Building Commissioning

A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions

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Report Prepared for:
California Energy Commission
Public Interest Energy Research (PIER)

July 21, 2009

Sponsored by the California Energy Commission, Public Interest Energy Research Program, through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Acknowledgments

This report would not have been possible without the support of my insightful and patient sponsors at the California Energy Commission's Public Interest Energy Research Program (PIER): Martha Brook and Norman Bourassa (Buildings) and Paul Roggensack and Pramod Kulkarni (Industry).

This work expands significantly on a report originally published in 2004 with co-authors Hannah Friedman, Tehesia Powell, Norman Bourassa, David Claridge, Tudi Haasl, and Mary Ann Piette, who helped to build the original analysis framework and case-study database.

Paul Mathew collaborated on a parallel research effort to evaluate monitoring-based commissioning (MBCx) projects throughout the University of California and California State University systems, and those projects are included in the database presented here. Karl Brown (California Institute for Energy and Environment) made that research possible by facilitating communication with the UC/CSU/IOU Monitoring-Based Commissioning (MBCx) program.

A number of individuals exerted considerable effort on gathering and tabulating data used in this study or augmenting previously published information. They include John Bynum (TAMU), Michael Anderson and Anna Levitt (Newcomb Anderson McCormick), Narendra Amarnani (County of Los Angeles), Eliot Crowe and Emilia Sibley (PECI), Geoffrey Bell and Steve "Futzmeister" Greenberg (LBNL), Jim Bradford (Nexant), Len Beyea (RetroCom Energy Strategies), Kimberlie Lenihan and Natasha Malik (NYSERDA), David McIntosh (Connecticut Power & Light), Margot Rode (Architectural Energy Corporation), and David Sellers (Facility Dynamics).

The following individuals provided data for the 2004 study (which remains part of our analysis): Edward Allen and David Jump (Quantum Consulting), Adam Benzuly (Affiliated Engineers, Inc.), Daren Goody (PECI), Martha Hewett (Minnesota Center for Energy and Environment), John Jennings (Northwest Energy Efficiency Alliance), Bing Tso (SBW Consulting), Jeffrey Warner (LBNL), and Phoebe Caner Warren (Seattle City Light).

Mark Wilson provided excellent copy-editing assistance.

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Executive Summary

The aim of commissioning new buildings is to ensure that they deliver, if not exceed, the performance and energy savings promised by their design. When applied to existing buildings, commissioning identifies the almost inevitable "drift" from where things should be and puts the building back on course. In both contexts, commissioning is a systematic, forensic approach to quality assurance, rather than a technology per se. Although commissioning has earned increased recognition in recent years—even a toehold in Wikipedia—it remains an enigmatic practice whose visibility severely lags its potential.

Over the past decade, Lawrence Berkeley National Laboratory has built the world's largest compilation and meta-analysis of commissioning experience in commercial buildings. Since our last report (Mills et al. 2004) the database has grown from 224 to 643 buildings (all located in the United States, and spanning 26 states), from 30 to 100 million square feet of floorspace, and from $17 million to $43 million in commissioning expenditures. The recorded cases of new-construction commissioning took place in buildings representing $2.2 billion in total construction costs (up from 1.5 billion). The work of many more commissioning providers (18 versus 37) is represented in this study, as is more evidence of energy and peak-power savings as well as cost-effectiveness. We now translate these impacts into avoided greenhouse gases and provide new indicators of cost-effectiveness. We also draw attention to the specific challenges and opportunities for high-tech facilities such as labs, cleanrooms, data centers, and healthcare facilities.

The results are compelling. We developed an array of benchmarks for characterizing project performance and cost-effectiveness. The median normalized cost to deliver commissioning was $0.30/ft^2 for existing buildings and $1.16/ft^2 for new construction (or 0.4% of the overall construction cost). The commissioning projects for which data are available revealed over 10,000 energy-related problems, resulting in 16% median *whole-building* energy savings in existing buildings and 13% in new construction, with payback time of 1.1 years and 4.2 years, respectively. In terms of other cost-benefit indicators, median benefit-cost ratios of 4.5 and 1.1, and cash-on-cash returns of 91% and 23% were attained for existing and new buildings, respectively. High-tech buildings were particularly cost-effective, and saved higher amounts of energy due to their energy-intensiveness. Projects with a comprehensive approach to commissioning attained nearly twice the overall median level of savings and five-times the savings of the least-thorough projects

It is noteworthy that virtually all existing building projects were cost-effective by each metric (0.4 years for the upper quartile and 2.4 years for the lower quartile), as were the majority of new-construction projects (1.5 years and 10.8 years, respectively). We also found high cost-effectiveness for each specific measure for which we have data. Contrary to a common perception, cost-effectiveness is often achieved even in smaller buildings.

Thanks to energy savings valued more than the cost of the commissioning process, associated reductions in greenhouse gas emissions come at "negative" cost. In fact, the median cost of conserved carbon is *negative*— -$110 per tonne for existing buildings and -$25/tonne for new construction—as compared with market prices for carbon trading and offsets in the +$10 to +$30/tonne range.

Further enhancing the value of commissioning, its non-energy benefits surpass those of most other energy-management practices. Significant first-cost savings (e.g., through right-sizing of heating and cooling equipment) routinely offset at least a portion of commissioning costs—fully in some cases. When accounting for these benefits, the net median commissioning project cost was reduced by 49% on average, while in many cases they exceeded the direct value of the energy savings. Commissioning also improves worker comfort, mitigates indoor air quality problems, increases the competence of in-house staff, plus a host of other non-energy benefits.

These findings demonstrate that commissioning is arguably the single-most cost-effective strategy for reducing energy, costs, and greenhouse gas emissions in buildings today. Energy savings tend to persist well over at least a 3- to 5-year timeframe, but data over longer time horizons are not available. It is thus important to "Trust but Verify," and indeed the field is moving towards a monitoring-based paradigm in which instrumentation is used not only to confirm savings, but to identify opportunities that would otherwise go undetected. On balance, we view the findings here as conservative, in the sense that they likely underestimate the actual performance of projects when all costs and benefits are considered. They certainly underestimate the technical potential for a scenario in which best practices are applied.

Applying our median whole-building energy-savings value (i.e. not best practices) to the stock of U.S. non-residential buildings corresponds to an annual energy-savings potential of $30 billion by the year 2030, which in turn corresponds to annual greenhouse gas emissions of about 340 megatons of CO_2 each year. The commissioning field is evolving rapidly. The delivery of services must be scaled up radically if the benefits are to be captured.

The fledgling existing-buildings commissioning industry has reached a size of about $200 million per year in the United States. Based on a goal of commissioning each building every five years, the potential size is about $4 billion per year, or 20-times the current number. To achieve the goal of keeping the U.S. building stock commissioned would require an increase in the workforce from about 1,500 to 25,000 full-time-equivalent workers, a realistic number when viewed in the context of the existing workforce of related trades.

Commissioning is more than "just another energy-saving measure." It is a risk-management strategy that should be integral to any systematic approach to garnering energy savings or emissions reductions. Commissioning ensures that a building owners get what they pay for when constructing or retrofitting buildings, it provides insurance for policymakers and program managers that their initiatives actually meet targets, and it detects and corrects problems that would eventually surface as far more costly maintenance or safety issues.

Commissioning is an underutilized strategy for saving energy and money and reducing greenhouse gas emissions while managing related risks. Reasons for this underutilization include a widespread lack of awareness of need and value on the part of prospective customers, insufficient professionalism within the trades, splintered activities and competition among a growing number of trade groups and certification programs, a misperception that it is not cost-effective in smaller buildings, the absence of commissioning-like requirements in most building codes, and omission or obfuscation of the strategy in most energy-efficiency potentials studies. It is important to strike a healthy balance between standardization and recognition that each building is unique and must be approached with an open mind.

"Commissioning America" in a decade is an ambitious goal, but "do-able" and very consistent with this country's aspirations to simultaneously address energy and environmental issues while creating jobs and stimulating economic activity.

Commissioning: The Stealth Energy-Saving Strategy

Walk into almost any home-improvement store today and be met by aisles brimming with compact fluorescent lamps. Climb atop a green building and behold a vegetated roof. Energy efficiency is all of a sudden commonplace with iconic imagery, or at least more so than it was just a few years ago. Yet, an equally important pathway to energy savings and greenhouse gas emissions reductions is virtually invisible to the typical building occupant, and too often even to the operators: the *commissioning* of new buildings and *retrocommissioning* of existing ones.[1]

For centuries, ship builders have "commissioned" vessels to ensure that they are ready for service; a risk-management process that includes installation and testing of equipment and ensuring that problems are corrected and the crew trained to maintain performance (Haasl and Heinemeier 2006a). After initial commissioning, ships are routinely inspected and serviced ("retrocommissioned") to maintain their performance. In this sense, people even routinely commission (inspect/service) their cars. Early forms of commissioning in buildings date to the 1950s in Europe, but arguably did not appear in the United States for several more decades (NEMI 2001). The commissioning of buildings for energy savings transitioned from being the subject of research projects in the 1980s, to a constellation of one-off pilot projects among a small vanguard of top-flight engineers in the 1990s, to ambitious scale-up efforts today.

The translation of this concept to buildings encompasses issues as diverse as access, safety, mechanical, landscaping, acoustics, water use, indoor air quality, and energy performance. This report focuses on commissioning as it pertains to energy performance in buildings, although other themes (particularly indoor environment) are often intertwined. While commissioning may seem like something that would be "standard practice" (and many building owners erroneously assume that it is), buildings are *rarely* commissioned, especially for energy savings. As a result, buildings are riddled with problems (Figure 1).

This situation is changing, albeit slowly. Commissioning is today used to save energy in ordinary buildings where no particular effort has previously been made to utilize energy-efficiency strategies, or to ensure and maximize performance of targeted energy-efficiency measures. The results are highly impressive. Case studies of large-scale commissioning efforts show attractive energy savings and payback times (Table 1).

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[1] Complicating an already difficult value proposition, the commissioning field is littered with competing terminology, naming systems, and proprietary marks. To avoid clutter, when discussing the topic we simply use the term "commissioning." If the reference is solely to new or existing buildings and that is not clear by the context, then we add clarifying language.

Figure 1. *Hall of shame – Visible evidence of problems addressed by commissioning*

Hot water valve motion impeded by piping layout [EMC no date (a)]

Damage to brick façade of pool building due to lack of proper sealing and air management [Martha Hewet, Minnesota Center for Energy and Environment (MNCEE)]

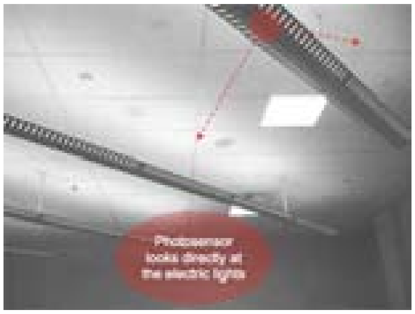
Inadequate fan cooling and excessive fan power due to poor fit between the light fixture and ducting, causing significant duct leakage [Martha Hewett, MNCEE]

Building envelope moisture entry [Aldous 2008]

Rust indicates poor anti-condensation heating control setpoints in supermarket refrigeration cabinet [Sellers and Zazzara 2004]

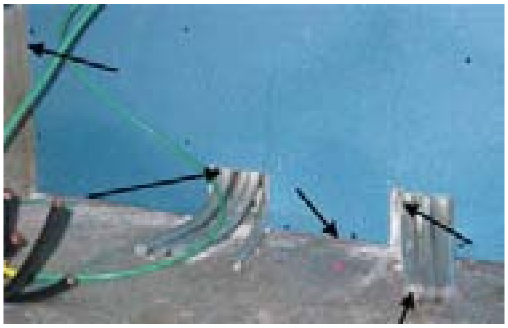
Building envelope moisture entry [Aldous 2008]

Photosensor (for daylight harvesting) shaded by duct [Deringer 2008]



Photosensor “sees” the electric lamps rather than task-plane illumination [Deringer 2008]

Plugged filter causing condensation on bottom of fan coil unit and damage to insulation coil resulting in poor air flow [Martha Hewett, MNCEE]



Air leakage in an underfloor air-distribution system [Stum 2008]

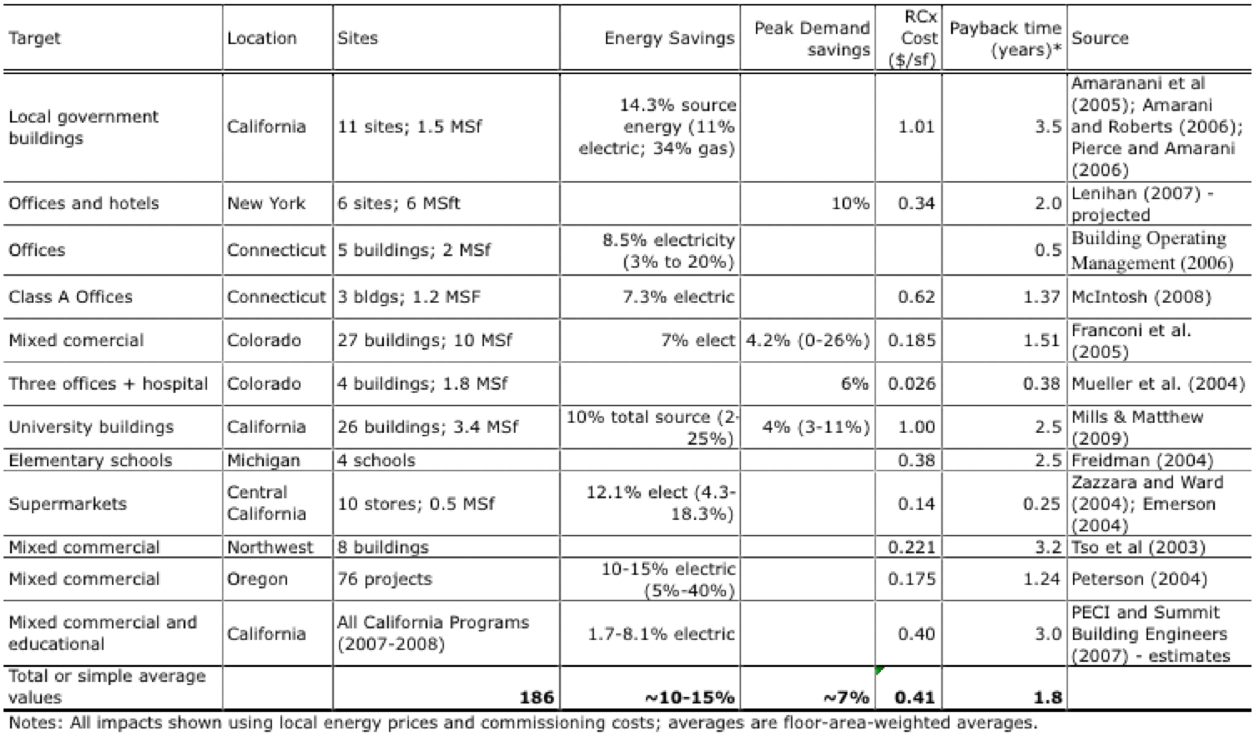
Zone damper actuator arm broken (no temperature control) [Martha Hewett, MNCEE]

Failed window film treatment.

Active humidification downstream of a condensing cooling coil at cleanroom facility [Sellers no date]

Exhaust fan hardwired in an “always on” position [Mittal and Hammond 2008]

Table 1. Examples of existing-building commissioning project costs and savings.



