigerant charge). Analysis results for the various combinations of energy efficiency features were aggregated, based on their weighting, to obtain overall typical case results for each house and commissioning phase case.

Table 4: "As-Found" House Conditions – Poor Case

| | Existing | New | Advanced |
|---|---|---|---|
| Insulation | No wall insulation<br>Ceiling:<br>R30 (D)<br>(all Climate Zones) | Walls:<br>R13 (D) (Coastal)<br>R19 (D) (Inland Valley)<br>Ceiling:<br>R30 (D) (Coastal)<br>R38 (D) (Inland Valley) | Walls:<br>R13 (Coastal)<br>R19 (Inland Valley)<br>Roof:<br>R22 (all climate zones) |
| Windows | Single Pane Aluminum | Clear Double Pane Aluminum | Clear Double Pane Aluminum |
| Envelope Air Tightness | Loose Existing Construction<br>NL = 1.4 | New construction<br>NL = 1.00 | Tighter new construction<br>NL = 0.25 |
| Ventilation | Bathroom and kitchen intermittent exhaust fans | Bathroom and kitchen intermittent exhaust fans | Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when the furnace runs for more than 20 minutes per hour) |
| Ducts | 28% total leakage to outside (split evenly between supply and return)<br>No duct insulation | 22% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation | 11% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation |
| Air Handler Flow | 15% reduction in fan flow<br>Standard motor | 15% reduction in fan flow<br>Standard motor | 15% reduction in fan flow<br>ECM Motor |
| Air Conditioner Refrigerant Charge | 15% undercharged<br>Capillary tube | 15% undercharged<br>TXV | 15% undercharged<br>TXV |
| Furnace AFUE | 78% | 80% | 90% |
| Nominal SEER | 10.00 | 10.00 | 10.00 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 5: Typical House Prototypes – Weighting of Characteristics

| Existing House | | Audit | Commissioning | Opportunity |
|---|---|---|---|---|
| Insulation | R0 Walls<br>R30 (D) Ceilings | 75% | 75% | - |
| | R11 Walls<br>R30/38 Ceilings | 25% | 25% | 100% |
| Windows | Clear Single Pane Aluminum | 75% | 75% | - |
| | Double Pane Vinyl Low-E | 25% | 25% | 100% |
| Envelope Air Tightness | NL = 1.2 | 50% | - | - |
| | Tightened to Std. 62.2P** | 50% | 100% | 100% |
| Duct Leakage | 28% leakage to outside | 50% | - | - |
| | 6% leakage to outside | 50% | 100% | 100% |
| Airflow and Charge | 15% low charge / airflow | 50% | - | - |
| | Correct charge / airflow | 50% | 100% | 100% |

| New House | | Audit | Commissioning | Opportunity |
|---|---|---|---|---|
| Insulation | R13/19 (D) Walls<br>R30/38 (D) Ceilings | 40% | - | - |
| | R13/19 Walls<br>R30/38 Ceilings | 60% | 100% | 100% |
| Windows | Double Pane Aluminum | 3% | - | - |
| | Double Pane Vinyl Low-E | 97% | 100% | 100% |
| Envelope Air Tightness | NL = 0.75 | 75% | - | - |
| | NL = 0.50 | 25% | 100% | 100% |
| Duct Leakage | 22% leakage to outside | 50% | - | - |
| | 6% leakage to outside | 50% | 100% | 100% |
| Airflow and Charge | 15% low charge / airflow | 50% | - | - |
| | Correct charge / airflow | 50% | 100% | 100% |

| Advanced House | | Audit | Commissioning | Opportunity |
|---|---|---|---|---|
| Insulation | R13/19 Walls<br>R22 Roof | 100% | 100% | 100% |
| Windows | Double Pane Aluminum | 3% | - | - |
| | Double Pane Vinyl Low-E | 97% | 100% | 100% |
| Envelope Air Tightness | NL = 0.25 | 25% | - | - |
| | NL = 0.17 | 75% | 100% | 100% |
| Duct Leakage | 11% leakage to outside | 50% | - | - |
| | 4% leakage to outside | 50% | 100% | 100% |
| Airflow and Charge | 15% low charge / airflow | 50% | - | - |
| | Correct charge / airflow | 50% | 100% | 100% |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

**Existing house commissioning case building envelope normalized leakage values (NL) are the level needed to meet the ventilation requirements of ASHRAE Standard 62.2P, and are: El Toro (NL = 0.65), Pasadena (NL = 0.56), Sacramento (NL = 0.49) and Fresno (NL = 0.54).

### *HVAC Equipment Sizes*

Our models assume that the HVAC equipment capacities modeled are sufficiently large enough to meet the loads every cooling hour of the simulation. This allows us to look at the relative energy savings between commissioning phases. In order to evaluate the impact of commissioning houses in which there are existing comfort issues, we modeled a second case, our "comfort call case". This case is discussed only in Appendix C.

### *Thermostat Setpoints*

In order to exchange data between our two hourly models (RESVENT, LBNL's ventilation model based on the LBL infiltration model, and DOE-2) and still obtain a realistic evaluation of temporal ventilation air change rates, we were limited to using a non-setback thermostat approach.

### *Weather Data*

The analysis was conducted for four California climate zones, two in transitional coastal-inland areas ([El Toro [climate zone 8] and Pasadena [climate zone 9]) and two in inland valley areas (Sacramento [climate zone 12] and Fresno [climate zone 13]). These climates were selected to reflect mild and more severe climates, areas with significant existing housing stock, and areas with increases in new residential construction. Table 6 summarizes the ASHRAE and National Weather Service climate data for these climates.

Table 6: Climate Data

| | | Cooling | | | | Heating | |
|---|---|---|---|---|---|---|---|
| | | Dry bulb Temperature * (F) | Wet bulb Temperature * (F) | Dry Bulb Temperature Range* (F) | Cooling Degree Days** | Dry bulb Temperature * (F) | Heating Degree Days** |
| El Toro (Long Beach) | 1% | 88 | 67 | 16.7 | 1201 | 43 | 1430 |
| | 2% | 84 | 66 | | | | |
| Pasadena (LA County) | 1% | 81 | 64 | 10.9 | 1537 | 45 | 1154 |
| | 2% | 78 | 64 | | | | |
| Sacramento | 1% | 97 | 69 | 33.3 | 1237 | 33 | 2749 |
| | 2% | 94 | 68 | | | | |
| Fresno | 1% | 101 | 70 | 30.9 | 1967 | 32 | 2556 |
| | 2% | 98 | 69 | | | | |

Sources: *ASHRAE 1997, **National Weather Service 2001

## ENERGY PERFORMANCE BENEFITS

The key, readily quantifiable benefits from commissioning California houses are improved energy utilization and reduced operating costs. To demonstrate these benefits, this section first will discusses the individual building improvements that we implemented in the commissioning and opportunity phases. It then discusses the synergistic impact of these improvements on energy consumption and energy-related operating costs.

### Building Improvements

Building improvements that we implemented in the commissioning and opportunity phases include insulation and window improvements, envelope air tightening and ventilation, duct efficiency improvements, airflow and refrigerant charge corrections, and using more efficient HVAC equipment. We expect that the combination of these improvements can reduce building space conditioning closer to what was expected when the heating and cooling systems were specified and installed. This reduces energy consumption and correspondingly, the occupant's energy bill. It also may improve occupant comfort, especially when the un-commissioned heating and cooling systems were not able to meet the total space conditioning loads. The following describes the improvements that we modeled.

#### *Insulation*

Tables 7 through 9 summarize the nominal (insulation material only) and net (whole assembly) R-values that we modeled for the wall and ceiling assemblies. The audit case assembly R-values reflect the effect of missing, compressed, and/or over-fluffed insulation installation. The existing houses (audit case) have no wall insulation, but have over-fluffed and missing nominal R-30 ceiling insulation (net R-18.5). By adding R-11 wall insulation and additional ceiling insulation to R-30 or R-38 during the opportunity phase, the net insulating values increase by 70% for the walls and by 37 to 40% for the ceilings of the existing houses. By correcting the insulation installation quality problems during the commissioning phase in new houses, net insulating values increase by 16% for walls, and by 37-40% for the ceilings. Because the advanced houses use blown-in cellulose (walls) and cocooned cellulose (roof) that are well installed and do not typically have voids, no commissioning-related insulation improvements are modeled for these houses.

Improving the insulation installation quality in new houses and adding insulation in under-insulated houses reduces envelope-related building space conditioning loads and can help reduce diurnal indoor temperature swings. It can also reduce envelope cold spots where condensation problems might occur and cause building decay and indoor air quality problems.

Table 7: Net Wall Assembly R-Values

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Existing | Coastal | R-0 | 2.7 | R-0 | 2.7 | R-11 | 9.1 |
| | Inland Valley | R-0 | 2.7 | R-0 | 2.7 | R-11 | 9.1 |
| New | Coastal | R-13 (D) | 8.3 | R-13 | 9.8 | R-13 | 9.8 |
| | Valley | R-19 (D) | 11.5 | R-19 | 13.8 | R-19 | 13.8 |
| Advanced | Coastal | R-13 | 9.8 | R-13 | 9.8 | R-13 | 9.8 |
| | Inland Valley | R-19 | 13.8 | R-19 | 13.8 | R-19 | 13.8 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 8: Net Ceiling Assembly R-Value

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Existing | Coastal | R-30 (D) | 18.5 | R-30 (D) | 18.5 | R-30 | 29.5 |
| | Inland Valley | R-30 (D) | 18.5 | R-30 (D) | 18.5 | R-38 | 37.5 |
| New | Coastal | R-30 (D) | 18.5 | R-30 | 29.5 | R-30 | 29.5 |
| | Inland Valley | R-38 (D) | 22.3 | R-38 | 37.5 | R-38 | 37.5 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table 9: Net Roof Assembly R-Value

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Advanced | Coastal | R-22 | 17.9 | R-22 | 17.9 | R-22 | 17.9 |
| | Inland Valley | R-22 | 17.9 | R-22 | 17.9 | R-22 | 17.9 |

*Windows*

Table 10 summarizes the shading coefficients and U-values of the windows modeled in each of the three cases. We assume that the clear (no low-e coating) double-pane windows of the new and advanced houses are replaced with the correct low-e double pane vinyl window in the commissioning phase. Low-e double pane vinyl windows are also installed in the existing houses during the opportunity phase.

Table 10: Window Thermal Properties

| | Audit | | | | Commissioning | | | | Opportunity | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Window Type | SHGC | SC | U | Window Type | SHGC | SC | U | Window Type | SHGC | SC | U |
| Existing | Single | .86 | 1.00 | 1.27 | Single | .86 | 1.00 | 1.27 | Double Low-E | .41 | .48 | .39 |
| New | Double | .75 | .87 | .51 | Double Low-E | .41 | .48 | .39 | Double Low-E | .41 | .48 | .39 |
| Advanced | Double | .75 | .87 | .51 | Double Low-E | .41 | .48 | .39 | Double Low-E | .41 | .48 | .39 |

Source: ASHRAE 1997. DOE 2.1E uses shading coefficients (SC) in determining window-related space conditioning loads. Shading coefficients are for glazing only. The Solar Heat Gain Coefficients (SHGC) is for glazing at normal incidence angles. U-values (U) are in Btu/F-ft$^2$-hr.

*Refrigerant Charge and Air-Handler Airflow Correction*

Running an air conditioner with low refrigerant charge and/or low air-handler airflow reduces equipment and system capacities and efficiencies (e.g., EER). Common airflow and charge deficiencies are 85% of the nominal air handler flow and 85% of the required refrigerant charge. The Proctor refrigerant charge algorithms (Proctor 2001) were used in conjunction with fan flow adjustment factors (Rodriguez 1995) to model this effect.

By correcting charge and air-handler airflow problems, air conditioners can more closely provide the expected cooling capacity and operate closer to the expected efficiencies. This reduces discomfort hours, air conditioner-related peak demand, and seasonal energy consumption. By incorporating refrigerant and airflow checks and corrections into the commissioning process, builders and contractors can expect that the equipment they specify is capable of providing the cooling capacity expected, thus reducing service calls and unnecessary equipment change-outs in the future.

*Envelope Air Tightening and Ventilation*

Tightening the building envelope takes place in the commissioning phase for all of the analysis cases. Envelope air tightening is a standard component of weatherization and energy-efficient construction efforts. It reduces the amount of uncontrolled ventilation, minimizes space-conditioning energy related to excess ventilation, allows better control of the indoor thermal environment and, correspondingly, increases occupant comfort. In tighter houses such as the advanced houses, adding mechanical ventilation allows occupants to better control air movement in their homes and to reduce point source indoor air quality problems (such as moisture and cooking odors).

Table 11 summarizes the ranges of annual effective air change rates calculated based on each of the analysis cases. Climate and case-specific values are provided in Appendix A. We calculated the annual effective air change rates using the methodology on which ASHRAE Standard 136 (ASHRAE 1993) is based, taking into account the hourly infiltration and ventilation airflow rate variations over the year. The effective air change rate is the constant outdoor air change rate that would result in the same average pollutant concentration over the same period of time as actually occurs under varying conditions.

The initial (audit case) effective ventilation rates range from 0.71 to 0.93 ACH (typical) and 0.82 to 1.08 ACH (poor), and are two to three times greater than the ventilation rates required by ASHRAE Standard 62.2P. The effective ventilation rates for the new houses range from 0.44 to 0.57 ACH (typical) and from 0.58 to 0.76 ACH (poor), and are up to double that required. The effective ventilation rates for the advanced houses are the lowest (0.40 to 0.46 ACH) and are 15 to 30% higher than the rate required by the ASHRAE standard.