Target	Location	Sites	Energy Savings	Peak Demand savings	RCx Cost ($/sf)	Payback time (years)*	Source
Local government buildings	California	11 sites; 1.5 MSf	14.3% source energy (11% electric; 34% gas)		1.01	3.5	Amaranani et al (2005); Amarani and Roberts (2006); Pierce and Amarani (2006)
Offices and hotels	New York	6 sites; 6 MSft		10%	0.34	2.0	Lenihan (2007) - projected
Offices	Connecticut	5 buildings; 2 MSf	8.5% electricity (3% to 20%)			0.5	Building Operating Management (2006)
Class A Offices	Connecticut	3 bldgs; 1.2 MSF	7.3% electric		0.62	1.37	McIntosh (2008)
Mixed comercial	Colorado	27 buildings; 10 MSf	7% elect	4.2% (0-26%)	0.185	1.51	Franconi et al. (2005)
Three offices + hospital	Colorado	4 buildings; 1.8 MSf		6%	0.026	0.38	Mueller et al. (2004)
University buildings	California	26 buildings; 3.4 MSf	10% total source (2-25%)	4% (3-11%)	1.00	2.5	Mills & Matthew (2009)
Elementary schools	Michigan	4 schools			0.38	2.5	Freidman (2004)
Supermarkets	Central California	10 stores; 0.5 MSf	12.1% elect (4.3-18.3%)		0.14	0.25	Zazzara and Ward (2004); Emerson (2004)
Mixed commercial	Northwest	8 buildings			0.221	3.2	Tso et al (2003)
Mixed commercial	Oregon	76 projects	10-15% electric (5%-40%)		0.175	1.24	Peterson (2004)
Mixed commercial and educational	California	All California Programs (2007-2008)	1.7-8.1% electric		0.40	3.0	PECI and Summit Building Engineers (2007) - estimates
Total or simple average values		**186**	**~10-15%**	**~7%**	**0.41**	**1.8**	

Notes: All impacts shown using local energy prices and commissioning costs; averages are floor-area-weighted averages.

Commissioning is one of the most potent and yet least understood strategies for managing energy use, costs, and associated greenhouse gas emissions in the buildings sector. Emblematic of the problem, commissioning is rarely if ever explicitly included in energy-efficiency-potential studies. An encouraging sign of the gradual mainstreaming of commissioning is the appearance of an article on the topic in Wikipedia in 2008.[2]

An industry survey in 2005 estimated that well-below 5% of existing buildings and as much as 38% of "commissionable"[3] new construction had been commissioned (NEMI 2005). An earlier survey in California estimated that 0.03% of existing buildings and 5% of new construction had been commissioned (PECI 2000). The former survey probably addressed all types of commissioning, whereas the latter focused on energy issues.

There is no national census defining how many buildings are candidates for commissioning, but practitioners say they are hard-pressed to find buildings that would not benefit from the practice. The National Oceanic and Atmospheric Administration (NOAA) stated that 88 of its 122 weather-forecasting data centers are in need of commissioning, and had completed 47 of these by 2004 (Lundstrom 2004).

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[2] See http://en.wikipedia.org/wiki/Building_commissioning

[3] The definition used here appears to be broader than just energy-driven commissioning, e.g., including safety systems. The share of buildings retrocommissioned for energy savings as thoroughly as many of those documented in this report could be lower by a factor of ten. The study assumes that one-third of all new construction (21% in the "commercial" sector, 25% multifamily, 34% industrial, and 54% institutional) is commissionable. The basis for this assumption is not clear, and, in this author's opinion the share could be far higher.

The commissioning practitioner community recognizes that market uptake has been slow. This is attributed to lack of understanding about what commissioning is and why it is needed, combined with a lack of a financial business case (*Cx Journal* 2005). Commissioning is most widely practiced in public buildings.

In addition to lack of awareness, commissioning is also a "stealth" energy-saving strategy in the sense that the deficiencies it corrects are almost always invisible to the casual observer, and unfortunately also to building designers, operators, and owners. Contributing to this state of affairs, these problems often do not present noticible symptoms such as occupant discomfort or noise (although in some cases these are indeed important clues and corresponding "non-energy" benefits of the fixes).

Momentum for commissioning is increasing. The impetus is coming from energy and environmental policymakers and the private sector, and is increasingly resonating with building owners' interest in greening their properties. Commissioning is required for buildings seeking the increasingly popular LEED (Leadership in Energy and Environment Design) rating, and building code officials (Kunkle 2005; Gowri 2009) are gradually studying and adopting mandatory commissioning or "commissioning-like" requirements. State-level initiatives such as California's Green Building Action plan are also promoting the practice. Meanwhile, in the private sector, energy utilities are rolling out increasingly ambitious incentive programs for commissioning, with at least 12 such programs currently in place (Criscione 2008). In one example, as of March 2008 the Southern California Edison commissioning program had secured 83 projects representing 25.5 million square feet of floorspace (Long and Crowe 2008a). Xcel Energy had a similar target in Colorado as of 2005 (Franconi et al. 2005). Other industries are also getting involved, notably insurance companies who are viewing commissioning as a risk-management strategy, and tailoring their insurance products and terms to encourage and reward it (Mills 2009a).

Commissioning is still far from mainstream. The untapped potential is huge. In 2004, Lawrence Berkeley National Laboratory estimated $18 billion per year of potential savings from commissioning throughout the United States (Mills et al. 2004). Analysis of a study published a year later suggests a potential savings for the top 13 (of 100) typical commercial buildings faults alone at $3.3–$17 billion per year (Table 2). As will be shown in the following pages, the potential is considerably higher today.

Table 2. Top faults causing energy inefficiencies in commercial buildings (top 13 of 100+)

	National Energy Waste (Quads, primary/year)	Electricity equivalent (BkWh/year)	Cost ($billion/year)
Duct leakage	0.3	28.6	2.9
HVAC left on when space unoccupied	0.2	19.0	1.9
Lights left on when space unoccupied	0.18	17.1	1.7
Airflow not balanced	0.07	6.7	0.7
Improper refrigerant charge	0.07	6.7	0.7
Dampers not working properly	0.055	5.2	0.5
Insufficient evaporator airflow	0.035	3.3	0.3
Improper controls setup / commissioning	0.023	2.2	0.2
Control component failure or degradation	0.023	2.2	0.2
Software programming errors	0.012	1.1	0.1
Improper controls hardware installation	0.01	1.0	0.1
Air-cooled condenser fouling	0.008	0.8	0.1
Valve leakage	0.007	0.7	0.1
Total (central estimate)	1.0	94.6	9.6
Total (range)	0.34-1.8	32.4-171.4	3.3-17.3

Adapted from Roth et al. (2005) assuming 10,500 BTU/kWh, and $0.10/kWh

What Commissioning Is (and Is Not)

Despite its 30-year history in the United States,[4] and hundreds of millions of square feet of floor area commissioned, most mainstream industry professionals would be hard-pressed to define building commissioning. A vanishingly small fraction of building owners/managers know what it is. Even efforts to explain it can leave many a listener mystified.

At the highest level, building commissioning brings a holistic perspective to design, construction, and operation that integrates and enhances traditionally separate functions. It does so through a meticulous "forensic" review of a building's disposition to identify suboptimal situations or malfunctions and the associated opportunities for energy savings.

The California Commissioning Collaborative has laid out plain-English definitions of the various forms of commissioning, which we quote verbatim in Box A (Haasl and Heinemeier 2006a-b). As can be surmised from these definitions, commissioning is necessarily a team effort, and usually led by a specialist but including the traditional trades such as designers, engineers, contractors, onsite operations and maintenance staff, and, hopefully, building owners.

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[4] A detailed historical timeline is provided here: http://www.peci.org/ncbc/cx_history.html

Box A. Commissioning Defined

The term commissioning comes from shipbuilding. A commissioned ship is one deemed ready for service. Before being awarded this title, however, a ship must pass several milestones. Equipment is installed and tested, problems are identified and corrected, and the prospective crew is extensively trained. A commissioned ship is one whose materials, systems, and staff have successfully completed a thorough quality assurance process.

Building commissioning takes the same approach to new buildings. When a building is initially commissioned it undergoes an intensive quality assurance process that begins during design and continues through construction, occupancy, and operations. Commissioning ensures that the new building operates initially as the owner intended and that building staff are prepared to operate and maintain its systems and equipment.

Retrocommissioning is the application of the commissioning process to existing buildings. Retrocommissioning is a process that seeks to improve how building equipment and systems function together. Depending on the age of the building, retrocommissioning can often resolve problems that occurred during design or construction, or address problems that have developed throughout the building's life. In all, retrocommissioning improves a building's operations and maintenance (O&M) procedures to enhance overall building performance.

Recommissioning is another type of commissioning that occurs when a building that has already been commissioned undergoes another commissioning process. The decision to recommission may be triggered by a change in building use or ownership, the onset of operational problems, or some other need. Ideally, a plan for recommissioning is established as part of a new building's original commissioning process or an existing building's retrocommissioning process.


Commissioning Process Overview

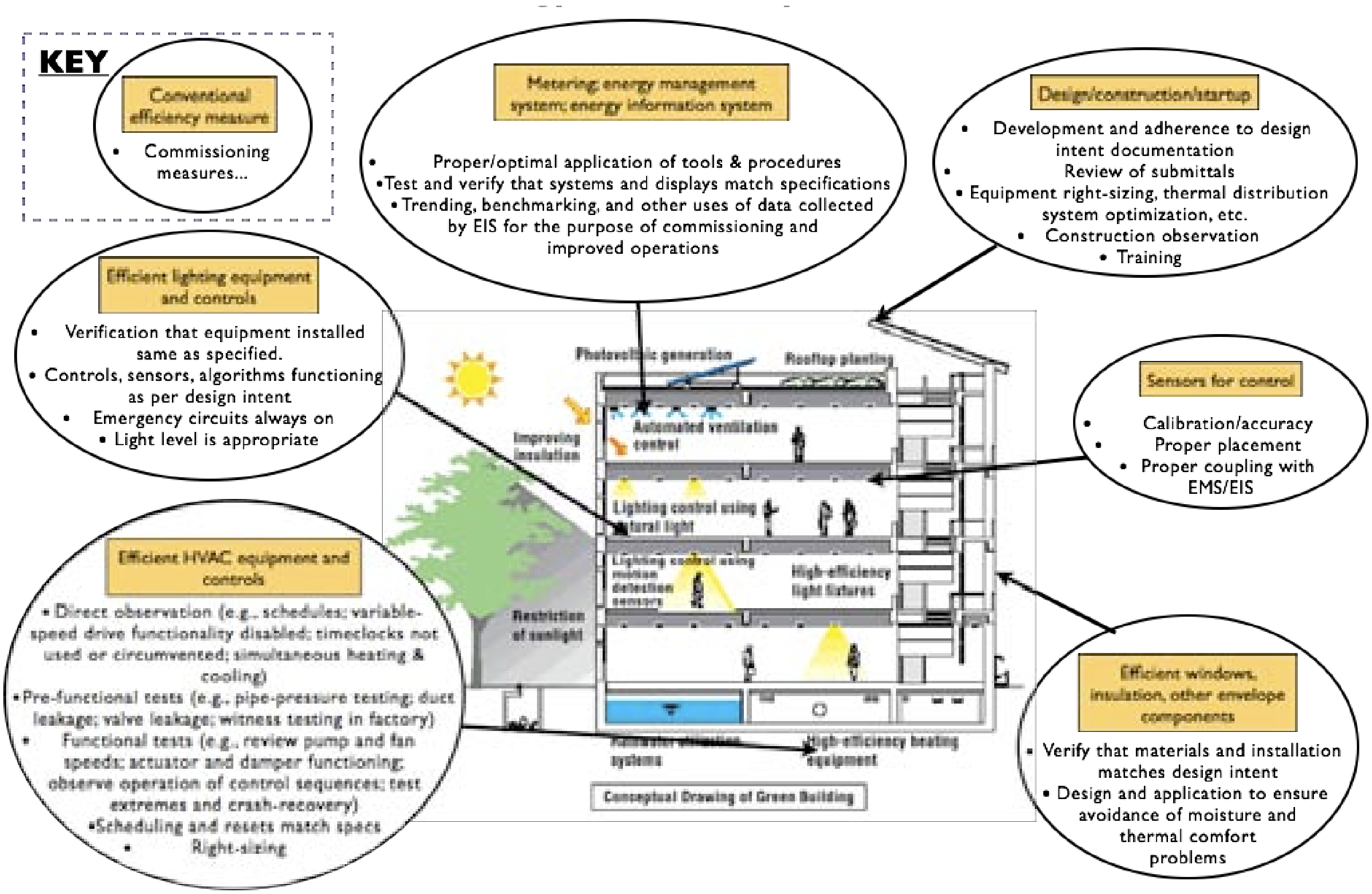

Retrocommissioning Process Overview

CSI for Energy Efficiency – Commissioning as Forensics

Unlike an efficient light bulb, commissioning is not a “commodity” product (or process). Each building is unique and presents unique problems for unique owners. Aspiration and budget can also vary; commissioning is performed at widely varying levels of effort and applied buildings as a whole (preferred) or to a specific sub-system or energy end-use.

Commissioning thus differs fundamentally from constructing or retrofitting facilities with better energy-using equipment (Figure 2). Commissioning complements these relatively familiar practices by ensuring and maintaining building energy performance (and other benfits, such as indoor environmental qulaity). On the same token, it can simply focus on saving energy by improving conventional building systems, irrespective of whether or not the building is equipped to be particularly energy efficient.

Figure 2. *Illustrative relationships between commissioning and energy-efficiency measures*



Commissioning improves on design and execution in new construction, or "tunes" the existing system (the metaphor to diagnosing and tuning a car is a loose but useful analogy). The costs of commissioning are thus largely time and labor, as opposed to materials or capital equipment. Persistence of the corrections (and associated energy savings) tends to be a concern, as many commissioning measures are operational and thus easily reversed if not monitored.

While the focus includes individual pieces of energy-using equipment, it is also a decidedly wholistic approach emphasizing the connections between components into systems.[5] Thus, "softer" elements are addressed, such as control logic or even the effectiveness of computer user interfaces or other communication systems used to visualize the building's disposition and energy use trends and make design and design intent unambiguous (Pollard 2009). Commissioning also differs from other energy-savings strategies in that it does not accept what is in a building (or design) as optimal (or even necessary), but, rather, asks fundamental questions such as "is that pump needed?" as opposed to "can we make that pump more efficient?"

While commissioning is not a panacea for the world's energy and climate problems, it is an element of a best-practices approach to achieving quality and high performance, while managing information and energy use throughout a building's lifecycle.

Commissioning as Risk Management

The world has become a riskier place, and buildings are no exception. With the enthusiasm and naivete about energy efficiency in the 1970s and 1980s, it was easy to assume that energy savings could be estimated with simple slide-rule methods and that promised energy savings would always materialize. Many studies and estimates of savings potential still assume that everthing works perfectly, an implicit inference that commissioning is universally applied (when in fact it rarely is).

The case of a data center provides a good illustration of these risks (Nodal 2008). Engineering calculations led the team to believe that electricity savings of 14.3% were being attained by a retrofit project. On closer inspection the savings were found to be exactly zero. Subsequent commissioning of the facility unearthed the causes of the lost savings, and not only restored them but boosted them to 19.2% (and 26% for peak demand).