The existing house envelope leakage is reduced during the commissioning phase to the levels needed to meet the ventilation requirements of ASHRAE Standard 62.2P: El Toro (NL = 0.65), Pasadena (NL = 0.56), Sacramento (NL = 0.49) and Fresno (NL = 0.54). This reduces the annual effective ventilation rates to 0.30 ACH, a reduction of 45 to 58% for the typical cases and 52 to 68% for the poor cases. For the new houses, we reduce the annual effective ventilation rates to 0.30 to 0.39 ACH, a reduction of 32 to 33% for the typical cases and 48 to 49% for the poor cases. Even with these large relative reductions in ventilation and no whole-house mechanical ventilation, all but one of the existing and new air-sealed cases still have effective air change rates equal to or greater than the Standard 62.2P requirements. The effective ventilation rate for the air-tightened El Toro new house is slightly below the Standard 62.2P requirement. Because the large reductions in building envelope leakage provide much lower effective air change rates that are closer to the Standard 62.2P values, we expect there should also be significant reductions in ventilation-related space conditioning energy consumption for the existing and new houses. We did not carry out separate simulations to isolate this reduction.

By reducing envelope leakage for the advanced case during commissioning, we found that the annual effective ventilation rate drops only slightly to 0.39 ACH. After these already tight building envelopes are tightened further, the central system fan runtime modulates upwards to deliver the required ventilation airflow. Had they not had mechanical supply ventilation systems, the advanced houses would not meet ASHRAE Standard 62.2P.

Table 11: Envelope Air Tightening and Ventilation
Annual Effective Ventilation Rates - Air Change per Hour (ACH)

| | Standard 62.2P Requirement | Audit Poor Case | Audit Typical Case | Commissioning & Opportunity |
|---|---|---|---|---|
| Existing | 0.38 | 0.82 to 1.08 | 0.71 to 0.93 | 0.39 |
| New | 0.34 | 0.58 to 0.76 | 0.44 to 0.57 | 0.30 to 0.39* |
| Advanced** | 0.34 | 0.40 to 0.41 | 0.40 to 0.41 | 0.39 |

* The El Toro new house does not meet Standard 62.2P when it is tightened to the 0.50 normalized leakage value.

** The advanced houses have mechanical supply ventilation systems, an outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when the furnace runs for more than 20 minutes per hour)

### *Duct Leakage and Thermal Distribution System Efficiency*

Poor construction and operation of residential thermal energy distribution systems can cause comfort problems, poor indoor air quality, and structural moisture problems, as well as wasted energy. In particular, ducts may be the single worst performer in the energy performance of a house (Jump et al. 1996). Much of the problem can be attributed to installing ducts outside of the conditioned space, duct leakage, duct insulation compression, and other poor installation practices. Reducing duct leakage increases the thermal distribution system efficiency, reduces the amount of energy lost to unconditioned space, and increases the amount of conditioned air delivered to the living spaces.

Table 12 summarizes the ranges of thermal distribution system efficiencies that we modeled (See Appendix A for climate and case specific data). The duct systems for the existing and new houses are located primarily in the unconditioned attics (63% of the total duct surface area) and respectively have 28% and 22% total duct leakage to the outside. By reducing duct leakage during commissioning of the existing houses, duct efficiencies increase from a range of 78 to 82% (poor) and 83 to 85% (typical) to a range of 88 to 90%. For the new houses, those duct efficiencies increase from a range of 81 to 85% (poor) and 83 to 85% (typical) to a range of 86 to 87%. The commissioned new house duct efficiencies are lower than those for the commissioned existing house because the new houses have proportionally more duct surface area in the attics. During the opportunity phase, these efficiencies may drop slightly when implementing smaller HVAC equipment with the same duct system (i.e., the duct system is oversized in relationship to the replacement equipment).

The advanced house duct systems are relatively airtight (11% total leakage to outside) and are located in the conditioned attic. We measured temperature differences between the attic of the Las Vegas Building America houses and outside that were 10% of the temperature difference measured in the control (non-cathedralized attic) house, so the advanced house ducts are modeled assuming that 10% of the duct surface area is in what Standard 152P considers an unconditioned attic and the remainder is in the conditioned space. When air-tightening the advanced house ducts during commissioning, the corresponding duct efficiencies rise only slightly: the audit case duct efficiencies range from 90 to 91% (poor) and 91 to 92% (typical) while the commissioning case duct efficiencies range from 93% to 94%.

Table 12: Thermal Distribution System Efficiencies

| | Audit | | Commissioning | | Opportunity** |
|---|---|---|---|---|---|
| | Poor | Typical* | Poor | Typical* | |
| Existing | 78 to 82% | 83 to 85% | 89 to 90% | 88 to 90% | 86 to 87% |
| New | 81 to 85% | 83 to 85% | 86 to 87% | 86 to 87% | 86 to 87% |
| Advanced | 90 to 91% | 91 to 92% | 93 to 94% | 93 to 94% | n/a |

*Thermal distribution systems efficiencies for the typical cases are aggregated based on the individual typical case component runs.

**Smaller HVAC equipment with the same duct system can result in slightly lower thermal distribution system efficiencies.

*More Efficient HVAC Equipment*

The opportunity case includes the installation of equipment with thermostatic expansion valve controls (TXVs), electronically commutated motors (ECMs), and higher-efficiency gas furnaces. Each of these improvements addresses a separate part of the energy picture: by installing more efficient equipment, the equipment is better able to meet the load and operate in a more efficient manner; the thermal expansion valve allows for better refrigerant control and less impact on air conditioner performance due to low refrigerant charge and low airflow conditions; the electronically-commutated motor reduces the air conditioning and furnace parasitic electricity consumption by 75% at low-speed heating airflow and 20% at high-speed cooling airflow; and the higher efficiency gas furnace reduces overall gas consumption and related carbon emissions.

## The House as a System – Commissioning Benefits

Rather than improving system and equipment efficiency on a component-by-component basis, commissioning considers the house as a system and takes advantage of the interactions between systems and components. By doing so, it is possible to leverage capital and operating cost savings to fund measures that are more expensive. Such an integrated approach allows energy-efficiency measures that make little sense individually (e.g., windows) to be cost-effective and attractive together within the whole system, due to concurrent benefits such as reduced equipment size and improved comfort (RMI 1997). In evaluating the commissioning-related benefits (energy and cost savings), we have quantitatively considered how several measures work synergistically to reduce energy consumption, operating costs, and environmental impacts.

## Energy Consumption

Our evaluation of the benefits from commissioning California's houses has considered two levels of related energy savings. The first is the amount of energy saved in the commissioning phase (basic tuning and tweaking) through improving building and duct air tightness, correcting air-handler airflow and refrigerant charge in new and existing houses alike, and by installing correct windows and improving insulation installation quality in new houses. The second level is the amount of energy saved during the opportunity phase if the homeowner implements all of the improvement opportunities suggested, plus improved insulation and windows in existing houses, and more efficient HVAC equipment (TXV, ECM, and 90% AFUE furnace efficiencies) for the existing and new houses.

*Aggregation of Energy Consumption Results*

Energy usage and corresponding savings are determined for each case by aggregating the individual building energy usage relating to the commissioning and opportunity measures. As discussed previously and in Appendix A, these values are derived from DOE-2.1E and other modeling that we used to determine annual electricity and natural gas consumption. The aggregate energy consumption values are based on space conditioning energy (cooling, heating, ventilation, and related fans). All results are discussed in terms of site energy.

*Typical Cases - Aggregation of Energy Consumption Results.* The typical case energy consumption results are calculated by weighting the aggregate energy consumption values for the individual typical case runs. For example, the electricity consumption results from the individual typical existing audit case runs are weighted based on the penetration rate of the individual components to obtain the average electricity consumption values for the typical existing audit case.

*Electricity Consumption and Savings*

The annual space conditioning-related annual electricity consumption rates and percent savings are summarized in Table 13. Electricity consumption values are provided per square foot of conditioned space to provide comparisons between building types. All savings percentages are reported in terms of savings over the audit cases.

*Audit Cases*

For the typical audit cases, the one-story existing houses use the highest annual space conditioning-related electricity consumption (1.6 to 4.3 kWh/ft$^2$ - yr[CPW1]). The electricity consumption of the advanced and new audit case houses are similar (0.7 to 1.8 kWh/ft$^2$/year and 0.6 to 1.8 kWh/ft$^2$/year, respectively). In all house types, the electricity consumption of the coastal houses is on the lower end of the range, followed by Sacramento and Fresno. The Fresno houses have almost double the electricity consumption as the Sacramento houses, driven by the more severe Fresno cooling climate. While the advanced audit case houses have tighter envelopes and ducts and mechanical ventilation systems, the coastal and Sacramento climate advanced houses use 9 to 24% more electricity than the new houses. We found that the tighter advanced houses had less available infiltration and ventilation-driven free cooling in these climates and required more air conditioning-related electricity consumption. The Fresno houses are less affected by infiltration-driven free cooling, resulting in lower electricity consumption for the advanced house than for the new house.

The poor cases represent houses in which all of the commissioning and opportunity measures would be applicable. As would be expected, compared to the typical cases, the poor audit cases use about 30% more electricity for the existing house and two to three times more for the new and advanced houses.

*Commissioning and Opportunity Cases*

*Existing Houses:* Commissioning activities in the existing houses include envelope and duct air-sealing and correcting air handler airflow and refrigerant charge. The typical existing cases, when commissioned, show a 14 to 18% reduction in electricity consumption. The poor existing cases have higher envelope leakage values and show a 20 to 28% reduction in post-commissioning electricity consumption. Taking it one step further in the opportunity phase (wall and increased ceiling insulation, low-e double pane window upgrades, and more efficient HVAC equipment), it is possible to reduce electricity consumption by 61 to 74% for the typical cases and 71 to 80% for the poor cases. Note that the inland valley climates have slightly higher commissioning-related savings percentages than the coastal climates. This percentage difference levels out when the additional opportunities are implemented.

*New Houses:* Commissioning activities in the new houses include correcting insulation installation problems, installing correct windows, envelope and duct air-sealing and correcting air handler airflow and refrigerant charge. The typical new houses, when commissioned, show a 7 to 11% reduction in electricity consumption. The poor new cases show a larger reduction in electricity consumption (55 to 71%), driven by replacing clear double pane windows with low-E double pane windows. The installation of more efficient HVAC equipment in the opportunity phase does not make a significant difference in the typical new cases. Savings are increased by one percentage point at most over the savings achieved in the commissioning phase.

*Advanced Houses:* Commissioning the advanced houses includes the same measures implemented in the new house (correcting insulation installation problems, installing correct windows, envelope and duct air-sealing, and correcting air handler airflow and refrigerant charge). As the advanced audit cases already have relatively air tight envelopes (NL=0.25) and ducts (11% leakage to outside), and do not have significant insulation installation problems, the savings are small (7 to 10%) for the typical cases. As found with the new poor cases, replacing incorrectly-installed clear double pane windows with the correct low-e double pane windows increases the savings significantly to 52 to 73%.

Table 13: Space Conditioning System Electricity

| | | Electricity Consumption (kWh/ft$^2$/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 1.62 | 2.20 | 2.29 | 4.26 | 2.13 | 2.87 | 3.04 | 5.69 |
| | Commissioning | 1.37 | 1.90 | 1.92 | 3.50 | 1.69 | 2.30 | 2.30 | 4.10 |
| | Opportunity | 0.42 | 0.69 | 0.75 | 1.66 | 0.42 | 0.69 | 0.75 | 1.66 |
| New Title 24 | Audit | 0.55 | 0.81 | 0.89 | 1.83 | 1.76 | 2.21 | 2.07 | 3.57 |
| | Commissioning | 0.51 | 0.75 | 0.81 | 1.62 | 0.51 | 0.72 | 0.81 | 1.62 |
| | Opportunity | 0.50 | 0.71 | 0.79 | 1.61 | 0.50 | 0.71 | 0.79 | 1.61 |
| Building America | Audit | 0.68 | 0.87 | 0.96 | 1.79 | 2.21 | 2.55 | 2.25 | 3.49 |
| | Commissioning | 0.61 | 0.79 | 0.89 | 1.67 | 0.61 | 0.79 | 0.89 | 1.67 |

| | | Electricity Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 15% | 14% | 16% | 18% | 21% | 20% | 25% | 28% |
| | Opportunity | 74% | 69% | 67% | 61% | 80% | 76% | 75% | 71% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 7% | 7% | 9% | 11% | 71% | 67% | 61% | 55% |
| | Opportunity | 8% | 12% | 11% | 12% | 72% | 68% | 62% | 55% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 10% | 10% | 7% | 7% | 73% | 69% | 60% | 52% |

### *Natural Gas Consumption and Savings*

The annual space-conditioning-related natural gas consumption and savings are summarized in Table 14. Compared to the new and advanced typical audit cases, the existing typical audit cases use two to four times more gas per square foot. Comparing the poor cases to the typical cases, the poor audit cases use about 40% more gas for the existing houses, about the same (coastal climates) to 20% more (inland climates) for the new houses, and about the same for the advanced houses.

Commissioning the existing and new houses results in significant natural gas savings. For the existing houses, savings range from 18 to 21% (typical cases) and 33 to 36% (poor cases). Implementing opportunity measures such as wall and improved ceiling insulation, double pane low-E windows, and improved HVAC equipment increases the existing house savings to 44 to 54% (typical cases) and 59 to 67% (poor cases). With these improvements, the opportunity phase existing houses use about the same amount of gas per square foot as the audit case new houses. For the new houses, commissioning-related savings range from 24 to 25% (typical cases) and 18 to 35% (poor cases). Improving the furnace efficiency in the opportunity phase increases these savings slightly to 28 to 31% (typical cases) and 22 to 41% (poor cases).

The advanced typical cases realize a small range of commissioning-related savings (2 to 3%). The corresponding poor cases see negative savings (-19 to –10%). These low and negative heating-related gas consumption savings are due to the reduction in heating season solar gain by installing the correct low-e double pane windows.