Buildings are increasingly more complex than meets the eye, and many factors must fall into place (and stay there) in order for energy savings to manifest. And the consequences of underattainment are increasing as projects are structured such that energy-savings streams service the debt incurred to finance the efficient technologies, greenhouse gas reductions credited to energy efficiency are taken to markets with the desire that they be converted to "offsets" and then money, and regulators strengthen their oversight. Meanwhile, new technologies for saving energy have an intrinsic degree of risk simply

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[5] There is an enormous literature on commissioning practices and case studies. Beyea (2009) provides very thorough review of the kinds of issues discovered and remedied during commissioning.

due to the lack of field experience and because some are more complex than the traditional technologies they replace.

As green buildings become a more significant part of the building stock, the insurance industry has been reasonably supportive of (Mills 2009a), but it is also very focused on changing “risk profiles.” Reports from the world’s largest brokers Marsh (2008) and Aon (Taylor 2008) encourage the practice, but also site concerns about issues ranging from unfulfilled energy warranties, to business interruptions, to liabilities posed by exotic materials and equipment that do not have the same track record as (less efficient) standard practices.

Jump (2007) notes that commissioning itself is vulnerable to similar risks if performance disappoints or if measurement and verification is inadequate:

- Risks to Owner:
    - Savings not delivered, no return on investment
    - No ability to track actual savings
    - Savings do not last, especially for “soft” measures that can be and often are defeated
- Risks to Energy-Efficiency Programs:
    - Claimed savings do not stand up to third-party review
    - Savings lifetimes are short
    - Negative impact on program realization rates
- Risk to Regulatory Agencies
    - Unreliable basis for program planning and accurate forecasting

As discussed later in this report, commissioning approaches that incorporate in-depth monitoring and verification can offer significantly enhanced risk-management benefits. The commissioning provider for one such project noted that:

> [Typical] savings are based on estimates, and rarely verified. In the long run, this can lead to problems with the perception of RCx [retrocommissioning] projects and programs. Monitoring-based commissioning programs provide the opportunity to develop tools to monitor and track savings, and notify operators when savings diminish. …[P]rojects … with the added metering and analysis, remain cost-effective, and provide added benefits of rigorous savings verification, energy tracking, diagnostic capabilities, and long-term persistence tracking. This provides added security for owners, energy efficiency program implementers, and their regulatory agencies, that the savings are real and last over time. (Jump et al. 2007).

Irrespective of the degree of monitoring and verification, to not commission at all is to invite a multitude of risks and underattainment of goals. It can be argued that commissioning is an essential risk-management component of any policy or program that aspires to attain a specific level of energy savings. Some have attempted to quantitatively define the relevant risks to formalize the process of targeting commissioning activities (Berner et al. 2006).

As will be demonstrated below, commissioning is also a tool for managing non-energy risks. Indeed, prevention of indoor-air-quality problems, premature equipment failure, and litigation are among the reasons commonly given for commissioning.

Quantifying Commissioning: A Meta-Analysis

There is a growing literature on commissioning, including large numbers of disparate case studies. Many of these case studies present some form of information on the costs of commissioning and resulting energy savings in actual buildings. However, the underlying methods, assumptions, data completeness, and level of data quality vary widely and are not always revealed. The goal of this study is to prepare a "meta-analysis" of this body of experience in order to benchmark and chart the overall trends across a variety of geographies, building types, and other variables. This requires applying decision rules in determining which projects qualify for inclusion together with methods for normalizing and standardizing the data to facilitate benchmarking and inter-comparisions.[6]

As with any evaluation activity, data quality control and quality assurance are essential. Our experience with doing this firsthand with many of the projects in this compilation did reveal (and correct) dozens of issues with math errors, incorrect units, conversions, or underlying assumptions.[7]

Data Sources and Analysis Methods

We build on our original compilation published in 2004 (Mills et al. 2004), which contained information and analysis for 224 buildings. We subsequently released a call for more data to hundreds of stakeholders in the commissioning community, including practitioners. The response was meager. Real-world projects rarely have budget or a client able to pay for data collection, let alone preparation of publications. Proprietary considerations also keep certain data out of the public domain.

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[6] Engineering assumptions: Basic assumptions: Electricity heat rate 10,400 British thermal units per kilowatt-hour (BTU/kWh). Greenhouse gas emissions factors (in carbon dioxide emissions equivalent, i.e., including other major greenhouse gases): electricity (2.0331 pounds/kWh), natural gas (112.49 pounds per million BTUs). Economic assumptions: Costs normalized to 2009 price levels ("US$2009"). Energy prices per U.S. Department of Energy, Energy Information Administration (USDOE/EIA- averages 5/2008-4/2009): electricity ($0.1043/kWh, and $120/kW-month demand charge), natural gas ($12.32/MBTU), central hot water ($15.26/MBTU), central chilled water ($16.21/MBTU), central steam ($17.12/MBTU). Where savings by fuel are not available, we use nominal reported total cost savings, inflation-adjusted per the energy price deflator and weighted electricity/fuel price by the relative national consumption per DOE/EIA's 2003 Commercial Buildings Energy Consumption Survey, CBECS. Measure lifetime for cost-benefit analysis: five years. General inflation correction using gross domestic product deflators from the U.S. Department of Commerce. Building construction costs inflation-corrected using Engineering News Record (McGraw-Hill), Engineering News Record, Building Cost Index. Commissioning costs inflation corrected using Engineering News Record (McGraw-Hill) Skilled Labor, and total Construction Cost indices. More detailed documentation is provided at http://cx.lbl.gov/2009-assessment.html.

[7] Recommended quality assurance procedures are noted here: http://cx.lbl.gov/qa.html

Several substantial cohorts of projects were ultimately recruited. We enlisted one large commissioning provider (Texas A&M University) to extract previously unpublished data from 63 prior projects around the country. Results from an evaluation of "monitoring-based commissioning" at 21 University of California and California State University sites were also migrated into the database (Mills and Mathew 2009). PECI provided data on 64 projects conducted under utility programs in California. Some projects from the original 2004 compilation were revisited, and missing information obtained, thereby upgrading that cohort of buildings.

We also combed the commissioning literature for individual or sets of candidate projects and obtained supplemental information by contacting authors, utility partners, or building owners. Many case studies we encountered did not qualify for inclusion. Many lacked critical information, such as the costs of commissioning or energy savings. Others included hypothetical savings from planned projects that had not yet been realized. Many included incomplete information, a common example of which is the fee paid to the commissioning provider but not the other costs incurred in-house or by other parties to deliver the complete commissioning service. In some cases retrofit costs and savings are mixed in with commissioning case studies, and we exclude these cases as well. For such projects, other useful data may still be available and included in the analysis (e.g., types of problems found or measures implemented).

To facilitate comparisions, the raw data are normalized to a standard U.S.-average commercial sector energy prices, and costs are inflation-corrected to 2009 levels. This is an important correction, as prevailing local energy prices for the projects in the database range from $0.02/kWh to $0.30/kWh for electricity and $0.62/MBTU to $10.22/MBTU for fuel. For energy use and savings data to be included, the data must be weather-normalized or based on engineering calculations indexed to standard weather conditions for the given location.

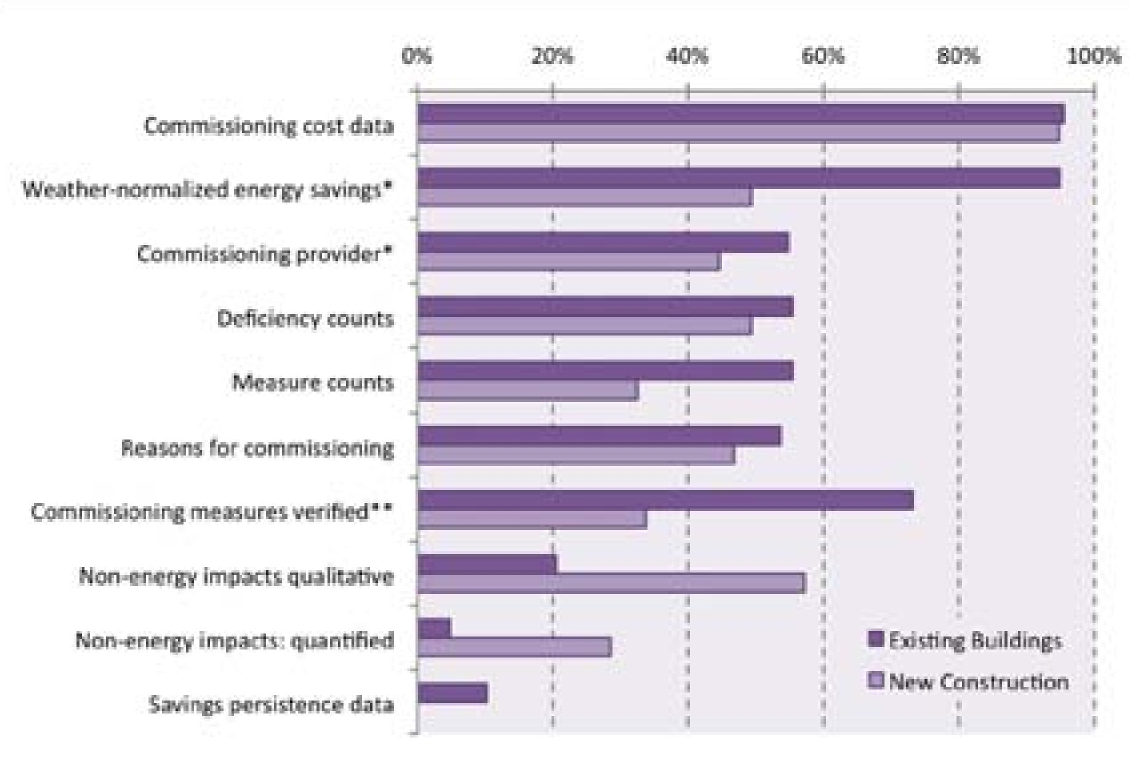
The resulting sample includes 332 commissioning projects in existing buildings and 77 in new-construction, spanning 26 states, representing a total of 643 buildings, 99 million square feet, and $43 million invested in the commissioning work (Figures 3 and 4).

Figure 3. *Sample by location, type, and size (square feet)*

	Total	Existing	New Construction
Education			
K-12	3,123,754	2,467,661	656,093
Higher education	12,029,520	11,401,833	627,687
Food Sales	983,402	848,039	135,363
Food Service	187,724	187,724	-
Health Care			
Outpatient healthcare	4,525,424	4,319,124	206,300
High-tech Facilities	-	-	-
Cleanrooms	301,000	-	301,000
Data Center	12,888	12,888	-
Laboratory	6,526,658	4,561,593	1,965,065
Inpatient	7,478,988	6,791,029	687,959
Lodging	10,037,291	9,880,307	156,984
Mercantile			
Retail	2,926,038	2,926,038	-
Service	227,000	227,000	-
Office	40,867,062	39,972,765	894,296
Public Assembly	3,166,611	2,476,985	689,626
Public Order and Safety	4,756,949	2,485,277	2,271,672
Religious Worship	12,500	12,500	-
Warehouse and Storage	175,379	13,500	161,879
Industrial	475,000	475,000	-
Other	1,411,622	1,351,622	60,000
Vacant	-	-	-
Total	**99,224,809**	**90,410,884**	**8,813,925**

* Note in some cases floor area is apportioned among more than one building type.

Figure 4. *Sample depth.*



* weighted by floor area

** some or all

Our sample includes data representing 37 commissioning providers covering about half of the floor area in the database, with only 1% known to be done in-house. The provider is unknown for the balance of the projects (Table 3). It is unknown how many providers exist in the market. The California Commissioning Collaborative presently recognizes 53 providers across the country.8

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[8] As of June 20, 2009. See http://www.cacx.org/resources/provider_list.html. Some providers in our study are not on this list.

Table 3. Commissioning providers in this study, by floor area.

	Existing Buildings (square feet)	%	New Construction (square feet)	%	Total	%
Abacus Engineered Systems, Inc.	95,405	0.1%	-	0.0%	95,405	0.1%
Affiliated Engineers, Inc.	-	0.0%	774,000	8.8%	774,000	0.8%
Architectural Energy Corporation	1,278,620	1.4%	230,000	2.6%	1,508,620	1.5%
Arup	176,000	0.2%	-	0.0%	176,000	0.2%
Casault Engineering	-	0.0%	170,566	1.9%	170,566	0.2%
CH2M Hill	-	0.0%	340,000	3.9%	340,000	0.3%
Cogent	1,900,200	2.1%	-	0.0%	1,900,200	1.9%
CTG Energetics	327,717	0.4%	-	0.0%	327,717	0.3%
Ecube	220,000	0.2%	-	0.0%	220,000	0.2%
EMC Engineers	1,506,188	1.7%	8,467	0.1%	1,514,655	1.5%
Energy Engineering & Design	490,000	0.5%	-	0.0%	490,000	0.5%
Environmental and Engineering Services, Inc.	-	0.0%	160,000	1.8%	160,000	0.2%
Facility Dynamics	1,014,133	1.1%	-	0.0%	1,014,133	1.0%
Facility Improvement Corporation	230,380	0.3%	-	0.0%	230,380	0.2%
Farnsworth Group	-	0.0%	767,176	8.7%	767,176	0.8%
HEC	376,500	0.4%	165,000	1.9%	541,500	0.5%
Henrikson	107,184	0.1%	-	0.0%	107,184	0.1%
Herzog/Wheeler	44,000	0.0%	-	0.0%	44,000	0.0%
Keithly/Welsch Associates Inc.	713,610	0.8%	173,000	2.0%	886,610	0.9%
MN Center for Energy and Environment	525,000	0.6%	-	0.0%	525,000	0.5%
Nexant	480,406	0.5%	-	0.0%	480,406	0.5%
Northwest Engineering Service, Inc.	213,000	0.2%	-	0.0%	213,000	0.2%
Notkin Engineering	-	0.0%	65,000	0.7%	65,000	0.1%
PECI	4,345,810	4.8%	371,000	4.2%	4,716,810	4.8%
Quantum Energy Services and Technologies, Inc. - QuEST	2,354,111	2.6%	-	0.0%	2,354,111	2.4%
RetroCom Energy Strategies	2,655,800	2.9%	-	0.0%	2,655,800	2.7%
Salas O'Brian	222,070	0.2%	-	0.0%	222,070	0.2%
Sebesta Blomberg	287,117	0.3%	-	0.0%	287,117	0.3%
Sieben Energy	623,000	0.7%	-	0.0%	623,000	0.6%
Solarc Architecture & Engineering	-	0.0%	96,500	1.1%	96,500	0.1%
Strategic Building Solutions	480,248	0.5%	-	0.0%	480,248	0.5%
Summit Building Engineering	90,712	0.1%	90,712	1.0%	181,424	0.2%
Systems West Engineers	172,400	0.2%	-	0.0%	172,400	0.2%
TAMU/ESL	26,429,206	29.2%	-	0.0%	26,429,206	26.6%
TESTCOMM, LLC	-	0.0%	195,390	2.2%	195,390	0.2%
UNL/ESL	675,885	0.7%	-	0.0%	675,885	0.7%
Van Zelm	765,064	0.8%	-	0.0%	765,064	0.8%
Western Montana Engineering	-	0.0%	23,300	0.3%	23,300	0.0%
Sub-total	48,799,766	54.0%	3,630,111	41.2%	52,429,877	52.8%
In-house	773,988	0.9%	301,000	3.4%	1,074,988	1.1%
Unknown	40,837,130	45.2%	4,882,814	55.4%	45,719,944	46.1%
Total	90,410,884	100%	8,813,925	100%	99,224,809	100%

Caveats and Conservatisms

The persistence of commissioning energy savings is perhaps the most significant caveat in analyses such as that presented in this report, although some concerns about the issue are ill-founded. Indeed, commissioning itself is needed largely *because* system performance does not persist. Commissioning can arguably increase the persistance of other energy measures (Pollard 2009). We acquired data on energy savings over multi-year periods following some of the projects, and this is summarized below. Negligible post-commissioning energy use/savings data have been collected for timeframes more than five years. However, the payback times we observe are within the likely period of savings persistence.