Table 14: Space-Conditioning-Related Natural Gas

| | | Natural Gas Consumption (Therm/ft$^2$/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 0.13 | 0.14 | 0.35 | 0.31 | 0.18 | 0.19 | 0.48 | 0.42 |
| | Commissioning | 0.11 | 0.11 | 0.27 | 0.25 | 0.12 | 0.13 | 0.31 | 0.28 |
| | Opportunity | 0.07 | 0.07 | 0.16 | 0.14 | 0.07 | 0.07 | 0.16 | 0.14 |
| New Title 24 | Audit | 0.07 | 0.07 | 0.18 | 0.16 | 0.06 | 0.07 | 0.21 | 0.18 |
| | Commissioning | 0.05 | 0.05 | 0.14 | 0.12 | 0.05 | 0.05 | 0.14 | 0.12 |
| | Opportunity | 0.05 | 0.05 | 0.12 | 0.11 | 0.05 | 0.05 | 0.12 | 0.11 |
| Building America | Audit | 0.04 | 0.04 | 0.09 | 0.09 | 0.03 | 0.03 | 0.08 | 0.08 |
| | Commissioning | 0.04 | 0.04 | 0.09 | 0.08 | 0.04 | 0.04 | 0.09 | 0.08 |

| | | Natural Gas Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 18% | 19% | 21% | 19% | 33% | 35% | 36% | 34% |
| | Opportunity | 44% | 47% | 54% | 53% | 59% | 62% | 67% | 66% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 25% | 24% | 24% | 24% | 18% | 22% | 35% | 34% |
| | Opportunity | 29% | 28% | 31% | 31% | 22% | 26% | 41% | 40% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 2% | 2% | 3% | 3% | -19% | -18% | -10% | -10% |

*Annual Operating Costs*

We calculated annual operating costs based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of $0.1071/kWh (EIA 2000) and $0.634/therm (EIA 2001). These values provide a base level of comparison. Energy price increases, such as those experienced during the winter 2000/2001 California energy crisis, will further enhance the attractiveness of commissioning California's houses. The annual space-conditioning-related annual operating costs and savings are summarized in Table 15.

As expected for the typical audit cases, the existing houses have the highest space conditioning-related operating costs ($0.26 to $0.65 per square foot). The new house operating costs are lower. While the advanced cases use 40 to 50% less gas than the new cases, they use up to 24% more electricity. As a result, the operating costs for the advanced houses are about the same as for the new houses ($0.10 to $0.29 per square foot for the new houses and $0.10 to $0.25 per square foot for the advanced houses). The corresponding existing poor audit cases have 33 to 36% higher operating costs while the new and advanced poor audit cases have two to three times the operating costs of the typical cases. This increase is primarily due to the large impact of clear versus low-E double pane windows in the poor new and advanced audit cases.

For the typical cases, commissioning results in operating cost savings of 15 to 18% for the existing houses, 12 to 17% for the new houses, and 6 to 8% for the advanced houses. Implementing opportunity phase building and equipment improvements results in 59 to

64% savings in the existing houses and a slight increase to 17 to 22% savings in the new houses.

Operating cost savings are highest for the poor cases, ranging from 25 to 30% for the existing cases, 50 to 62% for the new cases, and 45 to 66% for the advanced cases. The opportunity phase improvements result in 69 to 73% operating cost savings for the existing cases. Implementing the higher furnace efficiency and the ECM motor increases the new operating cost savings slightly to 51 to 63%.

Table 15: Space-Conditioning-Related Operating Costs

| | | Operating Costs ($/ft$^2$/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 0.26 | 0.32 | 0.46 | 0.65 | 0.34 | 0.43 | 0.63 | 0.88 |
| | Commissioning | 0.22 | 0.27 | 0.38 | 0.53 | 0.26 | 0.33 | 0.44 | 0.62 |
| | Opportunity | 0.09 | 0.12 | 0.18 | 0.27 | 0.09 | 0.12 | 0.18 | 0.27 |
| New Title 24 | Audit | 0.10 | 0.13 | 0.21 | 0.29 | 0.23 | 0.28 | 0.35 | 0.50 |
| | Commissioning | 0.09 | 0.11 | 0.17 | 0.25 | 0.09 | 0.11 | 0.17 | 0.25 |
| | Opportunity | 0.08 | 0.11 | 0.16 | 0.24 | 0.08 | 0.11 | 0.16 | 0.24 |
| Building America | Audit | 0.10 | 0.12 | 0.16 | 0.25 | 0.26 | 0.29 | 0.29 | 0.42 |
| | Commissioning | 0.09 | 0.11 | 0.15 | 0.23 | 0.09 | 0.11 | 0.15 | 0.23 |

| | | Operating Cost Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 16% | 15% | 18% | 18% | 25% | 24% | 30% | 30% |
| | Opportunity | 64% | 63% | 61% | 59% | 73% | 72% | 71% | 69% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 15% | 12% | 17% | 15% | 62% | 61% | 51% | 50% |
| | Opportunity | 17% | 17% | 22% | 18% | 63% | 62% | 54% | 51% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 8% | 8% | 6% | 6% | 66% | 63% | 48% | 45% |

## Non-Energy Benefits

In addition to reducing energy consumption and associated operating costs, implementing commissioning and opportunity measures helps improve building and system durability, reduces maintenance and material replacement costs, increases house resale value, improves indoor environmental quality, and benefits the environment and the economy.

### *Durability, Maintenance, Material Replacement, and Resale Value*

#### *Improved Durability*

By improving the building structure through airtightness, insulation, and window upgrades, we expect that there would be a reduction in building envelope failure problems, such as material decay due to moisture damage. A more uniformly insulated and airtight building envelope can help reduce cold spots, which foster moisture and material damage.

*Reduced Maintenance, Material, and Equipment Replacement*

Improving the air conditioner efficiency and increasing the delivered capacity in a well-performing house sets the stage for the house and equipment to operate as designed or expected. In the case of air conditioning systems, this could reduce the number of burned-out motors and compressors caused by incorrect refrigerant charge and low air-handler airflow. It follows that equipment could last longer, which would reduce replacement costs over the life of a house. There also could be a reduction in maintenance costs, especially related to equipment performance problems.

*Increased Resale Value*

Housing value and utility costs reported in the American Housing Survey (Nevin and Watson 1998) indicate that house resale value increases from $10 to $25 for each dollar of annual energy savings. This relationship was evaluated for a variety of sample sizes (national vs. all metropolitan statistical areas), housing types, and heating fuels. More specifically, for single-family detached houses, regardless of fuel type, they found a $20 average increase in housing resale value per dollar of annual energy savings.

The California Association of Realtors (CAR 2001) reports the average price of an existing; single-family detached house in California during January 2001 was $246,380 (based on 508,060 closed escrow sales) and $262,980 in March 2001 (Sinton 2001). Based on these prices and our energy analyses, and assuming a $20 average increase in housing resale value per dollar of annual energy savings, the energy savings realized through commissioning could result in average incremental resale value increases of:

- $1,200 to $3,500 (typical) and $2,500 to $7,600 (poor) in existing cases,
- $700 to $2,300 (typical) and $7,000 to $12,300 (poor) in new cases, and
- $400 to $700 (typical) and $8,400 to $9,500 (poor) in advanced cases.

Taking advantage of additional opportunities identified in the commissioning process could result in an additional incremental energy-related increased resale values from $3,600 to $7,600 (typical) and $4,800 to $10,000 (poor) more in existing cases and up to $400 more in poor new cases.

The energy-savings-related increased resale values described above are on the low end of the scale for the coastal climates and on the high end of the scale for the inland valley climates.

*Comfort and Indoor Air Quality*

An important benefit of commissioning is the improvement of thermal comfort, indoor air quality, and combustion safety (which in part affects indoor air quality). Indoor environmental quality issues are not directly addressed in the DOE-2.1E modeling, but we expect that by improving the building envelope and the building systems, thermal comfort can be improved by providing more uniform conditions throughout the house. Reducing infiltration reduces the amount of air that is brought into the house from crawlspaces, garages, and other areas having moisture or contaminants that negatively affect indoor air quality. Improving the building envelope through air tightening and improved insulation quality reduces cold spots that could lead to envelope moisture problems. Improving HVAC equipment through duct air tightening and correcting refrigerant charge and air-handler and duct airflow problems delivers more conditioning capacity to the house and is better able to keep the house comfort conditions closer to set-points and within occupants expectations. These improvements contribute to a better indoor environment.

*Environmental Protection*

By improving the durability and energy efficiency of California houses through commissioning, the environment benefits from reduced building energy consumption-related carbon emissions and lower embodied energy and waste over the lifetime of the houses.

*Reduced Carbon Emissions*

Typical households contribute carbon emissions to the atmosphere by using electricity and natural gas in their homes. By reducing electricity and natural gas consumption in California houses, we are able to reduce the corresponding carbon emissions into the atmosphere. For the purpose of this analysis, we are using a marginal emission rate of 0.10 kg/kWh of site energy consumption, based on utility electricity production using improved generation and emissions technologies. This marginal rate assumes that efficient, low-emission generation plants are used. For natural gas, we are using a marginal emission rate of 5.2 kg/therm of site energy consumption (ASHRAE 1997). Table 16 summarizes the space conditioning-related carbon emission reductions. As the carbon emissions scale with the amount of electricity and natural gas consumed in a house, the relative amount of carbon emission reductions follows the same general trends seen with electricity, natural gas and operating cost savings.

For the typical cases, commissioning the existing and new houses results in 200 to 600 kg/house/year carbon emission reductions (19 to 23%, existing, and 23 to 26%, new). The advanced house, due to its already advanced energy efficient construction, sees a smaller 30 to 60 kg/house/year carbon emission reduction (4%). When additional opportunities are implemented the carbon emission reductions almost triple in the existing houses, to 630 to 1630 kg/house/year (56 to 62%), and increase slightly in the new houses, to 260 to 750 kg/house/year (28 to 33%).

The commissioned poor existing and new cases have twice as much net carbon reductions as the typical houses, from 500 to 1450 kg/house/year (35 to 40%, existing, and 41 to 44%, new). The advanced houses see an almost ten-fold net carbon emissions, from 230 to 360 kg/house/year due to the replacement of clear double pane windows with low-e double pane windows. When additional opportunities are implemented the carbon emission reductions almost double in the existing houses, to 1070 to 2690 kg/house/year (71 to 77%) and increase slightly in the new houses, to 490 to 1430 kg/house/year (44 to 50%).

Table 16: Space Conditioning System – Related Carbon Emission Reductions

| | | Kg/house-year | | | | | |
|---|---|---|---|---|---|---|---|
| | | Typical | | | Poor | | |
| | | Electricity Related | Gas Related | Total Fuel Related | Electricity Related | Gas Related | Total Fuel Related |
| Existing | Commissioning | 40 to 110 | 180 to 550 | 220 to 610 | 70 to 230 | 460 to 1330 | 530 to 1440 |
| | Opportunity | 170 to 380 | 450 to 1400 | 630 to 1640 | 250 to 590 | 820 to 2440 | 1070 to 2690 |
| New | Commissioning | 10 to 50 | 210 to 570 | 220 to 580 | 310 to 490 | 140 to 960 | 460 to 1270 |
| | Opportunity | 10 to 50 | 250 to 720 | 260 to 750 | 320 to 490 | 170 to 1110 | 490 to 1430 |
| Advanced | Commissioning | 20 to 30 | 10 to 40 | 30 to 60 | 340 to 460 | -110 to -80 | 230 to 360 |

| | | Percent of Audit Case | | | | | |
|---|---|---|---|---|---|---|---|
| | | Typical | | | Poor | | |
| | | Electricity Related | Gas Related | Total Fuel Related | Electricity Related | Gas Related | Total Fuel Related |
| Existing | Commissioning | 14 to 18% | 20 to 24% | 19 to 23% | 20 to 28% | 39 to 42% | 35 to 40% |
| | Opportunity | 61 to 74% | 52 to 63% | 56 to 62% | 71 to 80% | 68 to 78% | 71 to 77% |
| New | Commissioning | 7 to 11% | 28 to 29% | 23 to 26% | 55 to 71% | 21 to 41% | 41 to 44% |
| | Opportunity | 8 to 12% | 33 to 36% | 28 to 33% | 55 to 72% | 26 to 47% | 44 to 50% |
| Advanced | Commissioning | 7 to 10% | 2 to 4% | 4% | 52 to 73% | -23 to 12% | 15 to 36% |

### *Lower Embodied Energy and Waste*

Qualitatively, because commissioning improves the envelope and its component systems and materials, material and equipment replacement are needed less frequently. The lifetime of the house is also lengthened. In terms of the environment, this translates into a lower use of natural resources and correspondingly, a lower embodied energy (the amount of energy required for manufacture, construction, and deconstruction and waste reduction and decay) over the lifetime of the house.

### *The Economy*

The economy, within and beyond the State of California, is a direct benefactor of the building improvements implemented in the commissioning and opportunity phases. Commissioning contributes to reduced energy costs, which frees up increased funds for other purposes; expanded business opportunities; the development of new industries; increased jobs for California residents; and increased tax revenues.

### *Reduced Energy Costs = Increased Funds for Other Purposes*

Improving the energy efficiency of California's houses will reduce energy bills for California residents. These reduced energy bills allow occupants opportunities to live better within their means and to use funds freed up by reduced energy costs to pursue other goals, such as education and improved health and comfort. This correspondingly helps the related California industries, such as education, health, and leisure-related industries.

*Expanded Business Opportunities*

California's construction, HVAC, rating and weatherization, and energy consulting industries already implement parts of the overall commissioning package on a piecemeal basis. Commissioning practices described here build upon this local business base. Integrating commissioning services into their current business practices will allow these industries to expand their services, provide additional benefits to their customers, and provide a much higher level of service in the short, medium, and long-term.

In order for these industries to expand, however, we need to insure that there are sufficient contractors and service providers. Because of their established business areas and skill sets, CHEERS raters and HVAC contractors are most able to expand their businesses to include commissioning. Home inspectors, who have a good general background and are trained to look for problems could learn how to do detailed instrumented testing and to implement commissioning improvements. As such, we see commissioning as an opportunity to expand the current market activities and open it up to new participants.

*Development of New and Expanded Industries*

The implementation of residential commissioning in California will influence the development of new measurement techniques, new technologies, and new services (such as integrated, whole-house commissioning and building improvement services). The expanding industries that implement residential commissioning practices in California should lead to best practice guides and protocols, improved building and energy codes, and enhanced Home Energy Rating Systems (HERS). The implementation of commissioning will begin to stimulate the development of improved products by equipment and component manufacturers and of improved services by HVAC contractors, energy service companies, and other residential market participants. The California building, HVAC, and energy service industries will be able to implement and market improved residential building energy systems, equipment and other products, and energy efficiency services as part of their normal business practices. There are opportunities for added market penetration of new products related to commissioning, Title 24, and HERS implementation in the new construction and existing residential market. This will result in the development of new industries, encompassing providers of expanded commissioning services and the segment of the manufacturing industries constructing and marketing new commissioning-related test equipment and materials within and outside of California.

*Increased Jobs for California Residents*

To maximize successful implementation of commissioning in the California residential market, a trained and knowledgeable work force is necessary. The existing construction, HVAC, weatherization, rating and energy consulting industries provide a structure within which the existing workforce can be trained to provide commissioning services. As residential commissioning becomes a part of these industries' normal operating procedures, this will result in more jobs for California, from technician to CEO.

*Increased Tax Revenues*

The State of California will receive additional tax revenues on sales and services relating to commissioning of California houses. In addition, California will receive income taxes related to the additional jobs required to perform commissioning services and implement commissioning and opportunity phase measures.

## CONCLUSIONS

### The Benefits of Commissioning

By commissioning California houses, many parties benefit. The magnitude of the benefits to a specific party or stakeholder depends on how that stakeholder weighs the commissioning-related economic and non-economic benefits.

The *occupants*, whether they are homeowners or renters, benefit from better performing systems and houses, increased comfort, and more efficient use of the energy they are paying for. The efficiency improvements result in reduced energy consumption and reduced energy bills, freeing up their energy dollars for other needs and goals. Homeowners see greater building and system durability and, correspondingly, longer lifetimes for house system and components. This reduces maintenance and replacement costs and increases home resale values. Through energy reductions and performance improvements realized by the implementation of commissioning, occupants help the environment by reducing carbon emissions, lowering embodied energy, and reducing use of natural resources.

Members of the *building community* (e.g., builders, HVAC contractors) benefit from an improvement in building and system performance and quality, which can reduce their callback and warranty costs. The building community, including HERS raters and house inspectors, will have access to an expanded market sector with a more diverse client base. This will allow them greater employment and greater revenues through increased business. They will see an integration of commissioning services into their normal business model, allowing for an expansion of maintenance and installation services.

The *utilities* benefit from reduced peak demand, translating into lower energy acquisition costs. The utilities also benefit from realizing lower carbon emissions, allowing them increased compliance with environmental regulations.

*Governmental bodies* (the California Energy Commission and the Air Resources Board) benefit from greater assurance that actual energy consumption and carbon emissions are closer to the levels mandated in codes and standards, resulting in better achievement of state energy conservation and environmental goals.

*Building code officials* benefit from better compliance with codes as the commissioning process catches construction defects and code problems.

The *insurance industry* benefits from reduced insurance claims and litigation due to problems caused by poor-performing building envelopes and systems.

The *banking industry* benefits from increased economic activity due to reduced house operating costs and increased revenues for commissioning-related businesses.

*The State* benefits directly and indirectly from commissioning activities. Improved building performance and better indoor environmental comfort helps improve the quality of life for California residents. The corresponding reduced energy bills free up money for residents to spend on other needs or goals, such as additional education and health and welfare. In the expansion of existing industries and the development of new industries related to commissioning, the state sees an increase in jobs and tax revenue, improving the quality of life for the state as a whole.

### Commissioning Makes Sense for California's Houses

While building codes and energy standards lead towards greater efficiency of new houses, commissioning results in even greater energy efficiency in both new and existing houses. Commissioning benefits limited to tuning and tweaking of existing buildings and systems (building air tightness, duct tightening, refrigerant charge and HVAC system airflow correction) may result in 15 to 30% HVAC-related operating cost savings. Implementing opportunities identified in the commissioning process (insulation, improved windows, more efficient HVAC equipment, and mechanical ventilation) may result in 60 to 75% HVAC-related operating cost savings in existing houses. In new houses, commissioning benefits related to correcting construction defects and tuning and tweaking the building and systems may result in 10 to 20% HVAC-related operating cost savings in typical houses and 50 to 60% savings in houses with significant problems (clear instead of low-e double glazed windows, poor installation quality and poor building and system performance). Advanced energy-efficient new construction with typical building and system performance problems may see up to 8% operating cost savings. Where significant problems occur, these buildings may realize up to 65% operating cost savings.

Commissioning also helps reduce peak demand and improve the indoor environment in a subset of homes throughout the state. Quantification of these benefits, however, requires further study.

### Houses Perform Closer to Expectations

Currently, the energy savings estimated due to energy codes are not being realized. By improving performance, it is more likely that the energy savings realized would be closer to estimates and expectations. For the occupant, defining expectations and acceptability is difficult. By improving building and system performance, the houses will be better able to provide sufficient space conditioning and improved thermal comfort which work towards meeting the occupant's expectations.

### Commissioning as Part of the Business Package

Various players in the building industry currently do some level of commissioning, however small. For example, through compliance credits, California's Title 24 energy code already provides some commissioning elements for evaluating the energy performance of new houses (e.g., visual inspection, functional performance diagnostics). Many of these elements can be integrated into new industry guidelines for testing and tuning system performance in new and existing houses.

The existing California residential building industry and new developing industries can be augmented and expanded to include commissioning services. The Home Energy

Rating Systems (HERS), home inspection services, and home performance consulting industries provide a framework within which to incorporate the commissioning model. Commissioning can be integrated into existing business models, however training and business assistance would be needed to make sure that businesses offering commissioning services to their clients are able to provide significant parts of the commissioning package. Implementing only one part of commissioning, such as correcting air handler airflow and refrigerant charge, without checking duct air tightness results in missed opportunities and leads the homeowner to believe that the house has been optimized and cannot perform any better. But, if that same contractor had been able to look at the house as a system and evaluate and tweak and tune the performance of all parts of the house, a much more efficient house would result and more opportunities may be implemented.

### Commissioning Helps California

The benefits of commissioning California's houses are widespread. The improvements incorporated in the commissioning phase results in a significant level of energy savings in existing houses as well as in new houses. Implementing the opportunity phase measures in existing houses can reduce their energy consumption per square foot down to the level of the new houses. Of course, this is at a greater cost than if it were implemented during the design and construction process. All of the stakeholders (occupants, homeowners, builders and contractors, utilities, state agencies, code authorities, the insurance and banking industry, the environment, and the economy) stand to benefit from the implementation of commissioning-related performance improvements in California's houses. By understanding the types and magnitudes of benefits, California's business community should be able to realize increased business and profitability.

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## APPENDIX A – MODELING ASSUMPTIONS

### Opaque Envelope Elements

The opaque envelope elements modeled include walls, ceilings, roofs and floors. Floors are un-insulated slab on grade. Table A-1 summarizes the overall characteristics of the remaining elements.

Table A-1: Wall, Ceiling and Roof Characteristics

| | Framing | Framing Fraction | Cavity Insulation Type | Interior Surface Type | Exterior Surface Type |
|---|---|---|---|---|---|
| Walls | All Existing Houses and Coastal New Houses:<br>2"x4" @ 16" on center<br>Inland New Houses:<br>2" x 6" @ 24" on center | 25% | Existing:<br>Blown Cellulose*<br>Title 24:<br>Fiberglass Batt<br>Advanced:<br>Blown Cellulose | ½" gypsum | Stucco |
| Ceiling | 2"x6" @ 24" on center | 10% | Existing and Title 24:<br>Blown Cellulose<br>Advanced:<br>None | ½" gypsum | Attic Air |
| Roof | 2" x 4" @ 24" on center | 10% | Existing and Title 24:<br>None<br>Advanced:<br>Blown Cellulose (Cocooned) | Attic air | Shingles, Building Paper, ½" Plywood |

*Opportunity case only.

*Insulation Installation Quality.* Several studies have found that insulation installation quality varies widely, often with missing, compressed, or improperly installed insulation. In a CEC-funded study, Davis Energy Group found that due to missing or compressed insulation, fiberglass wall insulation performed at 70% of its nominal value, affecting 8.3% of the net wall area (CEC 2000c). Christian et al. (1998) indicate that insulation deficiencies can increase whole-wall heat transfer by about 14%, increasing energy consumption and reducing comfort. Uniacke (2000) found that typically five percent of the attic floor area has no insulation at all while the rest of the attic is 20% under-insulated due to over-fluffing. Based on the Davis Energy Group and Oak Ridge studies, we assumed a wall insulation void factor of 30%. For the attics, we assumed that 2.5% of the insulation was missing and that the attic insulation was reduced by 20% due to over-fluffing. Building Science Corporation (Ueno 2001) specifies cocooned insulation methods and blown in cellulose for Building America houses, which eliminates insulation voids or over-fluffing. As such, we assume that the advanced houses do not have any insulation quality degradation.

For the new commissioning cases, our model assumes these installation problems are resolved. The model for the existing opportunity case assumes that R-11 wall insulation and additional ceiling insulation has been correctly installed. Tables A-2, A-3 and A-4 summarize the nominal and net (whole assembly) R-values for the wall, ceiling (existing and new houses), and roof (advanced houses) assemblies. Because the advanced houses use blown-in cellulose (walls) or cocooned cellulose (roof) cavity insulation that is well installed and does not typically has voids, no commissioning-related insulation improvements are modeled.

Table A-2: Net Wall Assembly R-Values

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Existing | Coastal | R-0 | 2.7 | R-0 | 2.7 | R-11 | 9.1 |
| | Inland Valley | R-0 | 2.7 | R-0 | 2.7 | R-11 | 9.1 |
| New | Coastal | R-13 (D) | 8.3 | R-13 | 9.8 | R-13 | 9.8 |
| | Valley | R-19 (D) | 11.5 | R-19 | 13.8 | R-19 | 13.8 |
| Advanced | Coastal | R-13 | 9.8 | R-13 | 9.8 | R-13 | 9.8 |
| | Inland Valley | R-19 | 13.8 | R-19 | 13.8 | R-19 | 13.8 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-3: Net Ceiling Assembly R-Value

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Existing | Coastal | R-30 (D) | 18.5 | R-30 (D) | 18.5 | R-30 | 29.5 |
| | Inland Valley | R-30 (D) | 18.5 | R-30 (D) | 18.5 | R-38 | 37.5 |
| New | Coastal | R-30 (D) | 18.5 | R-30 | 29.5 | R-30 | 29.5 |
| | Inland Valley | R-38 (D) | 22.3 | R-38 | 37.5 | R-38 | 37.5 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-4: Net Roof Assembly R-Value

| | | Audit | | Commissioning | | Opportunity | |
|---|---|---|---|---|---|---|---|
| | | Nominal | Net | Nominal | Net | Nominal | Net |
| Advanced | Coastal | R-22 | 17.9 | R-22 | 17.9 | R-22 | 17.9 |
| | Inland Valley | R-22 | 17.9 | R-22 | 17.9 | R-22 | 17.9 |

## Windows

The audit case existing houses are modeled with 1/8" thick, single-pane aluminum frame windows without thermal breaks. The audit case new houses (new and advanced) are modeled with 1/8" thick double-pane vinyl frame windows. They have ½-inch air gaps with a metal spacer. All windows are operable and are evenly distributed around the house perimeter, with a 1.5 foot overhang two feet above the windows. Interior drapes shade the windows during the cooling season.

In the commissioning phase, the clear (no low-e coating) double-pane windows of the new and advanced houses are replaced with correct low-e double-pane vinyl-frame windows having an emissivity of 0.05. Low-e double-pane vinyl-frame windows are also installed in the existing houses during the opportunity phase. Low-e coatings are located on the interior surface of the exterior pane. Table A-5 summarizes the shading coefficients and U-values of the windows that were modeled.

Table A-5: Window Shading Coefficients and U-Values

| | Audit | | | | Commissioning | | | | Opportunity | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Window Type | SHGC | SC | U | Window Type | SHGC | SC | U | Window Type | SHGC | SC | U |
| Existing | Single | 0.86 | 1.00 | 1.27 | Single | 0.86 | 1.00 | 1.27 | Double Low-E | 0.41 | 0.48 | 0.39 |
| New | Double | 0.75 | 0.87 | .51 | Double Low-E | 0.41 | 0.48 | 0.39 | Double Low-E | 0.41 | 0.48 | 0.39 |
| Advanced | Double | 0.75 | 0.87 | .51 | Double Low-E | 0.41 | 0.48 | 0.39 | Double Low-E | 0.41 | 0.48 | 0.39 |

Source: ASHRAE 1997. DOE2.1E uses shading coefficients (SC) in determining window-related space conditioning loads. Shading coefficients are for glazing only. The Solar Heat Gain Coefficient (SHGC) is for glazing at normal incidence angles. U-values (U) are in Btu/(°F-ft$^2$-hr).