Some commissioning recommendations are implemented in "real time" by the commissioning provider. It cannot necessarily be assumed that all remaining commissioning recommendations are ultimately implemented by the building owner. Analytical and evaluation efforts can thus be complicated by the fact that measures may be implemented gradually, and the commissioning reports may be completed before the client has finished implementation. We endeavor to report savings from measures that are verified to have been installed, if the information is clear in the source materials. The distinction can be important, as shown in one study where the savings from measures that were identified, implemented, and then "verified" to have been implemented were about 30% lower than the savings "identified" for subsets of 63 buildings in Colorado (Franconi et al. 2005). In another more dramatic example, peak-demand savings of 112 kW were identified but only 3.5 kW captured (Mueller et al. 2004). In another example, the Southern California Edison (SCE) program is reported to have captured 83% of the potential savings identified (Long and Crowe 2008). Conversely, ultimate outcomes can be better than anticipated, as was seen in the University of California/California State University (UC/CSU) Monitoring-Based Commissioning program, where achieved savings routinely exceeded projected savings (Mills and Mathew 2009). In our compilation, 230 of the existing-buildings projects and 22 of the new-construction projects had the implementation of some or all measures verified. In most of the remaining cases, information was not available on the status of implementation. Of those submissions providing detailed data on measures recommended during the commissioning process, only 2% were reported to have been rejected.

Perhaps the largest single undercounting of benefits is in the area of non-energy impacts. In many cases, the benefits are real, yet difficult (if not impossible) to quantify, e.g., in the case of improved indoor air quality. In most cases, no effort is made to quantify these benefits, and thus the overall benefits are understated.

Net commissioning costs can easily be overestimated because non-energy objectives (e.g., commissioning fire and safety systems) are frequently combined with the costs reported for commissioning projects. The level of documentation provided often provides no way to back these costs out of the calculation.

Also of importance, commissioning projects vary widely in their scope and ambition. Some projects are relatively comprehensive, while others may target only a single system (e.g., electrical heating, ventilating, and air conditioning (HVAC), but not lighting or other loads or fuels). Thus, energy savings attained are less than they might otherwise be with a more comprehensive approach. In some cases a commissioning program design can intrinsically limit the level of effort applied to achieving savings. In some of the California utility programs, budgets for investigation were fixed at $0.10 per square foot by the utility contracts, limiting the ability of commissioning providers to identify savings opportunities (Crowe 2009). In the UC/CSU program, sites could qualify for incentives with relatively low projected savings, and there was no requirement to exceed those savings, although many sites did so (Mills and Mathew 2009).

In determining the percentage savings, we divide the reported savings by whole-building energy use, even if every system in the building has not been addressed in the commissioning process. In come cases, data on all fuels are not reported, meaning that some savings may be uncounted. Commissioning can easily spur downstream energy savings that would not be captured in analyses that follow shortly upon completion of the initial commissioning. Such savings could arise from the training that commissioning projects often provide, as well as those from improved maintenance procedures and energy data monitoring, benchmarking, and feedback that should be instituted during commissioning.

Every effort is made to isolate the commissioning costs associated with energy savings and associated non-energy benefits, but it is likely that there are cases where unrelated objectives (e.g., ensuring functionality of security systems) have been included. Similarly, we seek to exclude costs associated with traditional retrofit or maintenance, but reporting is no doubt imperfect in practice. These effects would tend to inflate the cost and savings used in our analysis. We believe that the level of undocumented retrofit is very minimal.

On balance, we view the findings here as on the "conservative" side in the sense that they likely underestimate the actual performance of projects when all costs and benefits are considered. They certainly underestimate the technical potential for best practices.

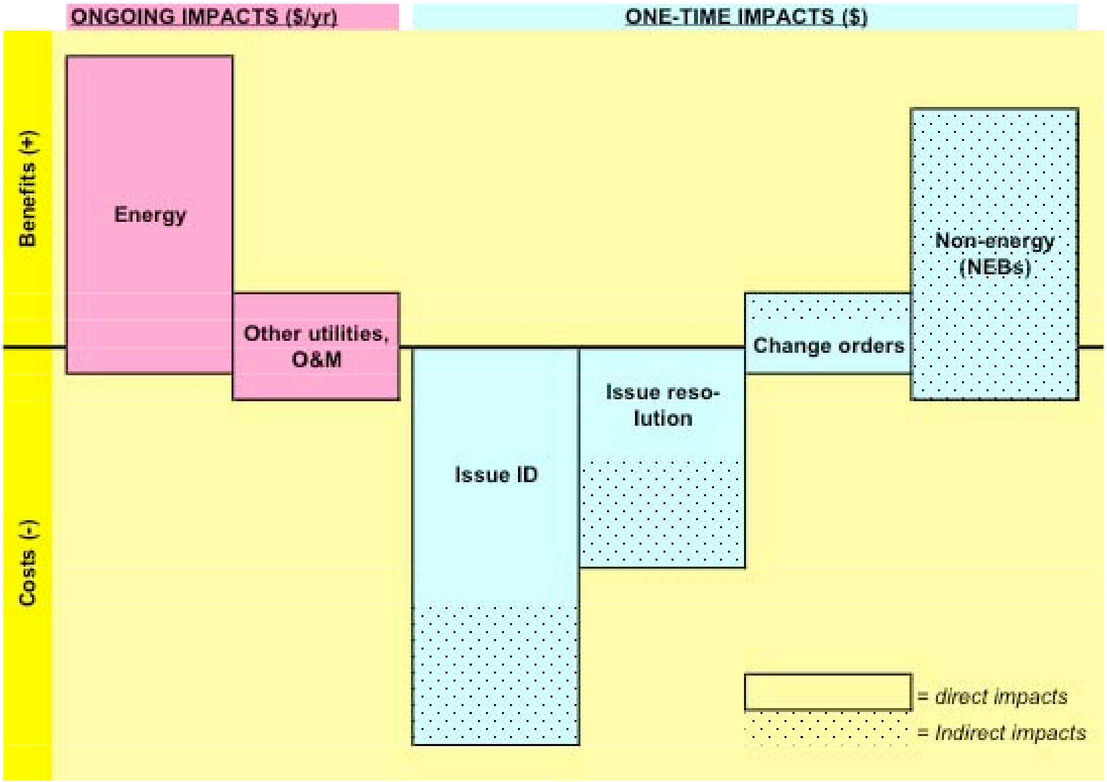
Commissioning Economics

The economic analysis of commissioning projects is arguably more complex than that applied to conventional energy-efficiency investments.

Commissioning can be said to have both costs and benefits (Figure 5). Benefits can include energy savings (although sometimes consumption increases when problems are fixed), reductions in other utilities or operations and maintenance costs. Costs include the identification and resolution of deficiencies (which can be paid through by a combination multiple parties, e.g., owners, utility incentives, or grants). Commissioning can influence the type and number of change orders or other non-energy benefits, resulting in either net delivery costs or net savings. Costs and benefits can occur at one point in time or be ongoing. Most studies do not quantify these "secondary" effects, but we include them where available (38 cases).

In rare cases (0.8% of our projects), energy use can actually increase after commissioning. This is generally a “good thing” insofar as it results from correcting an important operational deficiency (e.g., non-functioning equipment or insufficient ventilation).

Figure 5. *Conceptual map of commissioning costs and benefits*



In the real world, energy-related commissioning measures are often combined with non-energy ones, particularly those related to fire and safety systems. For energy cost-benefit analysis, it is important to isolate the relevant costs. In one example, about 95% of the new-construction commissioning cost of a Caltrans office in California was for correcting non-energy construction defects. Using the total value would have yielded an apparent energy payback time of 41 years, while the proper allocation of costs and benefits yields a payback time of only 2 years.

Not to commission is to “kick the ball ahead,” and defer costs to the future. By this perhaps generous definition, commissioning is not a “real” cost. For two buildings analyzed in detail, one author found that 46% and 62% of the deficiencies identified during commissioning would in the future manifest as higher repair and maintenance costs (Della Barba 2005). Similarly, 4% and 10% of the deficiencies would have resulted in shortened equipment life, while 13% and 5% would have adversely impacted occupant productivity. For comparison, only 11% and 10% were directly associated with energy costs. Friedman (2004) found over 500 deficiencies at four Detroit elementary schools and that correcting the problems avoided $100,000 in repair costs. Foregone energy savings amounted to an additional $110,000. In commissioning 10 schools in California’s Folsom Unified School District, 32% of the issues identified would have increased operations and maintenance costs, 37% comfort and indoor air quality, 6% safety, and 26% energy (Mittal and Hammond 2008).

The Impact of Commissioning: A Golden Opportunity for Saving Energy, Money, and Greenhouse Gas Emissions

Our results are within the range of that observed in smaller studies (Table 1), but they provide a far more definitive and well-normalized assessment than the existing constellation of isolated studies. This is thanks to the large sample size and screening process used to determine which projects to include, the breadth of the sample, and normalization processes that remove “noise” from the costs and savings analyses.

Table 4 provides a high-level summary of the characteristics of our sample, the investment made in commissioning, as well as the energy and economic outcomes. Table 5 and Figure 6 give key results for building types for which we have more than five examples in the database. (In some cases, sample sizes were too small to allow analysis of the new-construction cohort.)

We found median[9] whole-building energy savings of 16% for existing buildings and 13% for new construction. Fuel savings for existing buildings were similar, while those for saving centrally generated thermal energy were significantly higher (31%). Savings in peak electrical demand were achieved in many cases—median value 5%—but were often not the main focus of the commissioning projects, and so the potential is probably considerably greater.

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[9] The *median* value is often superior to the *average* (technically known as the “mean”) for representing the central tendency of a data set. The median of a list of numbers can be found by simply arranging all the observations from lowest value to highest value and picking the middle one (or the average of the two middle values if the list contains an even number of entries). The average is the sum of all the values in the list divided by the number of values. Per Wikipedia: “Suppose 19 paupers and 1 billionaire are in a room. Everyone removes all money from their pockets and puts it on a table. Each pauper puts $5 on the table; the billionaire puts $1 billion there. The total is then $1,000,000,095. If that money is divided equally among the 20 people, each gets $50,000,004.75. This is the average amount of money that the 20 people brought into the room. But the median amount is $5, since that would be the middle value in a ranked list. In a sense, the median is the amount that the typical person brought in. By contrast, the average is not at all typical, since nobody in the room brought in an amount approximating $50,000,004.75. By using the median, extreme outlying values don't skew the result.”

Table 4. Sample characteristics, investment, and outcomes.

	Total	Existing	New
Characteristics			
Number of projects	409	332	77
Number of buildings	643	561	82
Number of states	26	21	15
Identified commissioning providers [1]	37	28	15
Commissioned floor area			
total (square feet)	99,224,809	90,410,884	8,813,925
per building (median ksf)		190,907	67,987
Ownership (by % of floor area)			
Public	71%	69%	85%
Private	29%	31%	15%
Investment			
Commissioning Investment (US$2009) [2]			
total project cost (US$2009)	43,484,002	28,562,970	14,921,031
(US$2009/project)		49,075	86,546
(US$2009/ft^2)		0.30	1.16
cost as % of construction cost			0.4%
Outcomes			
Number of deficiencies identified [3]	10,180	6,652	3,528
Number of measures [3]	5,795	4,104	1,691
Energy Savings			
Total primary energy		16%	13%
Electricity		9%	*
Peak electrical demand		5%	*
Fuel		16%	*
Combined central thermal		31%	*
Central hot water		12%	*
Central chilled water		16%	*
Central steam		19%	*
Payback time (years) [4]		1.1	4.2
Cost-Benefit Ratio [4]		4.5	1.1
Cash-on-Cash Return [4]		91%	23%
Cost of Conserved Carbon ($/tonne) [4]		-110	-25

Notes: Statistics are median values. New values or ratios should not be computed by combining numbers in this table, as the sample sizes for which data are available vary by row.

[1] The provider is known for 55% of the floor area treated in existing-building projects and 43% in the new-construction projects.

[2] Gross costs (excluding non-energy impacts).

[3] Systematically undercounted because some projects reported "Yes/No" rather than absolute counts. These tabulated as 0.999 for tallying purposes.

[4] Including non-energy impacts for projects where the information is available.

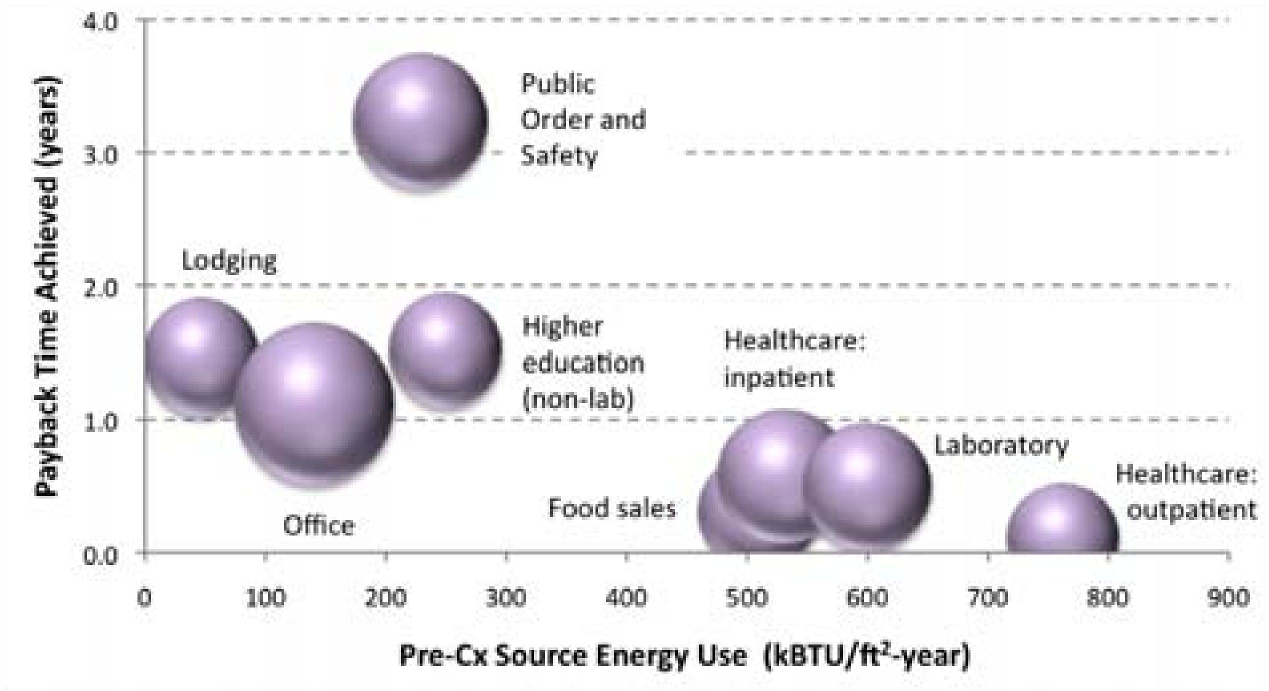
* no data

Table 5. Results by building type.