## Envelope Air Tightness and Ventilation

### *Air Tightness Levels in the Audit Phase (Pre-Commissioning)*

Normalized leakage (NL), as defined in ASHRAE Standard 119 – Air Leakage Performance for Detached Single-Family Residential Buildings (ASHRAE 1988), is an approximate surrogate for annual effective infiltration rates in absence of mechanical ventilation. We selected the building envelope normalized leakage values in this analysis so that they would represent the existing building stock and current new construction practices in California. Sherman and Matson (1997) have used measured building envelope leakage areas to determine a representative range of normalized leakage areas (NL) for U.S. housing. Our field measurements of four Las Vegas Pulte Building America houses resulted in an average normalized leakage of 0.25. We used these two sets of data to estimate normalized leakage values for the analysis cases. For the audit cases, the following normalized leakage values are assumed:

- the existing houses would be equal to that of the existing U.S. housing stock (NL=1.2) for the typical houses and one standard deviation greater for the poor houses (NL = 1.4),
- the new houses would be equal to that of the new California houses in the database (NL = 0.75) for the typical houses and one standard deviation greater for the poor houses (NL = 1.0), and
- the advanced houses would be equal to that found in the Las Vegas Pulte Building America houses (NL = 0.25).

*Air Tightness Levels in the Commissioned Houses*

The commissioning-phase air tightness goals were to tighten the houses to meet the requirements of corresponding standards, codes, or design specifications.

*Existing Houses.* In commissioning the existing house, we assume that it would be possible to tighten the existing house envelope to the level needed to meet the ventilation requirements of ASHRAE Standard 62.2P (ASHRAE 2000) through infiltration alone. Accounting for climatic differences, the resulting normalized leakage values ranged from 0.49 to 0.65. To determine the normalized leakage values for each of the existing houses, we used methodology based on ASHRAE Standard 136 (ASHRAE 1993). The resulting normalized leakage is given as:

$$NL = \frac{7.32 \cdot Q_{tot,62.2}}{\left(W \cdot A_f\right)} \qquad \textbf{Equation (A1)}$$

where:

$Q_{tot,62.2}$ = (3 cfm /100 $ft^2$) * $A_f$ [$ft^2$] + 7.5 cfm * (1+ number of bedrooms)

$W$ = ASHRAE Standard 136 climate factor

$A_f$ = Conditioned Floor Area [$ft^2$]

Bedrooms = Three (existing houses) and four (new and advanced houses)

*New Houses.* We assumed that the new house would be tightened to the default level assumed in Title 24 (NL=0.5) (CEC 2001).

*Advanced Houses.* Building Science Corporation specifies that the Tracy, CA Pulte Building America houses should have a normalized leakage value of 0.17 (Ueno 2000). We assumed that the advanced houses would be tightened to that level.

*Ventilation Systems*

Title 24 (CEC 1999) requires the installation of whole-house mechanical ventilation systems when the specific leakage area (SLA) is below 3.0 (NL = 0.3).

*Existing and New Houses.* The normalized leakage values for the existing and new houses are all above the 3.0 SLA and 0.3 normalized leakage values. Consequently, Title 24 does not require that these houses have mechanical ventilation systems nor are they traditionally installed in these houses. As such, we modeled only local, intermittent bathroom and kitchen exhaust fans in the existing and new houses. Table A-6 summarizes the airflow, fan power and operating schedules for these fans.

Table A-6: Intermittent Exhaust Fans

| | Airflow | Fan Power | Start | Run Time |
|---|---|---|---|---|
| Bathroom | 50 | 30 | 5 a.m. | 0.5 |
| Bathroom | 50 | 30 | 6 a.m. | 0.5 |
| Kitchen Fan | 100 | 60 | 4 p.m. | 0.5 |
| Clothes dryer | 250 | n/a | 7 p.m. | 1.0 |

*Advanced Houses.* Title 24 requires that the advanced houses, which we modeled with normalized leakage values of 0.25 and 0.17, have whole-house mechanical ventilation systems. The Pulte Building America Houses in Tracy, CA have supply-only mechanical ventilation. This system consists of an outside air duct connected to the return duct system of the central HVAC air-handler and is controlled with an AirCycler™ run-time controller (Ueno 2000). Outdoor air flows through the outside air duct due to return duct suction whenever the system blower operates. The controller turns on the blower whenever thermal demands are insufficient to cause the system to run a preset minimum time in any one-hour period. In this analysis, that minimum run time was 20 minutes per hour.

We calculated the whole-house ventilation airflow rate for the advanced ventilation system based on the ASHRAE Standard 62.2P requirements and the methods described by Rudd and Lstiburek (1999). ASHRAE 62.2P requires a continuous mechanical ventilation airflow rate of 1 cfm per 100 square foot of conditioned space plus 7.5 cfm per person, where the number of people equals one plus the number of bedrooms (ASHRAE 2000). To take into account the cycling of the central HVAC system, the outdoor airflow ($Q_{FAC}$) is three times the ASHRAE 62.2P required continuous mechanical ventilation airflow rate. Each hour's *actual* airflow was based on the actual run time of the blower in that hour ($t_{frac,i}$), but at a fraction of the forced-air outdoor airflow rate:

$$Q_{supply,i} = Q_{FAC} \times Max(t_{fac,i}, 20/60) \qquad \textbf{Equation (A2)}$$

In order to determine the central system hourly run time, thermal demands on the space conditioning system were evaluated using DOE 2.1E. A set of 8,760 hourly thermal part-load factors was saved to an hourly output file. Each part-load factor represents the fraction of an hour ($t_{frac,i}$) that the system had to run to meet the load imposed upon it by the house thermal demands. This part load profile is used by RESVENT to calculate the hourly effective ventilation rates. Fan energy associated with operating the system blower was calculated based on the additional ventilation-related central fan run time. The audit case HVAC systems run from 900 to 1000 hours for space conditioning alone. An additional 2000 hours of central fan runtime is needed to provide ventilation. When commissioned, the HVAC systems run from 400 to 900 hours for space conditioning and an additional 2000 to 2500 hours to provide ventilation. Note that this additional fan run time was not taken into account in the DOE-2 analysis.

### *RESVENT Results – Hourly and Annual Effective Ventilation Rates*

We calculated the hourly combined (infiltration and ventilation) airflow rates for each of the analysis cases and used them as hourly inputs into the DOE-2.1E model. These airflow rates are calculated by simulating the cases with a modified version of RESVENT.

RESVENT is a computer program developed by Sherman and Matson (1993, 1997), which uses the LBL infiltration model (Sherman and Modera 1984). RESVENT inputs include building characteristics (floor area, height, envelope leakage, and leakage distribution parameters), ventilation system factors (fan airflow rate, fan power, and operation schedules), and hourly weather data (temperature and wind speed). The houses are modeled with the windows closed. RESVENT calculates the hourly combined airflow rates by superimposing each hour's infiltration rate with the corresponding mechanical whole-house and local ventilation rates to determine the actual hour by hour ventilation rate ($Q_{tot,i}$).

$$Q_{tot,i} = \sqrt{Q_{inf,i}^2 + \left(Q_{l,i} - Q_{s,i}\right)^2} + Q_{s,i} \qquad \textbf{Equation (A3)}$$

where:

$Q_{inf,i}$ = Infiltration airflow rate (air changes per hour [ACH])

$Q_{li}$ = Larger of the mechanical ventilation airflow rates (air changes per hour [ACH])

$Q_{si}$ = Smaller of the mechanical ventilation airflow rates (air changes per hour [ACH])

Equation A3 differs from the analogous superposition equation that is presented in Section 4.4 of ASHRAE Standard 136 (ASHRAE 1993). The equation used here is assumed to provide better estimates for the combination of infiltration with unbalanced and balanced ventilation flows (Sherman 1992). The resulting hour-by-hour rates $Q_{tot,i}$ are provided as an input to DOE 2.1E to calculate the infiltration and ventilation-related component of the annual building energy consumption. These hour-by-hour rates are also used to calculate annual effective ventilation rates. The ASHRAE 2001 Handbook of Fundamentals (ASHRAE 2001) further discusses effective ventilation. The annual effective ventilation rates, as calculated using the ASHRAE 136 calculation method, and the ASHRAE Standard 62.2P target rates are shown in Table A-7. For the existing and new houses, values are reported for the two audit case normalized leakage values (typical and poor). The advanced poor and typical audit cases have the same normalized leakage value. As the ventilation system hourly ventilation airflows are dependent on the amount of time the HVAC system runs, ventilation values are provided based on the poor and typical cases.

## Table A-7: Annual Effective Ventilation Rates

| | | Normalized Leakage (NL) | Air Change Rates (ACH) | |
|---|---|---|---|---|
| | | | Standard 136 Based | Standard 62.2P Required |
| El Toro | | | | |
| Existing | Audit – Poor | 1.4 | 0.82 | 0.38 |
| | Audit – Typical | 1.2 | 0.71 | |
| | Commissioning & Opportunity | 0.65 | 0.39 | |
| New | Audit – Poor | 1.0 | 0.58 | 0.34 |
| | Audit – Typical | 0.75 | 0.44 | |
| | Commissioning & Opportunity | 0.50 | 0.30 | |
| Advanced | Audit – Typical | 0.25 | 0.40 | 0.34 |
| | Audit – Poor | 0.25 | 0.40 | 0.34 |
| | Commissioning | 0.17 | 0.39 | |
| Pasadena | | | | |
| Existing | Audit – Poor | 1.4 | 0.95 | 0.38 |
| | Audit – Typical | 1.2 | 0.82 | |
| | Commissioning & Opportunity | 0.56 | 0.39 | |
| New | Audit – Poor | 1.0 | 0.67 | 0.34 |
| | Audit – Typical | 0.75 | 0.51 | |
| | Commissioning & Opportunity | 0.50 | 0.34 | |
| Advanced | Audit – Typical | 0.25 | 0.41 | 0.34 |
| | Audit – Poor | 0.25 | 0.41 | 0.34 |
| | Commissioning | 0.17 | 0.39 | |
| Sacramento | | | | |
| Existing | Audit – Poor | 1.4 | 1.08 | 0.38 |
| | Audit – Typical | 1.2 | 0.93 | |
| | Commissioning & Opportunity | 0.49 | 0.39 | |
| New | Audit – Poor | 1.0 | 0.76 | 0.34 |
| | Audit – Typical | 0.75 | 0.57 | |
| | Commissioning & Opportunity | 0.50 | 0.39 | |
| Advanced | Audit – Typical | 0.25 | 0.40 | 0.34 |
| | Audit – Poor ed | 0.25 | 0.41 | |
| | Commissioning | 0.17 | 0.39 | |
| Fresno | | | | |
| Existing | Audit – Poor | 1.4 | 1.00 | 0.38 |
| | Audit – Typical | 1.2 | 0.85 | |
| | Commissioning & Opportunity | 0.54 | 0.39 | |
| New | Audit – Poor | 1.0 | 0.70 | 0.34 |
| | Audit – Typical | 0.75 | 0.53 | |
| | Commissioning & Opportunity | 0.50 | 0.36 | |
| Advanced | Audit – Typical | 0.25 | 0.41 | 0.34 |
| | Audit – Poor | 0.25 | 0.41 | |
| | Commissioning | 0.17 | 0.40 | |

* The advanced house effective air change rates are a function of HVAC central fan runtimes and thus are presented based on the typical and poor cases.

*Attic Leakage Values – DOE 2.1E Inputs*

The DOE 2.1E Sherman-Grimsrud infiltration subroutine calculated attic infiltration airflow rates. Attic airtightness is specified for this subroutine as a dimensionless fractional leakage value (the effective leakage area divided by the attic floor area).

The existing and new cases have unconditioned attics with the insulation located at the ceiling level. The leakage factor for these attics was assumed to be 1/400th of the attic floor area or a fractional leakage value of 0.0025.

The attics of the advanced houses are insulated at the roof level. As such, the attics in these houses are more closely coupled to the conditioned space than in the existing and new houses. In our field studies of Pulte Building America houses in Las Vegas, NV, we found that the attics had approximately 75% of the house total leakage to outside. Consequently, we used fractional leakage values of 0.00015 and 0.00010 respectively for the attics in the audit and commissioning cases.

**Duct Leakage Reduction**

Space-conditioning duct systems in un-retrofitted existing houses have 28% total duct leakage to outside on average (Jump et al. 1996). For new California houses, Title 24 assumes a default of 22% total duct leakage to outside (CEC 1999). Our field studies in Pulte Las Vegas Building America Houses measured 11% total duct leakage to outside. We used these rates respectively for the existing, new, and advanced houses.

The total duct leakage percentage and duct location, along with the heating, cooling, and annual thermal distribution system efficiency factors are shown in Table A-8. We assumed ducts are outside the conditioned space for the existing and new houses (63% in the attic) and inside the conditioned space for the advanced houses (10% in the attic due to the attic-outdoor temperature difference being 10% of that found in the control houses, as measured in the Las Vegas Pulte houses). In all cases, the duct leakage is split evenly between the supply and return ducts.

Through quality duct installation and sealing (including mastic and/or aerosol sealing methods), these duct leakage values can be reduced significantly, resulting in significant space conditioning energy savings and better comfort conditions. We assume that the thermal distribution system ducts are sealed as part of the commissioning process. In particular, we assume that the total duct leakage to outside can be reduced to 6% in the existing and new houses. This is the duct tightness level required in order to take the corresponding Title 24 compliance credit (CEC 1999). Building Science Corporation (Ueno 2000) specifies a total duct leakage to outside value of 4% for the Tracy, CA Building America houses. We assume that this leakage value is achieved when commissioning the advanced cases.

Table A-8: Thermal Distribution System Efficiencies

| | | | | Thermal Distribution System Efficiencies* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Typical | | | Poor | | |
| | | Total Duct Leakage to Outside | Duct Location | Heat | Cool | Avg. | Heat | Cool | Avg. |
| El Toro | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.85 | 0.80 | 0.83 | 0.80 | 0.75 | 0.78 |
| | Commissioning | 6% | | 0.91 | 0.86 | 0.88 | 0.92 | 0.86 | 0.89 |
| | Opportunity | 6% | | 0.90 | 0.84 | 0.87 | 0.90 | 0.84 | 0.87 |
| New | Audit | 22% | Attic | 0.85 | 0.81 | 0.83 | 0.84 | 0.78 | 0.81 |
| | Commissioning | 6% | | 0.88 | 0.84 | 0.86 | 0.88 | 0.84 | 0.86 |
| | Opportunity | 6% | | 0.89 | 0.84 | 0.86 | 0.89 | 0.84 | 0.86 |
| Advanced | Audit | 11% | Conditioned | 0.95 | 0.88 | 0.91 | 0.93 | 0.86 | 0.90 |
| | Commissioning | 4% | Attic | 0.96 | 0.89 | 0.93 | 0.96 | 0.89 | 0.93 |
| Pasadena | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.85 | 0.86 | 0.85 | 0.81 | 0.84 | 0.82 |
| | Commissioning | 6% | | 0.91 | 0.88 | 0.90 | 0.92 | 0.88 | 0.90 |
| | Opportunity | 6% | | 0.89 | 0.87 | 0.88 | 0.89 | 0.87 | 0.88 |
| New | Audit | 22% | Attic | 0.85 | 0.86 | 0.85 | 0.84 | 0.85 | 0.85 |
| | Commissioning | 6% | | 0.88 | 0.87 | 0.87 | 0.88 | 0.86 | 0.87 |
| | Opportunity | 6% | | 0.89 | 0.86 | 0.87 | 0.89 | 0.86 | 0.87 |
| Advanced | Audit | 11% | Conditioned | 0.95 | 0.90 | 0.92 | 0.93 | 0.90 | 0.91 |
| | Commissioning | 4% | Attic | 0.96 | 0.91 | 0.94 | 0.96 | 0.91 | 0.94 |
| Sacramento | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.83 | 0.85 | 0.84 | 0.78 | 0.83 | 0.81 |
| | Commissioning | 6% | | 0.90 | 0.88 | 0.89 | 0.91 | 0.88 | 0.89 |
| | Opportunity | 6% | | 0.87 | 0.86 | 0.86 | 0.87 | 0.86 | 0.86 |
| New | Audit | 22% | Attic | 0.85 | 0.85 | 0.85 | 0.82 | 0.85 | 0.83 |
| | Commissioning | 6% | | 0.88 | 0.86 | 0.87 | 0.88 | 0.86 | 0.87 |
| | Opportunity | 6% | | 0.87 | 0.86 | 0.87 | 0.87 | 0.86 | 0.87 |
| Advanced | Audit | 11% | Conditioned | 0.94 | 0.90 | 0.92 | 0.92 | 0.89 | 0.91 |
| | Commissioning | 4% | Attic | 0.96 | 0.91 | 0.93 | 0.96 | 0.91 | 0.93 |
| Fresno | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.84 | 0.83 | 0.83 | 0.79 | 0.80 | 0.79 |
| | Commissioning | 6% | | 0.90 | 0.86 | 0.88 | 0.91 | 0.87 | 0.89 |
| | Opportunity | 6% | | 0.87 | 0.85 | 0.86 | 0.87 | 0.85 | 0.86 |
| New | Audit | 22% | Attic | 0.85 | 0.83 | 0.84 | 0.83 | 0.82 | 0.82 |
| | Commissioning | 6% | | 0.88 | 0.85 | 0.87 | 0.88 | 0.85 | 0.87 |
| | Opportunity | 6% | | 0.87 | 0.85 | 0.86 | 0.87 | 0.85 | 0.86 |
| Advanced | Audit | 11% | Conditioned | 0.94 | 0.89 | 0.91 | 0.92 | 0.88 | 0.90 |
| | Commissioning | 4% | Attic | 0.96 | 0.90 | 0.93 | 0.96 | 0.90 | 0.93 |

*The thermal distribution system efficiencies are aggregated based on the thermal distribution system efficiencies of the individual typical case component runs.

### *Modeling Duct Leakage in DOE 2.1E*

The DOE 2.1E RESYS and RESYS-2 -heating and cooling subroutines use a single annual DUCT-LOSS variable to account for the amount of heating and cooling energy lost through duct leakage. For simplicity, we calculated the annual duct loss factor to be the average of the heating and cooling seasonal duct efficiencies. We calculated the heating and cooling seasonal duct efficiencies, or thermal distribution system efficiencies, for each case using ASHRAE Standard 152P (ASHRAE 1999). The thermal distribution system efficiency is the amount of heating or cooling delivered to the space through the modeled duct system compared to the amount that would be delivered to the space via a non-ducted system. Inputs to the 152P model include house characteristics (floor area, number of stories), duct system characteristics (duct system location, surface area, number of registers, duct leakage as a percent of total system airflow), equipment characteristics (heating and cooling capacities and airflows), and climate data. We calculated the duct surface areas and numbers of registers based on the Standard 152P default "per unit floor area" assumptions.

## Air Handler Airflow and Refrigerant Charge

We determined the effects of refrigerant charge and system airflow deficiencies on cooling system capacities and efficiencies using charge and airflow degradation algorithms developed by Proctor Engineering Group (Proctor 2001), which are included in the REGCAP model (Siegel 2001). Specifically, we used these algorithms to determine the sensible capacity and efficiency at each of the standard rating points, such as for a 95°F outdoor air dry-bulb temperature and a 67°F evaporator entering air wet-bulb temperature. We calculated the corresponding total capacity using a sensible heat ratio of 0.78. We modeled four charge and airflow cases with nominal SEER 10 air conditioners. Full airflow (100%) is 400 cfm/ton and reduced (85%) flow is 340 cfm/ton. We used the resulting data (sensible capacity, total capacity, and energy input ratio) to determine air conditioner performance curve fits for use in the DOE 2.1E models.

## Thermostat Set-Points

In order to interchange data between our two hourly models (RESVENT and DOE-2) and still obtain a realistic evaluation of temporal ventilation air change rates, we were limited to using a non-setback thermostat approach. 68°F heating and 78°F cooling thermostat setpoints were modeled.

## HVAC Equipment Sizing

Our analysis quantifies the relative energy and cost savings between cases. To insure that the heating and cooling hourly loads are met by the HVAC systems modeled for each of the analysis cases, the HVAC systems are sized based on DOE 2.1E's recommended equipment capacities for that case. DOE 2.1E uses the peak loads on design days and, in this case, the user-specified equipment performance curves to determine the heating and cooling equipment capacities at standard conditions.

For cooling, we selected the next larger commercially available air conditioning equipment above the DOE 2.1E recommended cooling capacity. For heating, the gas furnace modeled is the next larger commercially available gas furnace that has sufficient heating capacity to provide the DOE 2.1E recommended heating capacity and that has sufficient airflow for the cooling mode (based on a nominal 400 cfm per ton of air conditioning).

*Equipment Sizing for the "Comfort Call Case" Analysis*

The "comfort call case" analysis is included in Appendix C. This case assumes that the existing HVAC equipment in the pre-commissioned house may not be able to meet the cooling loads completely. After commissioning, these systems are better able to meet the cooling loads. Because HVAC equipment would not be changed out as part of the commissioning phase, the audit and commissioning cases have the same equipment sizes. Assuming that equipment is sized based on how the house should be in a best-case scenario (good insulation, correct windows, tight envelope and ducts, correct charge and air flow), the equipment used for these cases is what would be required to meet the commissioning case loads. The equipment capacities modeled for the opportunity case are based on the opportunity case loads.

### Energy Prices

The California energy industry is going through a volatile time, resulting in uncertainty regarding future rates. In the event of rate increases, the case for commissioning becomes even stronger with higher cost savings and greater benefits to the homeowner and other stakeholders. As such, we have chosen to provide results based on a more conservative level, using the California average energy rates reported by the EIA for 1999. Our analyses are based on an electricity rate of \$0.1071/kWh (EIA 2000) and a natural gas rate of \$6.63/(100 $ft^3$) or \$0.634/therm (EIA 2001).

### Environmental Impact - Carbon Emissions

We can approximate carbon savings achieved based on the level of estimated energy savings. The carbon impact is determined based on data from the EIA State Electricity Profile (EIA 2000). EIA reports that 23% of California in-state utility-generated electricity is produced using carbon-producing fuels (petroleum and natural gas). While out-of-state-generated electricity consumed in California may be produced using a higher percentage mix of carbon producing fuels (coal, petroleum and natural gas) than in-state electricity generation, we are assuming the 23% value for this analysis. Based on Koomey's 1993 emission efficiency data (Koomey 1993), the 1993 California generating fuel mix produces 0.15 kg of carbon per kWh of site electricity consumption. With improvements in generation and emission technologies, the California value could be as low as 0.10 kg/kWh. For the purpose of this analysis, we are using the 0.10 kg/kWh value. For natural gas, we are using a marginal emission rate of 5.2 kg/therm of site energy consumption (ASHRAE 1997).

### Summary of Analysis Case Assumptions

The following three tables (Tables A-9 through A-11) summarize our assumptions for the analysis cases (audit cases, commissioning cases, and opportunity cases). Note that for the opportunity cases, we assumed that any improvements that have taken place during the main commissioning activity remain in place for the opportunity cases.

Table A-9: DOE-2 Modeling Assumptions - Existing Houses

| | Audit Case | Commissioning Case | Opportunity Case |
|---|---|---|---|
| Insulation | No wall insulation<br>Ceiling Insulation with voids and over-fluffing<br>Ceiling:<br>R30 (D) (all) | No wall insulation<br>Ceiling Insulation with voids and over-fluffing<br>Ceiling:<br>R30 (D) (all) | Walls:<br>R13 (all)<br>Ceiling:<br>R30 (Coastal)<br>R38 (Inland Valley) |
| Windows | Clear Single-Pane Aluminum-Frame | Clear Single-Pane Aluminum-Frame | Low-E Double-Pane Vinyl-Frame |
| Envelope Air Tightness | Loose Existing Construction<br>NL = 1.2 (typical)<br>NL = 1.4 (poor) | Tighten to meet 62.2P:<br>El Toro: NL = 0.65<br>Pasadena: NL = 0.56<br>Sacramento: NL = 0.49<br>Fresno: NL = 0.54 | Tighten to meet 62.2P<br>El Toro: NL = 0.65<br>Pasadena: NL = 0.56<br>Sacramento: NL = 0.49<br>Fresno: NL = 0.54 |
| Ventilation | Bathroom and kitchen intermittent exhaust fans | Bathroom and kitchen intermittent exhaust fans | Bathroom and kitchen intermittent exhaust fans |
| Ducts | 28% total leakage to outside split evenly between supply and return)<br>No duct insulation | 6% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation | 6% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation |
| Air Conditioner Refrigerant Charge | 15% undercharged<br>Capillary Tube | 100% Charge<br>Capillary Tube | 100% Charge<br>TXV |
| Air Handler | 15% fan flow reduction<br>Standard motor | 100% Airflow<br>Standard motor | 100% Airflow<br>ECM Motor |
| Furnace Efficiency [AFUE] | 78% | 78% | 90% |
| Nominal SEER | 10.00 | 10.00 | 10.00 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-10: DOE-2 Modeling Assumptions – New House

| | Audit Case | Commissioning Case | Opportunity Case |
|---|---|---|---|
| Insulation | Insulation to Title 24 Package D minimums, but with voids and over-fluffing<br>Walls:<br>R13 (D) (Coastal)<br>R19 (D) (Inland Valley)<br>Ceiling:<br>R30 (D) Coastal)<br>R38 (D) (Inland Valley) | Insulation to Title 24 Package D minimums, no voids or over-fluffing<br>Walls:<br>R13 (Coastal)<br>R19 (Inland Valley)<br>Ceiling:<br>R30 (Coastal)<br>R38 (Inland Valley) | Insulation to Title 24 Package D minimums, no voids or over-fluffing<br>Walls:<br>R13 (Coastal)<br>R19 (Inland Valley)<br>Ceiling:<br>R30 (Coastal)<br>R38 (Inland Valley) |
| Windows | Clear Double-Pane Aluminum-Frame | Low-E Double-Pane Vinyl-Frame | Low-E Double-Pane Vinyl-Frame |
| Envelope Air Tightness & Ventilation | New construction<br>NL = 0.75 (typical)<br>NL = 1.00 (poor) | Tighter new construction<br>NL = 0.5 | Tighter new construction<br>NL = 0.5 |
| Ventilation | Bathroom and Kitchen intermittent exhaust fans | Bathroom and Kitchen intermittent exhaust fans | Bathroom and Kitchen intermittent exhaust fans |
| Ducts | 22% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation | 6% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation | 6% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation |
| Air Conditioner Refrigerant Charge | 15% undercharged<br>TXV | 100% Charge<br>TXV | 100% Charge<br>TXV |
| Air Handler Flow | 15% fan flow reduction<br>Standard motor | 100% Airflow<br>Standard motor | 100% Airflow<br>ECM Motor |
| Furnace Efficiency | 80% | 80% | 90% |
| Nominal SEER | 10.00 | 10.00 | 10.00 |

*(D) denotes degraded installation quality. Insulation R-value listed is the nominal R-value for the insulating material. The net R-value used in the model takes into account framing factors and insulation installation quality degradation due to missing, compressed or over-fluffed insulation.