	Pre-Cx EUI ($kBTU/ft^2$-year)	Source Energy Savings (%)	Simple Payback Time (PBT - years)	Number of buildings (by PBT)
K-12			3.3	19
Higher education	250	11%	1.5	165
Food Sales	510	12%	0.3	10
Food Service				
Inpatient	532	15%	0.6	15
Outpatient	764	10%	0.1	13
Cleanrooms				
Data Center				
Laboratory	600	14%	0.5	50
Lodging	48	12%	1.5	38
Retail			1.4	9
Service				
Office	141	22%	1.1	145
Public Assembly			1.0	6
Public Order and Safety	229	16%	3.2	15

Values only shown when the sample size is five or more buildings.

Figure 6. *Results by building type. from Table 5. Circle diameter is proportional to percent energy cost savings. For reference, "Office" = 9%. Public order and Safety includes prisons.*



Deficiencies and Their Resolutions

The initial payoff from the commissioning process is the unearthing of problems in the building that, remaining undetected, would burden the facility with higher operation and maintenance costs. In some cases the costs can expand to include hampered productivity or safety.

Many individual case studies delineate the deficiencies and how they were addressed. For example, Barr-Rague and Wilkinson (2005) provide a highly detailed case study of how almost 250 deficiencies were identified and remedied in a 150,000 square-foot middle-school building in New Jersey. Della Barba (2005) found almost 2500 deficiencies throughout 9 college buildings.

Information on the deficiencies and measures implemented to resolve them was available for 122 (about one-third) of the projects in the this study, and we have mapped them to a consistent framework (Figure 7). We identified 6652 deficiencies for existing buildings and 3528 for new-construction.[10] A wide diversity of problems was found. For existing buildings, problems were by far most common in air-handling and distribution systems. For new-construction, problems were most common in the mechanical systems. The low incidence of reported problems in plug loads and envelopes is probably a combined reflection of their relative simplicity (compared to HVAC systems) and that most commissioning providers are specialists in mechanical systems.

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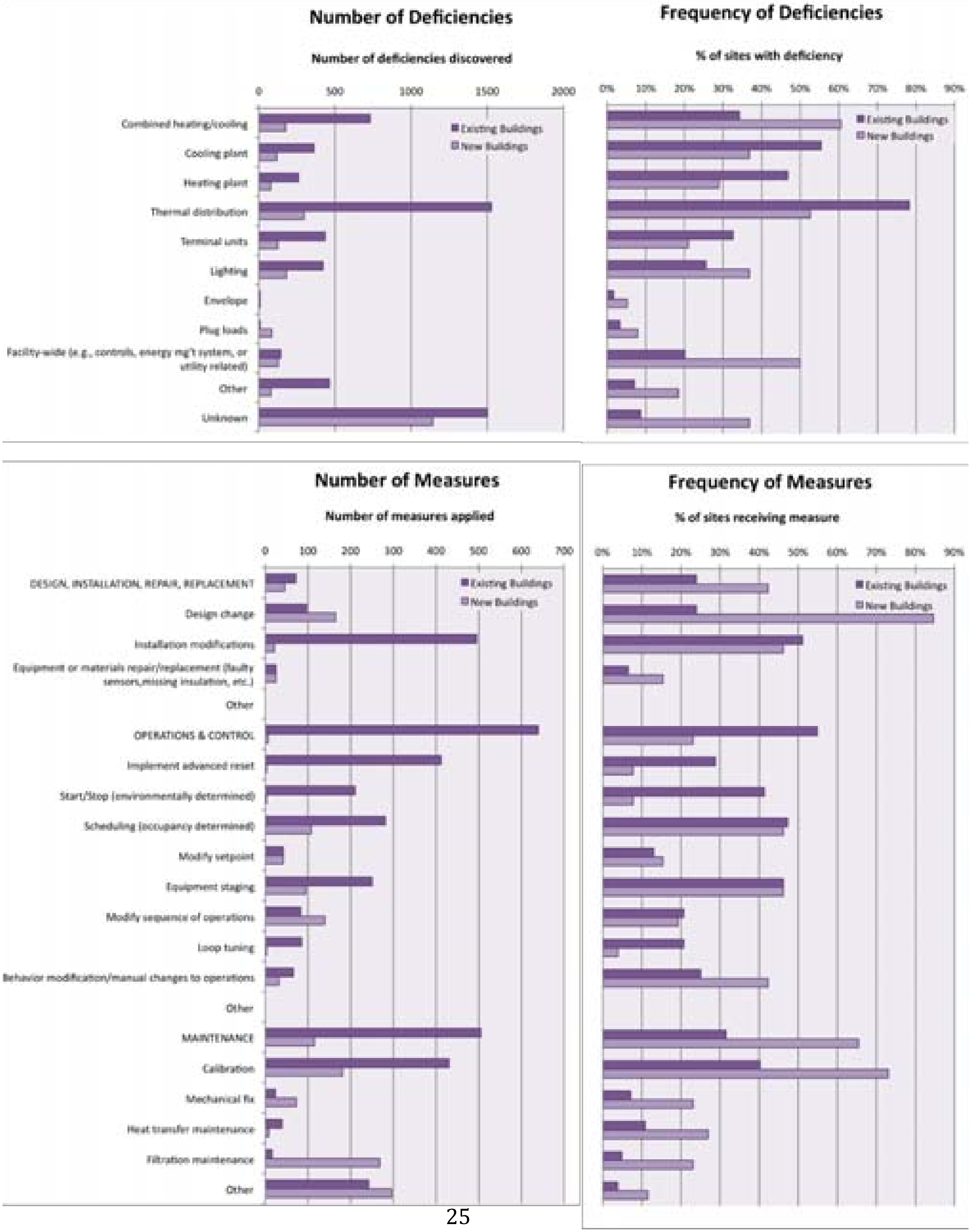
[10] For a subset of these (2145 cases in existing buildings, and 1186 cases in new construction), we have the exact correlation of deficiencies with the resolution. These are provided in the online supplementary information, at http://cx.lbl.gov/2009-assessment.html.[11] For more on the energy-efficiency potential in these facilities, see http://hightech.lbl.gov

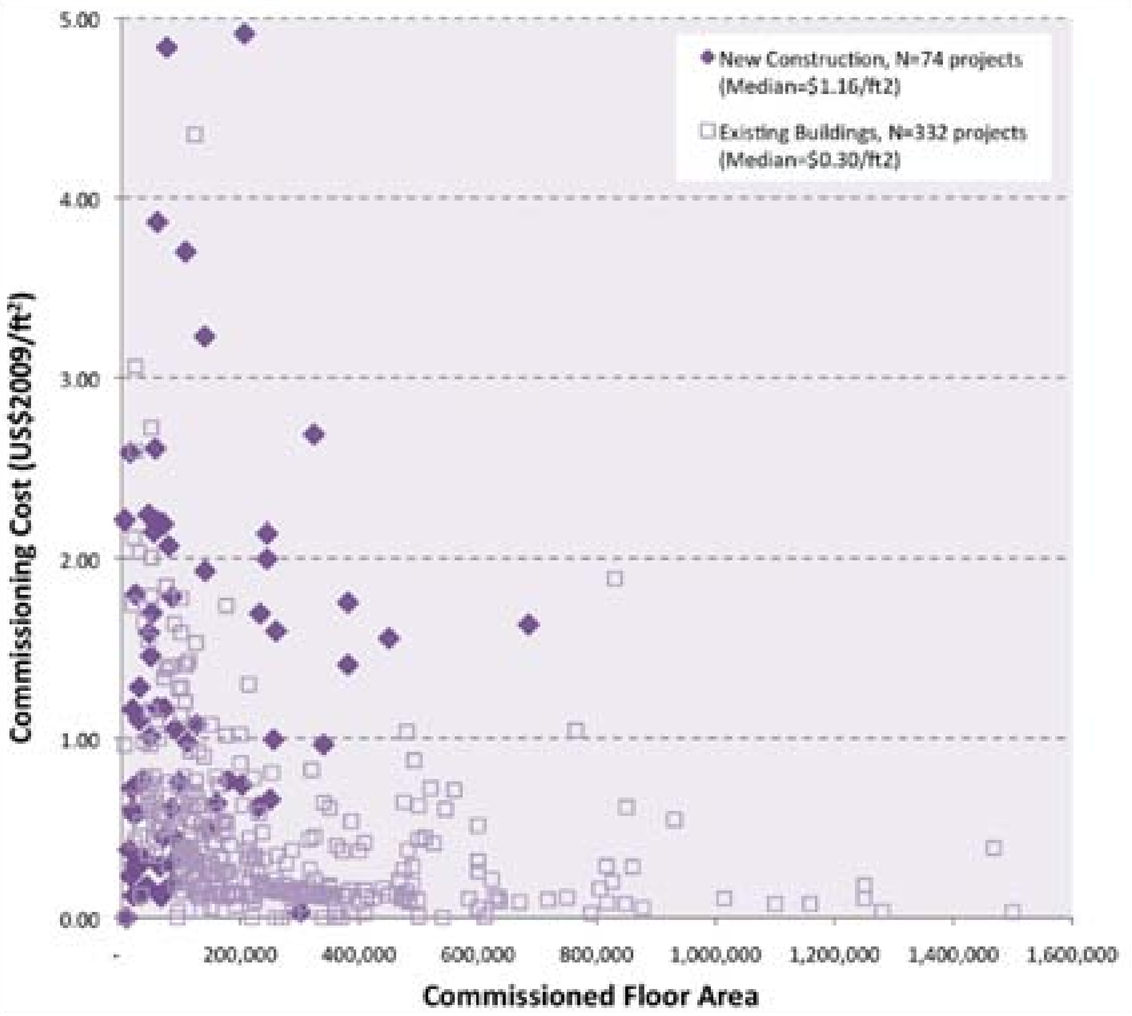
Figure 7. *Types of Problems (Deficiences) and their solutions (Measures)*



Energy, Economy, Environment

Approximately $43 million (inflation-adjusted 2009 USD) was spent on commissioning the projects in our database. The average investment per existing building was $49,000 and $87,000 for new construction. Across the 561 existing buildings for which commissioning-cost data are available, we find a median normalized cost of $0.30/square foot (ft^2) (inflation-adjusted to US$2009 currencies). The corresponding value for new-construction commissioning is $1.16/ft^2 (82 buildings). These values exclude non-energy benefits, which are in some cases quantifiable in economic terms. For existing buildings, normalized costs tend to decline with building size (Figure 8), but with large variances. In the case of new construction, pricing appears to be more proportional to total project cost. The nature of activities required for new-construction commissioning may be less dependent on project size.

Figure 8. *Commissioning cost as a function of building size*

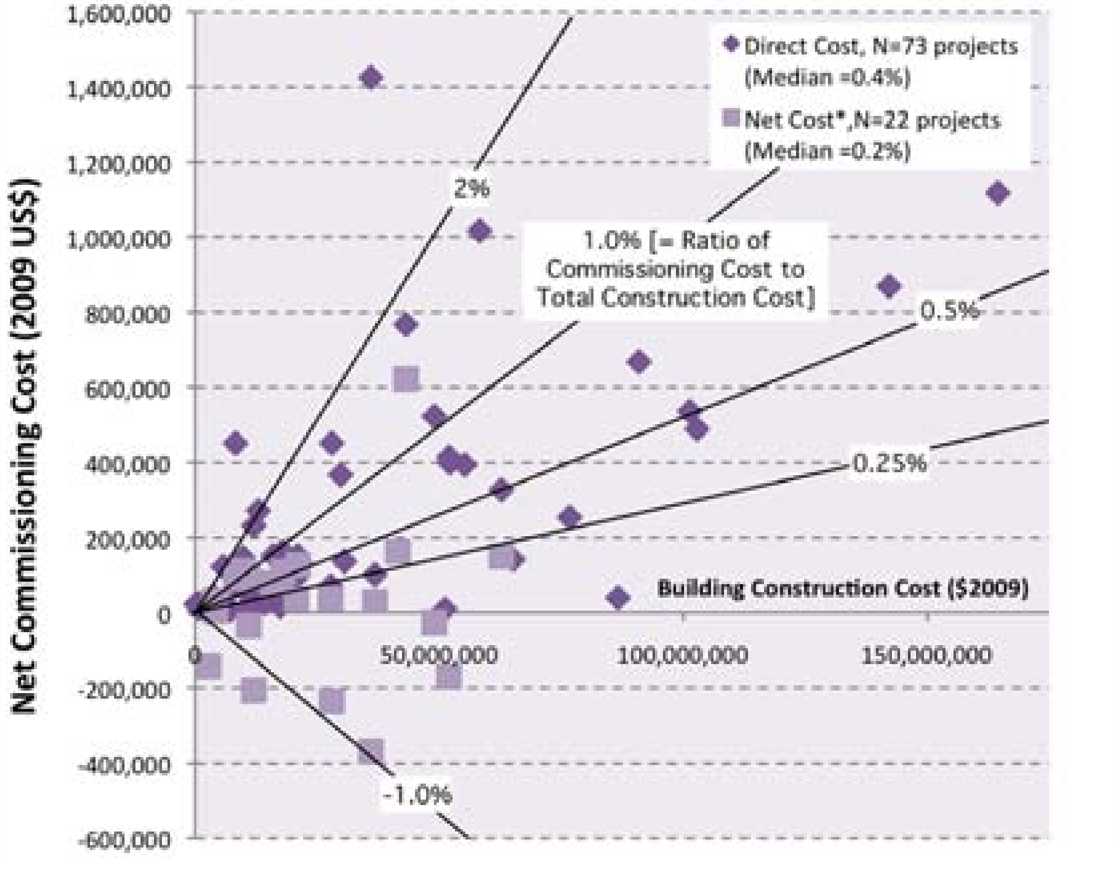


The higher normalized costs tend to correlate with projects having a substantial effort to measure and verify savings (Mills and Mathew 2009).

A more common cost metric in the case of new construction is the cost of commissioning as a percentage of total building construction cost, which has a median value of 0.4% for our sample. When non-energy impacts are included, the values decline significantly, becoming zero or even negative in many cases (Figure 9).

In evaluating commissioning cost-effectiveness, it is important not to mistake or use as a surrogate the commissioning provider's fees for total project costs. We have seen this done in other studies, and often not disclosed to the reader. For the 32 cases where we had the information on external commissioning provider fees for existing-building projects, the fees averaged 45% of total costs, with a minimum value of 9%. For the 44 cases where we had the information for new-construction projects, the fees averaged 85% of total costs, with a minimum value of 56%.

Figure 9. *New-construction commissioning cost as a fraction of total construction cost. "Net Cost" includes first-cost savings where applicable.*



The seven panels in Figure 10 summarize the core energy-savings and cost-benefit findings from our compilation. The charts show the median values for a series of metrics, together with the top and bottom twenty-fifth percentile for the set of projects as a whole. This provides an indication of the central tendencies of the results as well as the spread. The cost-benefit indicators combine all costs and benefits. Building owners enjoy even higher levels of cost-effectiveness where they receive rebates or other forms of incentives or subsidies. Across our sample, partial or full utility rebates were received in 84% of the cases in existing buildings projects, and 68% of the cases in new-construction projects. Where rebates were given, they represented about 80% of project costs for new and existing buildings alike.

The percentage weather-normalized *whole-building* energy savings was roughly similar between existing and new buildings, as was the variance, with median values of 16% and 13% (small sample size), respectively. More than a quarter of all buildings saved in excess of 30%.

While commissioning projects at one time focused exclusively on obtaining energy savings, they are increasingly also targeting peak-demand reductions (Franconi et al. 2005; Lenihan 2007; Mills and Mathew 2009). Within our database, 54 existing-buildings projects include savings in peak demand (median value 5.4%, with the upper quartile at 12%), and another 11 new-construction projects report savings but without pre-/post values (and thus the percentage savings cannot be determined).

Median commissioning costs were \$0.30/ft^2-year for existing buildings and \$1.16/ft^2 for new construction. Median cost savings were \$0.29/ft^2-year for existing buildings and \$0.18/ft^2-year for new construction. To address the needs of a diverse array of users, we employ four cost-benefit tests.

- **Simple Payback Time:** This is the project cost divided by the first-year cost savings. Where savings equal the cost, the payback time is one year. Where the payback time is the same or more rapid than that available through alternative investment options, the project can be deemed cost-effective. Median paybacks were 1.1 and 4.2 years, for existing buildings and new construction, respectively.

- **Benefit-Cost Ratio:** This is the sum of project benefits over the assumed measure lifetime divided by the project cost. If the ratio is greater than 1, the project can be deemed cost-effective. The median ratios were 4.5 for existing buildings and 1.1 for new construction.

- **Cash-on-Cash Return:** This is the ratio of first-year cost savings from the project divided by project cost, expressed as a percentage return (inverse of the payback time). If the return is equal to or greater than alternative investment returns (e.g., 10%) then the project can be deemed cost-effective. We offer this metric because it is widely used in the real estate industry. The median returns were were 91% for existing buildings and 23% for new construction.

- **Cost of Avoided Carbon:** This is the annualized project cost minus annual savings, divided by annual greenhouse gas emissions reductions (measured in carbon dioxide [CO_2] equivalents). The value can thus be negative—and in fact commonly is—when the cost of commissioning is exceeded by the energy savings. If the value is less than zero or less than the cost of purchasing emissions offsets in the marketplace, then the project can be deemed cost-effective. The median costs of avoided carbon were -$110/tonne for existing buildings and -$25/tonne for new construction.

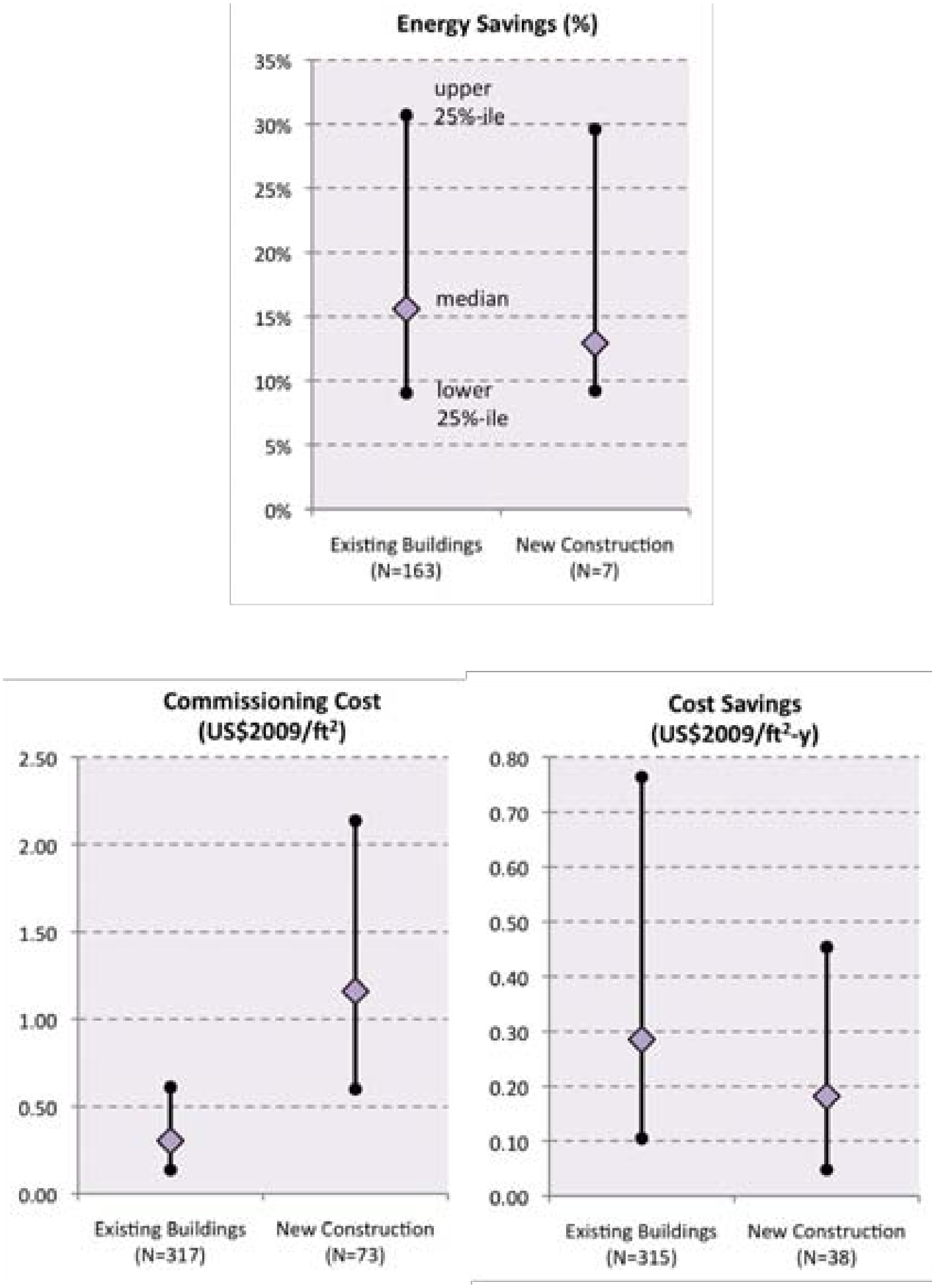
In each case, we adjust the project cost to include non-energy impacts (positive or negative) in the rare cases where the information is available. We assume that the project lifetime is 5 years, which means that savings accrue and project costs are amortized over a much shorter period of time than with long-lived energy retrofits. Measure life is not a factor for payback time or cash-on-cash return, which makes these particularly robust metrics. We assume that energy prices grow at the rate of general inflation, i.e., future energy savings are valued the same as savings today in inflation-adjusted terms.

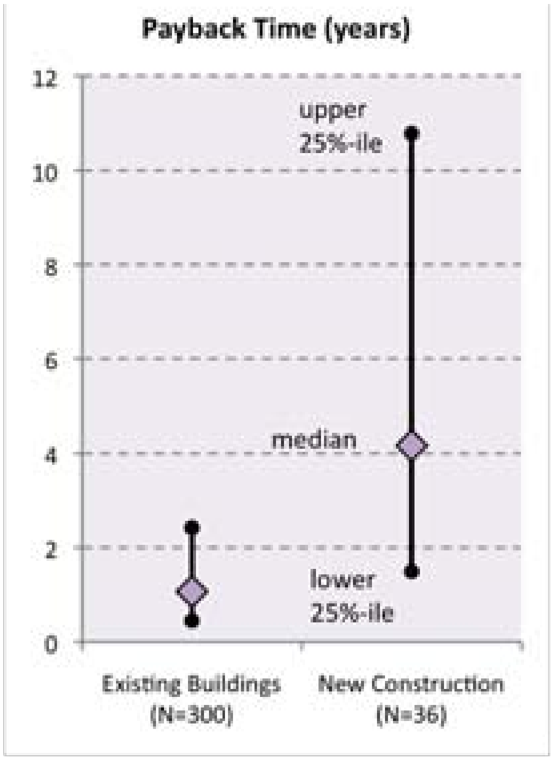
These results are on a par with those we found with a smaller sample in 2004 (Mills et al. 2004). The variations have no practical significance in terms of the attractiveness of commissioning compared to other energy-efficiency measures.

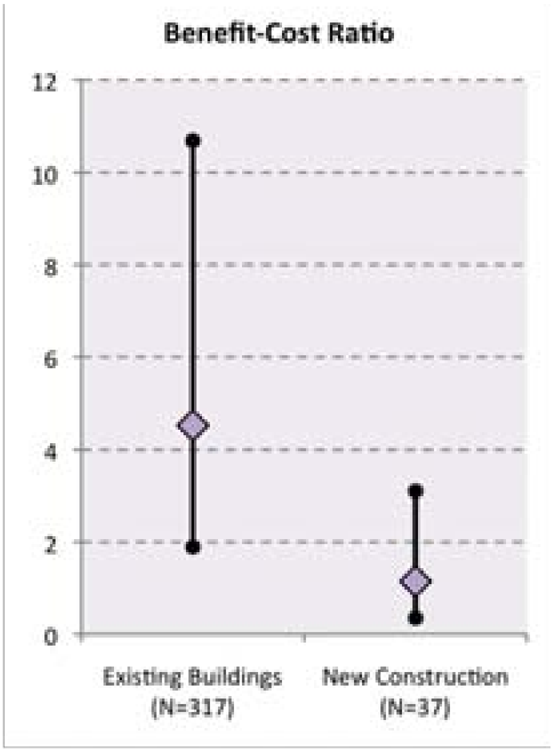
It is noteworthy that virtually all existing building commissioning projects were cost-effective by each metric. We also found that commissioning was cost-effective for each specific measure for which we have data (Figure 11). The median performance was cost-effective for new-construction, although a number of cases would not be viewed as cost-effective by most building owners.

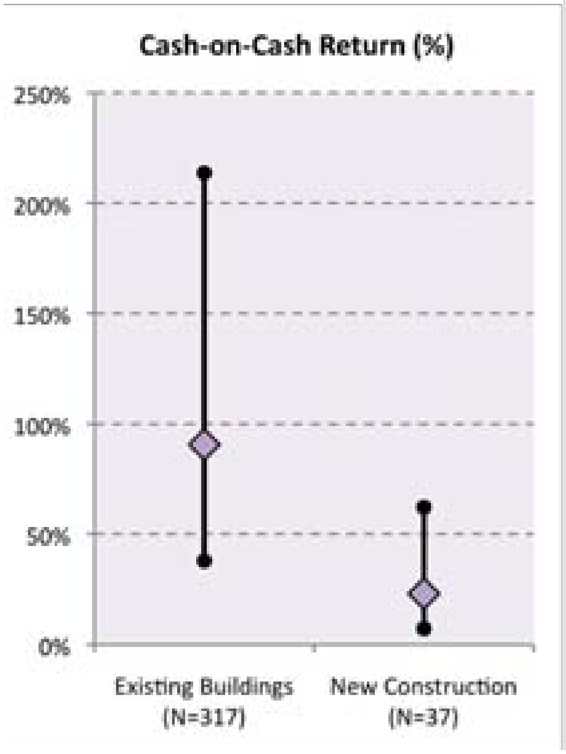
As shown in Figure 12, we observed a wide range of costs and savings. Payback times varied as well but were highly attractive in virtually all cases. It is notable that payback times showed little correlation with how much money was spent to conduct the commissioning, suggesting that skill plays a large role. Contrary to views that smaller buildings are not good candidates for commissioning, attractive payback times were achieved across our sample for buildings of all sizes (Figure 13). Unfortunately, many utility programs that promote and incentivize commissioning exclude smaller buildings. For example, the 2003 Xcel Energy program excluded buildings below 75,000 square feet (and preferred ones over 250,000 square feet) (Mueller et al. 2004).

Figure 10. *Benchmarks for energy savings and cost-effectiveness*




Payback Time (years)


Benefit-Cost Ratio


Cash-on-Cash Return (%)

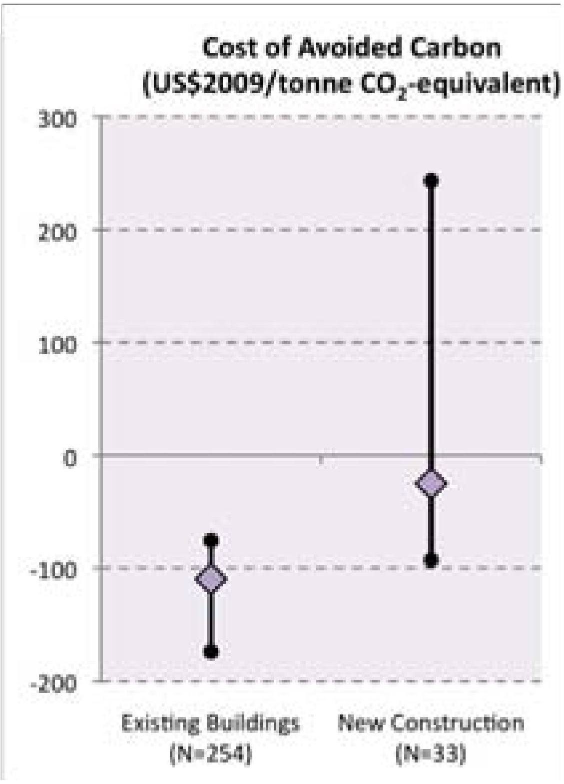

Cost of Avoided Carbon (US$2009/tonne CO_2-equivalent)

Figure 11. *Payback times by type of problem ("Deficiencies") and by resolution ("Measures")*

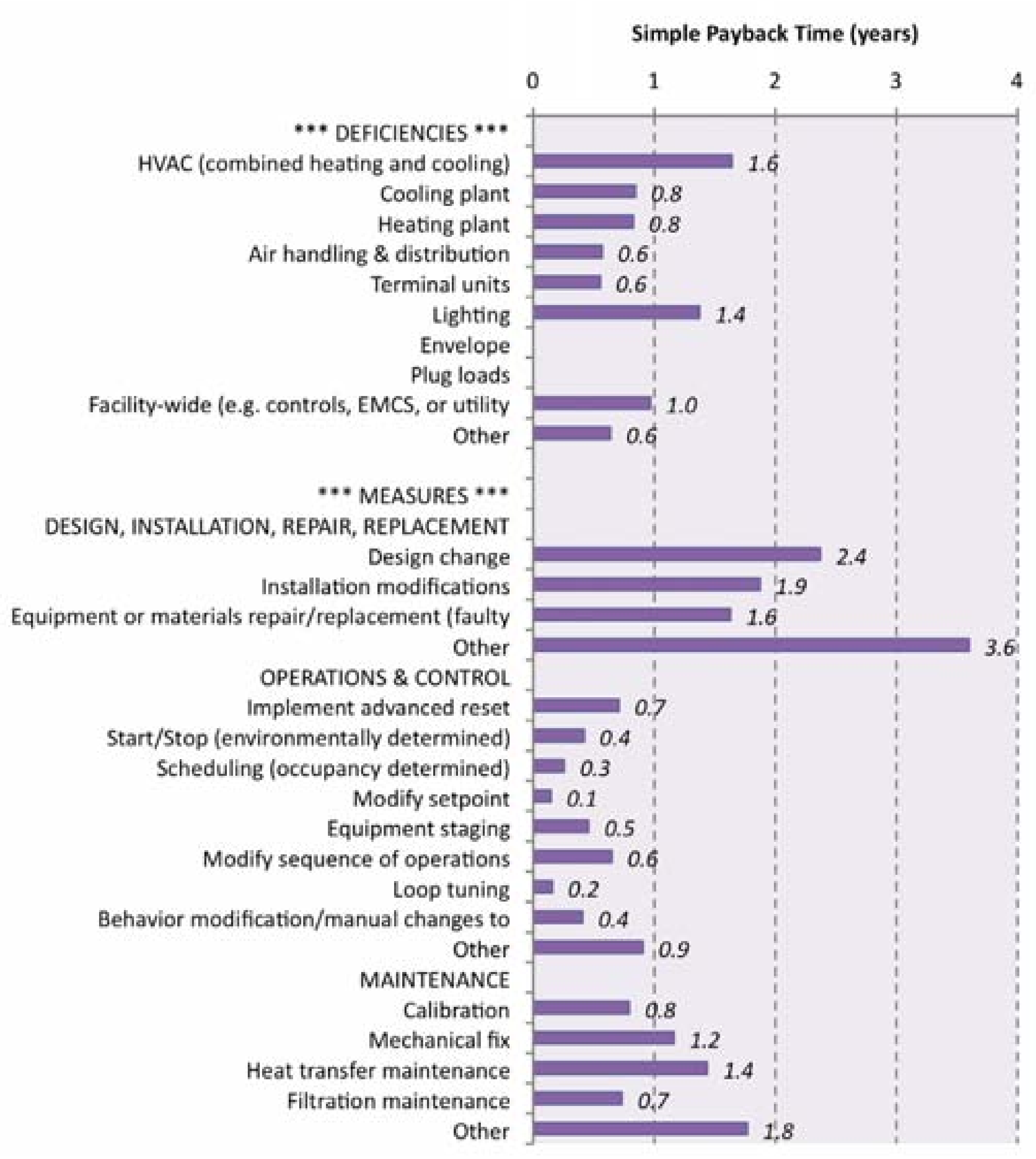


Figure 12. *Commissioning costs, savings, and payback times: existing buildings (above) and new construction (below)*