Table A-11: DOE-2 Modeling Assumptions – Advanced House

| | Audit Case | Commissioning Case |
|---|---|---|
| Insulation | Building America Minimum R-Values, blown in and cocooned cellulose, no voids.<br>Walls:<br>R13 (Coastal)<br>R19 (Inland Valley)<br>Roof:<br>(attic inside conditioned space)<br>R22 (all) | Building America Minimum R-Values, blown in and cocooned cellulose, no voids.<br>Walls:<br>R13 (Coastal)<br>R19 (Inland Valley)<br>Roof:<br>(attic inside conditioned space)<br>R22 (all) |
| Windows | Clear Double-Pane<br>Aluminum-Frame | Low-E Double-Pane<br>Vinyl -Frame |
| Envelope Air Tightness | Typical tighter new construction<br>NL = 0.25 | Typical tight new Building America construction<br>NL = 0.17 |
| Ventilation | Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when furnace runs for more than 20 minutes per hour) | Mechanical supply ventilation system, outside air duct to return side of furnace, sized to ASHRAE 62.2P (nominal 62.5 cfm airflow, the ventilation rate can be up to 20% higher when furnace runs for more than 20 minutes per hour) |
| Ducts | 11% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation | 4% total leakage to outside (split evenly between supply and return)<br>R4.2 Duct Insulation |
| Air Conditioner Refrigerant Charge | 15% undercharged<br>TXV | 100% Charge<br>TXV |
| Air Handler Flow | 15% reduction in fan flow<br>ECM Motor | 100% Airflow<br>ECM Motor |
| Furnace Efficiency | 90% | 90% |
| Nominal SEER | 10.00 | 10.00 |

## APPENDIX B: PEAK DEMAND

Most of the electrical loads reduced through commissioning are associated with cooling and will thus have the greatest influence on summer peak demand in California. This reduction will put less strain on generating, transmission, and distribution resources and will allow utilities flexibility in shifting resources and loads to meet peak demand. Houses with reduced peak loads (lower cooling loads) perform better in extreme climates or during power outages than houses with high cooling loads. Table B-1 summarizes the space-conditioning-related peak electrical demands and percent savings predicted by DOE-2 for each of the cases. These results are discussed in terms of actual peak rather than an averaged peak that takes diversity into account.

As expected, the typical advanced houses have the lowest peak demand, followed by the new houses. The existing houses have the highest peak demand. Due to larger cooling loads and equipment sizes, the peak demands for the poor audit cases are higher than for the typical audit cases, ranging from 40% higher for the existing houses to 50 to 75% higher for the new and advanced houses.

Commissioning results in significant peak savings: 22 to 24% (typical) and 34 to 38% (poor) for the existing cases, 15 to 19% (typical) and 50 to 56% (poor) for the new cases, and 6 to 7% (typical) and 38 to 44% (poor) for the advanced cases. Implementing the opportunity phase in the existing houses increases these peak savings to 57 to 59% (typical) and 70 to 71% (poor). Twenty percent of the HVAC system fan peak energy is saved with the installation of the ECM motors in the new houses. This contributes to slightly greater peak savings in the opportunity phase for the new houses.

Table B-1: Space-Conditioning-Related Peak Demand

| | | Peak Demand Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 22% | 22% | 23% | 24% | 35% | 34% | 37% | 38% |
| | Opportunity | 59% | 59% | 59% | 57% | 70% | 70% | 71% | 70% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 15% | 15% | 18% | 19% | 50% | 56% | 51% | 50% |
| | Opportunity | 18% | 24% | 19% | 18% | 51% | 56% | 51% | 50% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 7% | 6% | 7% | 7% | 42% | 44% | 39% | 38% |

## APPENDIX C: COMFORT CALL CASE

The "comfort call" case allows us to look at the effect of commissioning a house where the existing HVAC equipment may not be able to provide sufficient comfort levels. This may result in a "comfort call" to an HVAC contractor.

In selecting the HVAC equipment sizes for the "comfort call" case, we assume that changing out equipment for equipment that can meet the new load would be part of the opportunity phase and not a normal part of the "tuning and tweaking" commissioning package. In this analysis, the cooling equipment sizes are limited to traditional residential sizes (five tons or less). By using the commissioning phase equipment sizes for the audit phase, we can evaluate the assumption that systems are sized assuming that no system induced problems (e.g., duct leakage, low refrigerant charge, and low air handler airflow) impact the amount of space conditioning actually delivered to a home's living space. As the commissioning phase equipment is sized for the commissioning phase loads, the effect of commissioning on thermal comfort with undersized units can be evaluated. As the opportunity cases include installing equipment that meets the load, we have modeled the opportunity phase cases with the HVAC equipment necessary to meet the opportunity phase loads. For specificity, any case with greater than a five ton cooling loads are modeled with five ton cooling equipment. This results in loads not able to be met for all of the audit cases and for the existing commissioning cases in the inland valley (Sacramento and Fresno).

The following summary compares the "comfort call" data in Table C-1 on a house-by-house type basis for each benefit type. Following this summary are more detailed tables and information regarding climate-specific results. As one might except these results show the same general trends as those in the main body, but the size of the savings has been reduced, reflecting the fact that for some hours of the year the commissioning saves no energy, but does improve comfort conditions.

*Existing Houses*

*Electricity.* Using the commissioning phase equipment for both the audit and commissioning phases result in 7 to 12% (typical) and 10 to 19% (poor) electricity savings. In the opportunity phase, adding insulation, low-e double pane windows, and equipment with a thermostatic expansion valve (TXV) and an electronically commutated motor (ECM) results in substantial savings compared to the audit case. Within this phase, the overall electricity saving range from 60 to 70% for the typical cases and from 70 to 80% for the poor cases.

*Natural Gas.* Natural gas savings are about 20% for the typical cases and from 30 to 35% for the poor cases. Implementing the opportunity phase improvements substantially increases natural gas savings to 44 to 54% for the typical cases and from 59 to 67% for the poor cases.

*Operating Costs.* As the audit cases have cooling equipment with degraded performance and lower capacities than needed to meet the cooling loads, the commissioning phase cost savings range from 10 to 15% (typical) and 17 to 26% (poor). Implementing the opportunity phase measures substantially increases the cost savings, ranging from 56 to 62% (typical) and 66 to 71% (poor).

Table C-1: Commissioning-Related Energy and Operating Cost Savings
Comfort Call Cases

| | | Electricity Consumption Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 7 to 12% | 10 to 19% |
| | Opportunity | 57 to 72% | 66 to 78% |
| New | Commissioning | 1 to 9% | 49 to 68% |
| | Opportunity | 2 to 10% | 50 to 68% |
| Advanced | Commissioning | 6 to 7% | 48 to 69% |

| | | Natural Gas Consumption Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 17 to 21% | 33 to 36% |
| | Opportunity | 44 to 54% | 59 to 67% |
| New | Commissioning | 24 to 25% | 17 to 35% |
| | Opportunity | 28 to 31% | 21 to 41% |
| Advanced | Commissioning | 2 to 3% | -19 to -15% |

| | | Energy Operating Cost Savings | |
|---|---|---|---|
| | | Typical | Poor |
| Existing | Commissioning | 10 to 15% | 17 to 26% |
| | Opportunity | 56 to 62% | 66 to 71% |
| New | Commissioning | 10 to 17% | 45 to 58% |
| | Opportunity | 14 to 22% | 47 to 60% |
| Advanced | Commissioning | 5 to 6% | 41 to 62% |

### *New Houses*

*Electricity.* The electricity savings in the commissioning phase are up to 10% (typical) and 50 to 70% (poor). In the opportunity phase, adding equipment with a TXV and an ECM increases savings only slightly (one to seven percentage points more).

*Natural Gas.* Natural gas savings in the commissioning phase are about 25% for the typical cases and from 18 to 35% for the poor cases. In the opportunity phase, installing a higher efficiency furnace (90% instead of 80%) increases natural gas savings slightly to about 30% for the typical cases and from 22 to 41% for the poor cases.

*Operating Costs.* Operating cost savings in the commissioning phase range from 10 to 17% (typical) and 45 to 58% (poor). In the opportunity phase, installing the HVAC equipment with a TXV, an ECM, and higher furnace efficiency increases cost savings to 14 to 22% (typical) and from 47 to 60% (poor).

### *Advanced Houses*

Because the advanced houses are already engineered and designed to be energy efficient, relative savings for the typical cases are lower than those for the typical existing and new houses. For the advanced houses, the primary difference between the typical and the poor cases is the incorrect installation of clear glazing in place of low-e glazing. Correcting this problem in the poor cases drives the energy consumption and savings closer to the levels seen with the new houses.

*Electricity.* The commissioning phase electricity saving range from 6 to 7%. The poor case savings range from 48 to 69%.

*Natural Gas.* Natural gas savings range from 2 to 3% for the typical cases. Due to a reduction in solar gains when the incorrect clear double pane windows are replaced with low-e double pane windows, the poor advanced commissioning cases have higher gas consumption, resulting in negative gas savings, from –19 to –15%.

*Operating Costs.* The typical case operating cost savings range from 5 to 6%. The operating cost savings for the poor case are higher, ranging from 41 to 62%.

*Electricity Consumption and Savings – Comfort Call Cases – Detailed Results*

The annual space conditioning-related annual electricity consumption rates and percent savings are summarized in Table C-2. Electricity consumption values are provided per square foot of conditioned space to provide comparisons between building types. All savings percentages are reported in terms of savings over the audit cases.

To evaluate issues related to undersized HVAC equipment, the "comfort call" cases are modeled with a maximum of five tons cooling capacity. The audit cases have the same equipment as modeled for the commissioning cases. As mentioned earlier, the five-ton limit results in inadequate cooling capacity for all of the audit cases and for the Sacramento and Fresno poor commissioning cases. The lower audit case electricity consumption values and corresponding lower relative savings percentages are a direct result of the undersized equipment modeled for these cases.

*Existing Houses:* For the existing cases, commissioning results in 7 to 12% electricity consumption savings for the typical cases and 10 to 19% savings for the poor cases. Implementing additional opportunities increases the savings percentages to just under the levels found with the cases. The opportunity phase changes increase savings to 57 to 72% for the typical cases and to 66 to 78% for the poor cases.

*New Houses:* For the typical cases, new house savings range from to 8 to 9% for the inland valley climates. As the coastal typical cases showed only 1 to 2% savings through commissioning, there are negative savings with the corresponding case due to the audit cases' inadequate cooling capacities. The poor cases; however, have 50 to 68% savings for the commissioning and opportunity phases.

*Advanced Houses:* The advanced houses' commissioning-related electricity savings range from 6 to 7%. After the opportunity phase, the savings for the poor cases range from 48 to 69%.

Table C-2: Space Conditioning-Related Electricity – Comfort Call Cases

| | | Electricity Consumption (kWh/ft$^2$/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 1.48 | 2.04 | 2.06 | 3.90 | 1.88 | 2.57 | 2.63 | 4.96 |
| | Commissioning | 1.37 | 1.89 | 1.88 | 3.42 | 1.69 | 2.30 | 2.26 | 4.01 |
| | Opportunity | 0.42 | 0.69 | 0.75 | 1.66 | 0.42 | 0.69 | 0.75 | 1.66 |
| New Title 24 | Audit | 0.51 | 0.77 | 0.88 | 1.78 | 1.57 | 1.86 | 1.80 | 3.19 |
| | Commissioning | 0.51 | 0.75 | 0.81 | 1.62 | 0.51 | 0.72 | 0.81 | 1.62 |
| | Opportunity | 0.50 | 0.71 | 0.79 | 1.61 | 0.50 | 0.71 | 0.79 | 1.61 |
| Building America | Audit | 0.65 | 0.84 | 0.96 | 1.78 | 1.98 | 2.25 | 2.13 | 3.22 |
| | Commissioning | 0.61 | 0.79 | 0.89 | 1.67 | 0.61 | 0.79 | 0.89 | 1.67 |

| | | Electricity Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 8% | 7% | 9% | 12% | 10% | 11% | 14% | 19% |
| | Opportunity | 72% | 66% | 64% | 57% | 78% | 73% | 71% | 66% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 1% | 2% | 8% | 9% | 68% | 61% | 55% | 49% |
| | Opportunity | 2% | 7% | 10% | 10% | 68% | 62% | 56% | 50% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 7% | 6% | 7% | 6% | 69% | 65% | 58% | 48% |

*Natural Gas Consumption and Savings – Comfort Call Cases – Detailed Results*

The annual space-conditioning-related natural gas consumption and savings are summarized in Table C-3. Commissioning savings range from 17 to 21% (typical) and 33 to 36% (poor) for the existing cases, from 24 to 25% (typical) and 17 to 35% (poor) for the new cases, and from 2 to 3% (typical) and –19 to –15% (poor) for the advanced cases. The opportunity measures increase the gas savings to 44 to 54% (typical) and 59 to 67% (poor) for the existing cases, and from 28 to 31% (typical) and 21 to 41% (poor) for the new cases.

Table C-3: Space-Conditioning-Related Natural Gas – Comfort Call Cases

| | | Natural Gas Consumption (Therm/ft2/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 0.13 | 0.14 | 0.35 | 0.31 | 0.18 | 0.19 | 0.48 | 0.42 |
| | Commissioning | 0.11 | 0.11 | 0.28 | 0.25 | 0.12 | 0.13 | 0.31 | 0.28 |
| | Opportunity | 0.07 | 0.07 | 0.16 | 0.14 | 0.07 | 0.07 | 0.16 | 0.14 |
| New Title 24 | Audit | 0.07 | 0.07 | 0.18 | 0.16 | 0.06 | 0.06 | 0.21 | 0.18 |
| | Commissioning | 0.05 | 0.05 | 0.14 | 0.12 | 0.05 | 0.05 | 0.14 | 0.12 |
| | Opportunity | 0.05 | 0.05 | 0.12 | 0.11 | 0.05 | 0.05 | 0.12 | 0.11 |
| Building America | Audit | 0.04 | 0.04 | 0.09 | 0.09 | 0.03 | 0.03 | 0.08 | 0.07 |
| | Commissioning | 0.04 | 0.04 | 0.09 | 0.08 | 0.04 | 0.04 | 0.09 | 0.08 |

| | | Natural Gas Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 17% | 18% | 21% | 19% | 33% | 33% | 36% | 34% |
| | Opportunity | 44% | 47% | 54% | 54% | 59% | 61% | 67% | 66% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 25% | 24% | 24% | 24% | 17% | 20% | 35% | 34% |
| | Opportunity | 29% | 28% | 31% | 31% | 21% | 24% | 41% | 40% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 2% | 2% | 3% | 3% | -19% | -18% | -15% | -15% |

*Annual Operating Costs – Comfort Call Cases – Detailed Results*

We calculated annual operating costs based on the annual electricity and natural gas consumption values for each case, using the DOE/EIA 1999 California annual fuel costs of $0.1071/kWh (EIA 2000) and $0.634/therm (EIA 2001). These values provide a base level of comparison. Energy price increases, such as those experienced during the winter 2000/2001 California energy crisis, will further enhance the attractiveness of commissioning California's houses. The annual space-conditioning-related annual operating costs and savings are summarized in Table C-4.