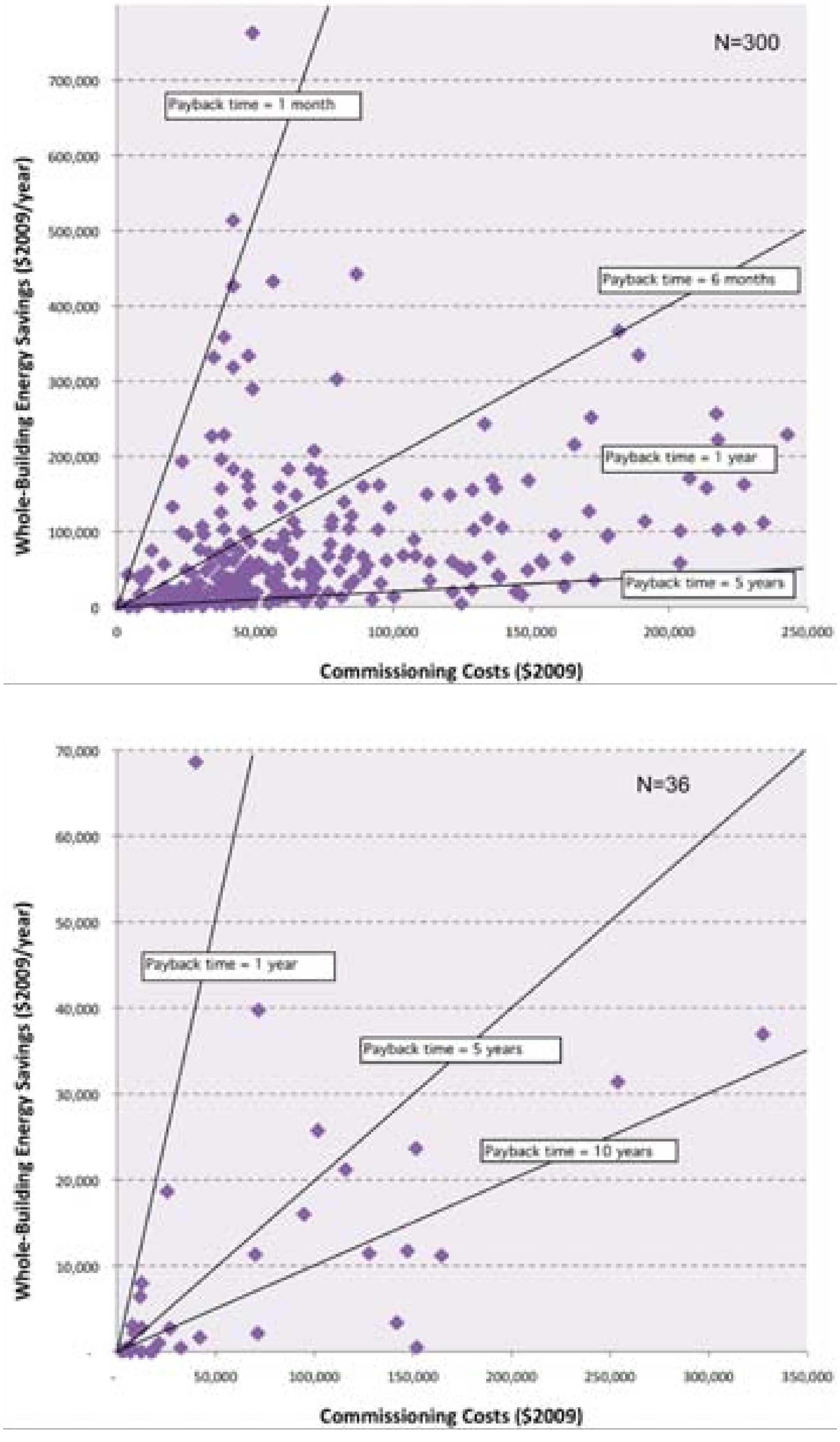
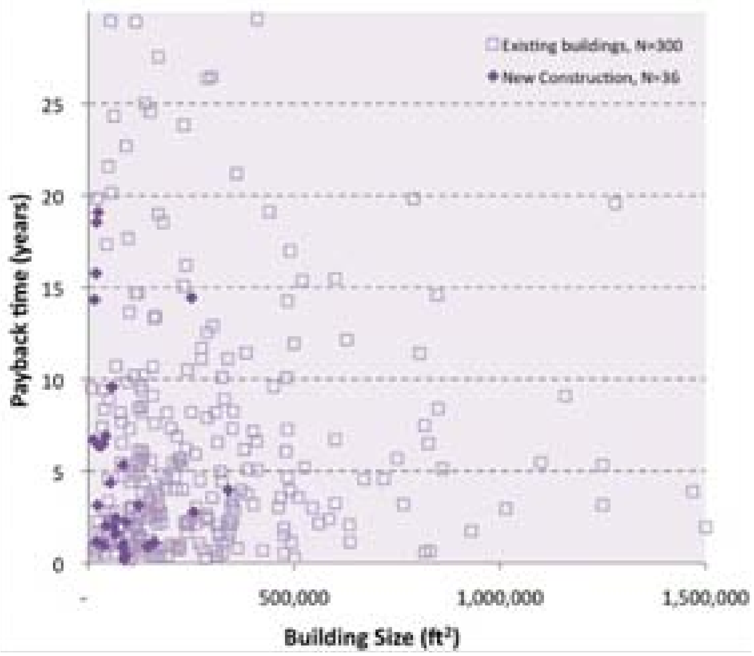
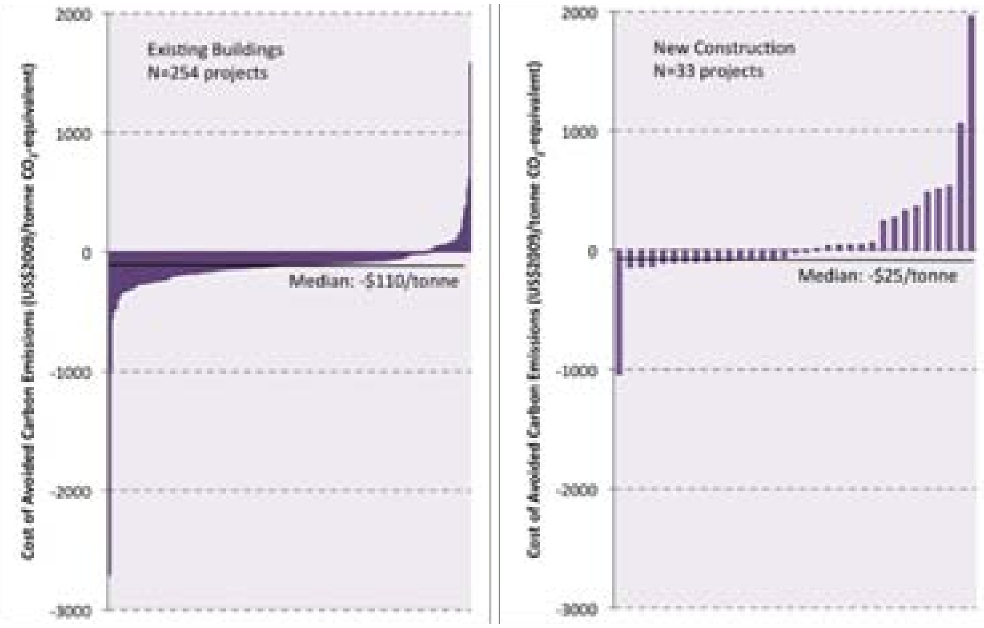


Figure 13. *Commissioning payback time versus building size*



Project costs and energy savings can be cross-referenced with the forms of energy saved (e.g., electricity versus fuel) to determine the amount of greenhouse gas reductions achieved. In almost 90% of the existing-building cases, the cost of avoided carbon was negative, as was the case for over half of the new-construction cases (Figure 14). This metric has been used to rank various emissions-reduction strategies in "carbon abatement curves," as will be discussed below.

Figure 14. *The ranked cost of conserved carbon for existing-building projects in the database: Existing buildings and new construction.*



Non-Energy Impacts

Non-energy benefits are a major driver of decisions to utilize commissioning, although adverse non-energy outcomes should also be studied (hence our use of the neutral term "impacts"). The importance of these impacts is evidenced in the titles from the following BetterBricks case studies:

- "Community Colleges of Spokane –Enhancing Teaching and Learning for Health Care Professionals"
- "Othello Community Hospital – Insuring Operation of Critical Systems"
- "Riverside School District – Correcting Mechanical and Indoor Air Quality Problems"

Indeed, non-energy benefits are in many cases the primary reason—or the *only* reason—for embarking on commissioning projects. Customers are often surprised to find, after the fact, that energy savings were achieved. The utility commissioning programs in Nebraska attribute part of their success on focusing first on improving building comfort (Criscione 2008).

We gathered qualitative data on the reasons for commissioning for 178 existing buildings projects and 36 new-construction projects. While energy savings are cited as a driver in 90% of the cases, this is followed by a desire to ensure or improve thermal comfort, productivity, and indoor air quality for occupants (Figure 15). Ensuring system performance per se is an driver in about half of the cases, and training and occupant operators or occupants is a driver in about a third of the cases. For new construction, ensuring equipment performance, indoor environmental quality, and occupant productivity are cited more often than is obtaining energy savings.

We obtained data on observed post-project non-energy impacts for 68 existing building commissioning projects and 44 new-construction commissioning projects, representing a total of 480 identified non-energy benefits. For existing buildings, improved thermal comfort and extended equipment life are among the most cited non-energy benefits experienced after the projects are completed (Figure 16), while equipment life is the most-cited benefit for new construction, followed by improved thermal comfort.

In 38 cases, the non-energy impacts were quantified. As seen in Figure 17, these can significantly offset the direct cost of the commissioning. Where the value shown in the diagram is less than zero, the non-energy benefits exceeded the first costs. In some cases, the benefits exceed the costs, rendering the projects instantaneously cost-effective. The actual net median commissioning project cost was reduced 49%.