We found that the operating cost savings due to commissioning range from 10 to 15% (typical) and 17 to 26% (poor) for the existing cases, from 10 to 17% (typical) and 45 to 58% (poor) for the new cases, and from 5 to 6% (typical) and 41 to 62% (poor) for the advanced cases.

Correspondingly, the opportunity-related percent operating cost savings range from 56 to 62% (typical) and 66 to 71% (poor) for the existing cases, from 10 to 17% (typical) and 47 to 58% (poor) for the new cases; and from 5 to 6% (typical) and 41 to 62% (poor) for the advanced cases.

Table C-4: Space-Conditioning-Related Operating Costs – Comfort Call Cases

| | | Operating Costs ($/ft2/year) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | 0.24 | 0.30 | 0.44 | 0.60 | 0.32 | 0.39 | 0.59 | 0.80 |
| | Commissioning | 0.21 | 0.27 | 0.37 | 0.51 | 0.26 | 0.33 | 0.44 | 0.61 |
| | Opportunity | 0.09 | 0.12 | 0.18 | 0.26 | 0.09 | 0.12 | 0.18 | 0.27 |
| New Title 24 | Audit | 0.10 | 0.12 | 0.21 | 0.28 | 0.21 | 0.24 | 0.32 | 0.45 |
| | Commissioning | 0.08 | 0.11 | 0.17 | 0.24 | 0.09 | 0.11 | 0.17 | 0.25 |
| | Opportunity | 0.08 | 0.10 | 0.16 | 0.24 | 0.08 | 0.11 | 0.16 | 0.24 |
| Building America | Audit | 0.09 | 0.11 | 0.16 | 0.24 | 0.23 | 0.26 | 0.28 | 0.39 |
| | Commissioning | 0.09 | 0.11 | 0.15 | 0.23 | 0.09 | 0.11 | 0.15 | 0.23 |

| | | Operating Cost Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 11% | 10% | 15% | 15% | 18% | 17% | 26% | 24% |
| | Opportunity | 62% | 61% | 59% | 56% | 71% | 70% | 69% | 66% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 12% | 10% | 17% | 14% | 58% | 54% | 47% | 45% |
| | Opportunity | 14% | 15% | 22% | 17% | 60% | 55% | 50% | 47% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 6% | 5% | 5% | 5% | 62% | 58% | 45% | 41% |

*Peak Electrical Demand and Savings – Comfort Call Cases – Detailed Results*

Table C-5 summarizes the space conditioning-related peak demand savings for the Comfort Call Cases.

*Existing Houses:* Commissioning existing houses in the inland valley climates results in small or negative peak savings: 0% (typical cases) and -2 to 2% (poor cases). The negative savings are due to the audit cases' inadequate cooling capacities. In contrast, commissioning the existing houses in the coastal climates results in larger peak demand savings: 7 to 8% (typical cases) and 12% (poor cases). Reducing space conditioning loads and improving HVAC equipment efficiency in the opportunity phase for the existing houses results in considerable peak demand savings in all climates: from 39 to 51% (typical cases) and 45 to 60% (poor cases).

*New and Advanced Houses:* Peak demand savings from commissioning range from 5 to 15% (typical cases) and 16 to 27% (poor cases). For the advanced houses, the peak demand savings in the typical case range from 5 to 6%. The peak demand savings range from 19 to 28% for the poor cases. The ECM motor installed in the new houses in the opportunity phase slightly increases the peak savings.

Table C-5: Space-Conditioning-Related Peak Demand Savings – Comfort Call Cases

| | | Peak Demand Savings (% of Audit Case) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Typical | | | | Poor | | | |
| | | El Toro | Pasadena | Sacramento | Fresno | El Toro | Pasadena | Sacramento | Fresno |
| Existing | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 8% | 7% | 0% | 0% | 12% | 12% | 2% | -2% |
| | Opportunity | 51% | 51% | 46% | 39% | 60% | 60% | 53% | 45% |
| New Title 24 | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 10% | 5% | 15% | 11% | 18% | 16% | 27% | 17% |
| | Opportunity | 13% | 15% | 15% | 10% | 20% | 17% | 27% | 16% |
| Building America | Audit | - | - | - | - | - | - | - | - |
| | Commissioning | 6% | 5% | 6% | 6% | 22% | 19% | 28% | 22% |

*Reduced Carbon Emissions – Comfort Call Cases – Detailed Results*

Table C-6 summarizes the space conditioning-related carbon emission reductions. As the carbon emissions scale with the amount of electricity and natural gas consumed in a house, the relative amount of carbon emission reductions follows the same general trends seen with electricity, natural gas and operating-cost savings. The carbon emission reductions are slightly less than found when the HVAC system capacities meet the cooling loads over all hours.

Table C-6: Space Conditioning System – Related Carbon Emission Reductions
Comfort Call Cases

| | | Kg/house-year | | | | | |
|---|---|---|---|---|---|---|---|
| | | Typical | | | Poor | | |
| | | Electricity Related | Gas Related | Total Fuel Related | Electricity Related | Gas Related | Total Fuel Related |
| Existing | Commissioning | 20 to 70 | 170 to 540 | 190 to 570 | 30 to 140 | 450 to 1300 | 480 to 1390 |
| | Opportunity | 160 to 330 | 450 to 1430 | 610 to 1630 | 210 to 480 | 810 – 2460 | 1020 to 2730 |
| New | Commissioning | 0 to 40 | 210 to 560 | 220 to 580 | 250 to 390 | 140 to 950 | 400 to 1200 |
| | Opportunity | 0 to 40 | 250 to 720 | 250 to 740 | 250 to 400 | 170 to 1110 | 430 to 1360 |
| Advanced | Commissioning | 10 to 30 | 10 to 40 | 20 to 60 | 310 to 390 | -150 to -80 | 160 to 290 |

| | | Percent of Audit Case | | | | | |
|---|---|---|---|---|---|---|---|
| | | Typical | | | Poor | | |
| | | Electricity Related | Gas Related | Total Fuel Related | Electricity Related | Gas Related | Total Fuel Related |
| Existing | Commissioning | 7 to 12% | 21 to 24% | 17 to 22% | 10 to 19% | 38 to 42% | 32 to 39% |
| | Opportunity | 57 to 72% | 51 to 63% | 55 to 63% | 66 to 78% | 68 to 78% | 70 to 77% |
| New | Commissioning | 1 to 9% | 28 to 29% | 23 to 26% | 49 to 68% | 20 to 41% | 38 to 43% |
| | Opportunity | 2 to 10% | 33 to 36% | 28 to 33% | 50 to 68% | 4 to 21% | 41 to 49% |
| Advanced | Commissioning | 6 to 7% | 2 to 4% | 3 to 4% | 48 to 69% | -23 to -17% | 11 to 31% |

*Input Assumptions – Comfort Call Cases*

The following tables summarize input assumptions calculated and used when modeling the comfort call cases. The assumptions behind these tables are the same as discussed in Appendix A.

Table C-7: Annual Effective Ventilation Rates - Comfort Call Cases

| | | Normalized Leakage (NL) | Air Change Rates (ACH) | |
|---|---|---|---|---|
| | | | Standard 136 Based | Standard 62.2P Required |
| El Toro | | | | |
| Advanced | Audit – Typical | 0.25 | 0.41 | 0.34 |
| | Audit – Poor | 0.25 | 0.43 | |
| | Commissioning | 0.17 | 0.39 | |
| Pasadena | | | | |
| Advanced | Audit – Typical | 0.25 | 0.43 | 0.34 |
| | Audit – Poor | 0.25 | 0.46 | |
| | Commissioning | 0.17 | 0.39 | |
| Sacramento | | | | |
| Advanced | Audit – Typical | 0.25 | 0.41 | 0.34 |
| | Audit – Poor | 0.25 | 0.43 | |
| | Commissioning | 0.17 | 0.39 | |
| Fresno | | | | |
| Advanced | Audit – Typical | 0.25 | 0.43 | 0.34 |
| | Audit – Poor | 0.25 | 0.45 | |
| | Commissioning | 0.17 | 0.40 | |

* The advanced house effective air change rates are a function of HVAC central fan runtimes.

## Table C-8: Thermal Distribution System Efficiencies – Comfort Call Cases

| | | | | Thermal Distribution System Efficiencies* | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Typical | | | Poor | | |
| | | Total Duct Leakage to Outside | Duct Location | Heat | Cool | Avg. | Heat | Cool | Avg. |
| El Toro | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.85 | 0.80 | 0.82 | 0.78 | 0.74 | 0.76 |
| | Commissioning | 6% | | 0.92 | 0.86 | 0.89 | 0.92 | 0.86 | 0.89 |
| | Opportunity | 6% | | 0.90 | 0.84 | 0.87 | 0.90 | 0.84 | 0.87 |
| New | Audit | 22% | Attic | 0.84 | 0.80 | 0.82 | 0.80 | 0.77 | 0.78 |
| | Commissioning | 6% | | 0.88 | 0.84 | 0.86 | 0.88 | 0.84 | 0.86 |
| | Opportunity | 6% | | 0.89 | 0.84 | 0.86 | 0.89 | 0.84 | 0.86 |
| Advanced | Audit | 11% | Conditioned Attic | 0.95 | 0.88 | 0.91 | 0.93 | 0.86 | 0.89 |
| | Commissioning | 4% | | 0.96 | 0.89 | 0.93 | 0.96 | 0.89 | 0.93 |
| Pasadena | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.85 | 0.85 | 0.85 | 0.78 | 0.83 | 0.80 |
| | Commissioning | 6% | | 0.92 | 0.88 | 0.90 | 0.92 | 0.88 | 0.90 |
| | Opportunity | 6% | | 0.89 | 0.87 | 0.88 | 0.89 | 0.87 | 0.88 |
| New | Audit | 22% | Attic | 0.84 | 0.85 | 0.85 | 0.80 | 0.83 | 0.82 |
| | Commissioning | 6% | | 0.88 | 0.87 | 0.87 | 0.88 | 0.86 | 0.87 |
| | Opportunity | 6% | | 0.89 | 0.86 | 0.87 | 0.89 | 0.86 | 0.87 |
| Advanced | Audit | 11% | Conditioned Attic | 0.95 | 0.90 | 0.92 | 0.93 | 0.89 | 0.91 |
| | Commissioning | 4% | | 0.96 | 0.91 | 0.94 | 0.96 | 0.91 | 0.94 |
| Sacramento | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.83 | 0.84 | 0.84 | 0.75 | 0.81 | 0.78 |
| | Commissioning | 6% | | 0.91 | 0.87 | 0.89 | 0.91 | 0.88 | 0.89 |
| | Opportunity | 6% | | 0.87 | 0.86 | 0.86 | 0.87 | 0.86 | 0.86 |
| New | Audit | 22% | Attic | 0.84 | 0.85 | 0.84 | 0.79 | 0.83 | 0.81 |
| | Commissioning | 6% | | 0.88 | 0.86 | 0.87 | 0.88 | 0.86 | 0.87 |
| | Opportunity | 6% | | 0.87 | 0.86 | 0.87 | 0.87 | 0.86 | 0.87 |
| Advanced | Audit | 11% | Conditioned Attic | 0.94 | 0.90 | 0.92 | 0.92 | 0.89 | 0.90 |
| | Commissioning | 4% | | 0.96 | 0.91 | 0.93 | 0.96 | 0.91 | 0.93 |
| Fresno | | | | | | | | | |
| Existing | Audit | 28% | Attic | 0.90 | 0.86 | 0.88 | 0.75 | 0.77 | 0.76 |
| | Commissioning | 6% | | 0.91 | 0.86 | 0.89 | 0.91 | 0.86 | 0.89 |
| | Opportunity | 6% | | 0.91 | 0.85 | 0.88 | 0.87 | 0.85 | 0.86 |
| New | Audit | 22% | Attic | 0.84 | 0.82 | 0.83 | 0.80 | 0.80 | 0.80 |
| | Commissioning | 6% | | 0.88 | 0.85 | 0.87 | 0.88 | 0.85 | 0.87 |
| | Opportunity | 6% | | 0.87 | 0.85 | 0.86 | 0.87 | 0.85 | 0.86 |
| Advanced | Audit | 11% | Conditioned Attic | 0.92 | 0.88 | 0.90 | 0.92 | 0.88 | 0.90 |
| | Commissioning | 4% | | 0.96 | 0.90 | 0.93 | 0.96 | 0.90 | 0.93 |

*The thermal distribution system efficiencies are aggregated based on the thermal distribution system efficiencies of the individual typical case component runs.

Table C-9: Thermal Distribution System Efficiencies – Comfort Call Cases

| | Audit | | Commissioning | | Opportunity** |
|---|---|---|---|---|---|
| | Poor | Typical* | Poor | Typical* | |
| Existing | 76 to 80% | 82 to 88% | 89 to 90% | 89 to 90% | 86 to 87% |
| New | 78 to 82% | 82 to 85% | 86 to 87% | 86 to 87% | 86 to 87% |
| Advanced | 89 to 91% | 90 to 92% | 93 to 94% | 93 to 94% | n/a |

*Thermal distribution systems efficiencies for the typical cases are aggregated based on the individual typical case component runs.

**Smaller, HVAC equipment with the same duct system can result in slightly lower thermal distribution system efficiencies.

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