Figure 15. *Reasons for commissioning*

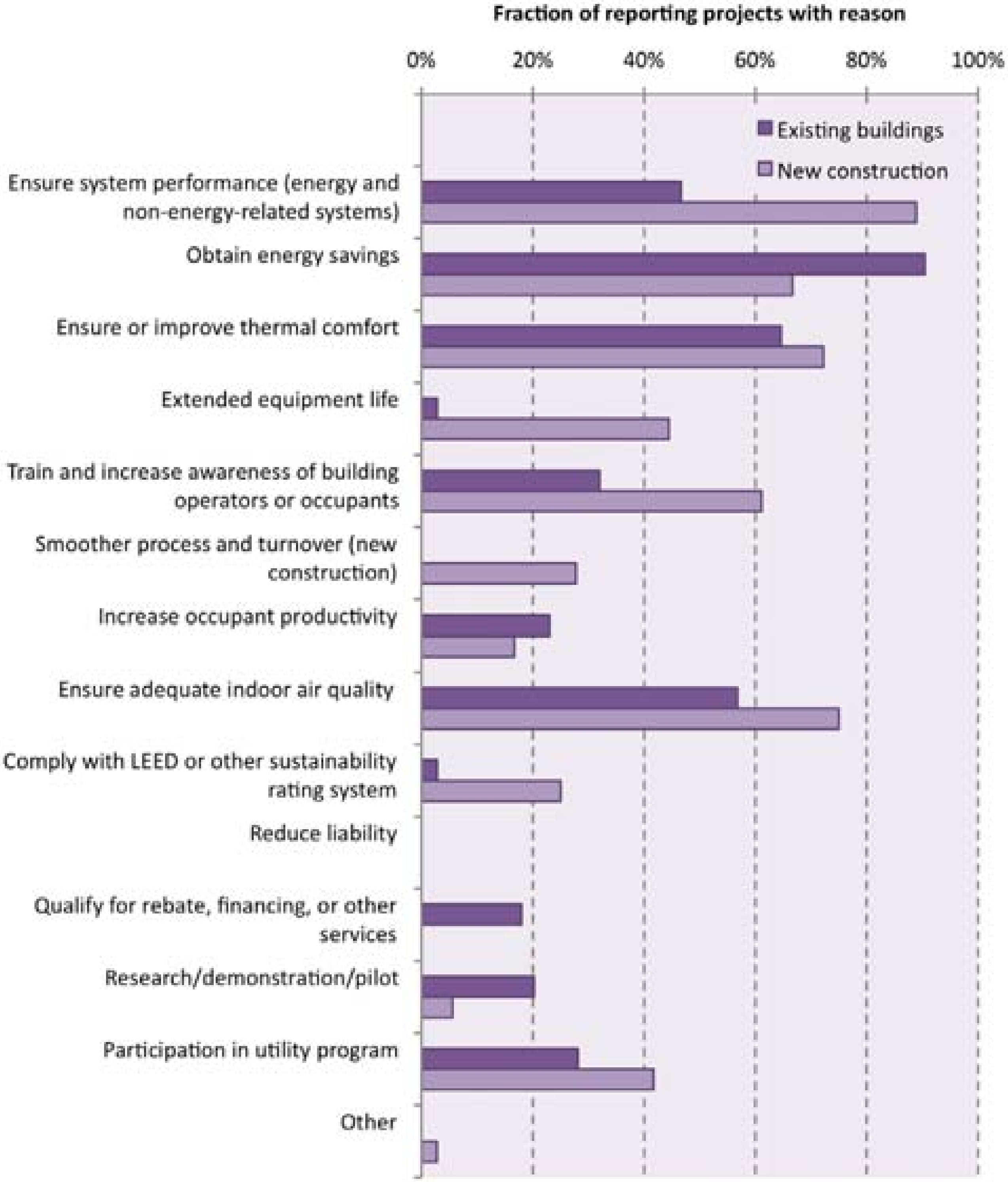


Figure 16. *Non-energy benefits observed following commissioning.*

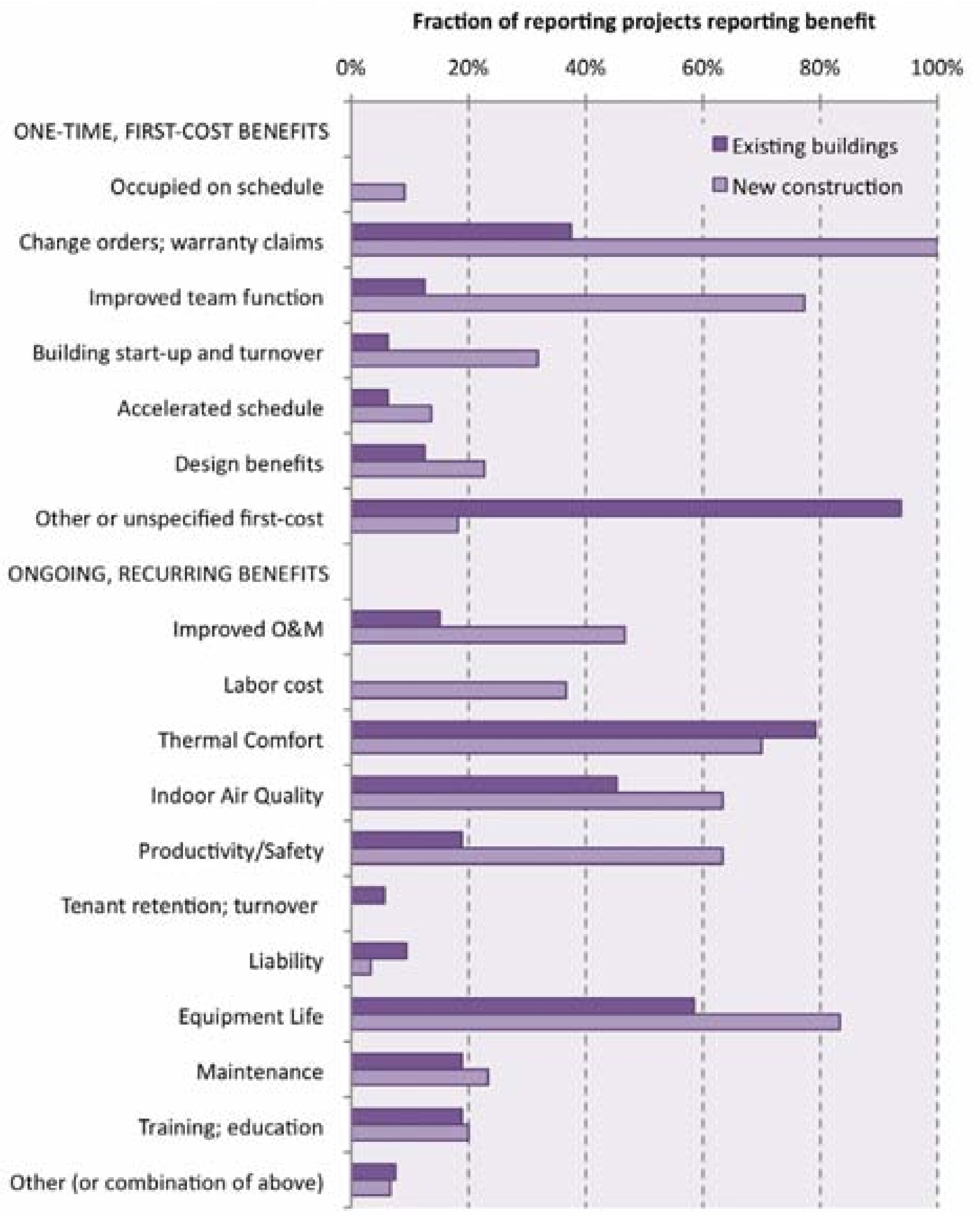
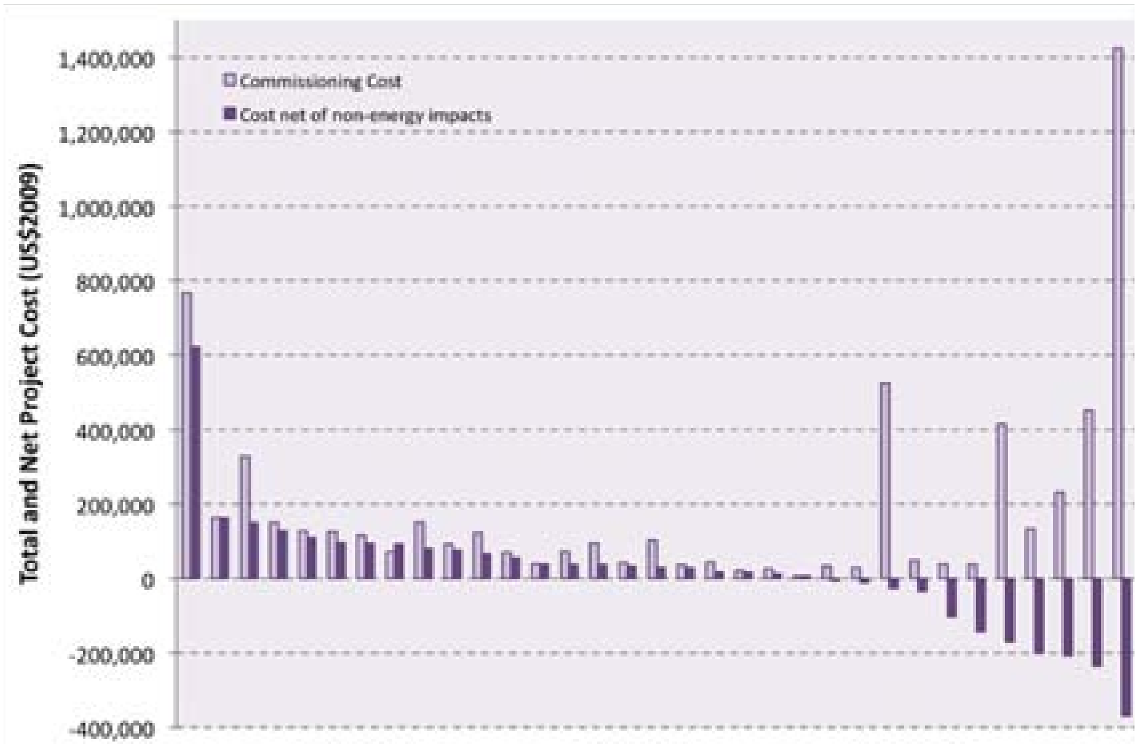


Figure 17. *First-cost savings often offset part or all nominal commissioning project costs*



Excludes ongoing non-energy benefits

High-Tech Facilities: The Commissioning Mother Lode

High-tech facilities have at times been passed over in the quest for energy savings, often under the pretense that they "must" already be optimized, and other times under the pretense that they are mission-critical and should not be disturbed. Observers sometimes incorrectly assume that these facilities are routinely commissioned for energy savings. While it is true that they receive a far higher level of quality assurance in construction and operation than traditional buildings, energy performance *per se* is usually not a central focus.

For the purposes of this report, "High-tech" facilities include labs, data centers, cleanrooms, healthcare, and specialized research facilities such as particle accelerators. While specialized on the one hand, these facility types are also pervasive, occurring in private industry (from semiconductor fabs to hospital operating rooms) to educational institutions (from high school to university labs), and in the public sector (from agricultural research labs to high-energy physics facilities). Across the United States, high-tech facilities in the private and public sector have been estimated to spend upwards of $10 billion per year on energy (Mills 2009b).

They have a number of common characteristics, including: around-the-clock operation, high air-change rates and critical activities and safety requirements that rely on proper indoor environmental control building performance. In some cases all of the air is "once-through" and/or requires dehumidification, with far larger volumes of air needing to be treated than in conventional buildings. Taken together, these requirements tend to translate into particularly high energy-intensities, and correspondingly large opportunities for energy savings (Mills et al. 2007).[11] There are a number of articles and reports addressing commissioning in high-tech facilities, although many of them are not focused on energy issues and indeed many make no mention whatsoever of energy.

However, while we have found that commissioning can be cost-effective in virtually any building type or size, the results are particularly impressive in high-tech facilities. For example, one of the data centers analyzed for this report (Nodal 2008) had a pre-comissioning energy intensity of over 900 kWh/ft^2-year (or almost $100/ft^2-year), which is about 100 times the energy bill of a typical office building. Just the savings ultimately achieved by commissioning this one facility—173 kWh/ ft^2-year—is 10 times the median *pre*-commissioning energy use for the non-high-tech buildings in our database.

A small proportion of reports in the commissioning literature address the specific needs of these facilities. Many of those that do so focus on non-energy issues, rather than energy (Ross 2008; Hydeman et al. 2005). However, some energy-specific resources do exist, such as the Labs21 guide to commissioning existing laboratories for energy efficiency (Bell 2007), which, for example, cites the special importance of fume hoods and specialty pressure- or volume-controlled HVAC systems used for safety purposes.[12]

While problems identified in the commissioning of high-tech facilities can appear in ordinary buildings, the cost—in terms of excessive energy use—when they occur in high-tech facilities is far, far higher. Some technical issues and opportunities are unique to these facilities, as are some of the barriers. Because these facilities are also highly mission-critical, the non-energy benefits having to do with factors such as safety, equipment life, and reliability often associated with energy-related commissioning can be very substantial.

Laboratory facilities are the most widely documented type of commissioning case studies in high-tech facilities. As an example of the scores of deficiencies discovered in the construction of a laboratory facility, Pinnix et al. (2004) found that none of the 163 fume hoods had properly installed alarm monitors (a serious safety issue), while many had faulty control devices and/or miscalibrations.

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[11] For more on the energy-efficiency potential in these facilities, see http://hightech.lbl.gov

[12] A bibliography of readings on commissioning high-tech facilities is located here: http://cx.lbl.gov/hightech.html.

The commissioning of data centers has been treated in exceedingly few publications and reports. Findings from a case study of commissioning the HVAC system of a data center at the NOAA weather forecasting office in Jacksonville, Florida (Lundstrom 2004) are indicative of the kinds of problems that can otherwise go undetected in these types of facilities:

- No balancing dampers were installed to the branch ductwork for balancing, making it impossible to balance the system to improve hot/cold spots.
- Some of the electric duct heater serving zones were significantly oversized.
- Condenser coils were corroded and need to be replaced (coils were not coated for high salt content atmosphere).
- The condensing units had incorrect head pressure control and hot gas bypass connections.
- The exhaust fan was only producing 33% of design flows.
- The access door on the air ductwork was removed during an inspection and was not reinstalled.
- The fan status controls were not responding to the control system.
- The discharge temperature was controlled off the zone with the lowest setpoint, not the zone with the highest actual temperature, causing many zones to be hot.
- The temperature and humidity sensors were out of calibration.
- The lead-lag operation of the redundant air-handler units (AHUs) was not functioning in a fail-safe manner.
- The control sequence was not operating correctly.
- Many of the electric duct heaters were not staging correctly, due to incorrect wiring.
- Cooling load calculations revealed that the requirements were 10% less than the original system design (a reflection at least in part of overestimation of internal loads at the time of design).

And, after the preceding items were fixed by a separate contractor, the commissioning authority reinspected and found the following new issues:

- OA damper drive motors on two AHUs were not installed properly on the shaft linkage.
- SCRs for electric duct heaters (EDHs) on two AHUs were not correctly set up.
- Temperature sensors were not correctly mounted downstream of EDHs.
- The damper jackshaft arm on the outside-air damper on the two AHUs was stripped at the damper connection.
- Direct digital control (DDC) programs for some zones were not responding correctly.
- Specific items in the operator workstation graphics were missing or mislabeled.
- The return air damper for one AHU was broken.

Cleanrooms are another important class of “high-tech” (and highly energy-intensive) facility. They, perhaps more than any other facility type, suffer from a misconception that they are routinely commissioned for energy savings. In fact, they are routinely "qualified" or "certified" to ensure that the manufacturing process within will be error-free and yield a predictably acceptable product (e.g., semiconductor wafers). However, the qualification process rarely includes energy performance. A cleanroom can be operating "perfectly" and yet use far more energy than necessary. Moreover, there are intense pressures to construct cleanrooms quickly, and there is well-founded apprehension about interventions that could compromise the process.

While attention on the commissioning of cleanrooms (and most other types of spaces) tends to focus on the mechanical systems, a recent report points out the importance of considering building envelopes. In this case (Sellers 2009), inspections of the envelope of a cleanroom in the final stages of construction found that 6% of the circulated air was leaking. Other end uses—such as plug loads or "tools"—get much less attention.

To our knowledge, quantification of energy-focused commissioning in cleanrooms has been offered only once in the open literature, in an important paper and associated presentations by Sellers and Irvine (2001). In that report, a cleanroom was traditionally "qualified" during construction and all was well. Symptoms began to emerge that the HVAC system was not functioning properly, which led to a series of discoveries and adjustments to the control system. To provide a frame of reference for the prodigious energy use by these types of facilities, electricity consumption of ~100,000 kWh per day and 1,800 therms of natural gas use per day translated to $5000 per day (at energy prices that are very low by today's standards – $0.039/kWh and $4.4/therm).

Following are some of the problems identified during commissioning this cleanroom:

- Key temperature sensors were out of calibration, by nearly 10°F in one case.
- A critical valve was inadvertently not connected to control system, resulting in 24x7 heating and extensive simultaneous heating and cooling.
- A preheat coil controller had been set at 110°F during a start-up test and associated control sequences were severely sub-optimized.
- The absence of alarms for pre-heat temperatures.
- Presence of frustrating controls and user interfaces that resulted in their being devalued and ignored.
- Air was over-dehumidified, and thus over-humidified in response.

The bottom line was $60,000 to $80,000 per year in energy savings (for a small fraction of the space that had been completed), at a one-time commissioning cost of $4,700 to $8,000. The corrections also yielded significant safety-enhancing benefits, which helped avoid costly future disruptions and potentially costly contamination of the process.

This project did not have the benefit of a measured baseline and post-commissioning measured savings. An estimate of savings was based on a calculated baseline rooted in an observed operating condition combined with calculated savings based on what engineering principles say will happen after correcting problems identified in the commissioning process. With this in mind, a very rough extrapolation of lessons learned to the rest of the facility (not yet completed at the time of the study), suggests annual savings of about $540,000, or about 30% of the facility's entire energy bill, and a payback time of 0.01 years (about 4 days). As with any case study, these specific results will not necessarily apply to other similar facilities, but this story serves as a clear indication that commissioning in cleanrooms should be taken quite seriously and that further study is merited.

Our database contains data for 115 high-tech facilities, representing 19 million square feet of floor area (Table 6). Percentage energy savings tended to be somewhat higher than other building types, while absoulte savings were significantly higher because of initial energy intensities. Payback times were also among the lowest of any building type we evaluated.

Table 6. High-tech facilities in the compilation.

	Existing Buildings		New Buildings		TOTAL	TOTAL
	# bldgs	ft^2	# bldgs	ft2	**# bldgs**	**ft^2**
Cleanrooms	0	0	1	301,000	**1**	**301,000**
Data Center	2	12,888	0	0	**2**	**12,888**
Laboratory	50	4,561,593	18	1,965,065	**68**	**6,526,658**
Healthcare: inpatient	17	6,791,029	9	687,959	**26**	**7,478,988**
Healthcare: outpatient	14	4,319,124	4	206,300	**18**	**4,525,424**
Total	83	15,684,633	32	3,160,324	**115**	**18,844,957**

The Value of First-cost Savings Can Eclipse Those of Ongoing Energy Savings

An oft-cited non-energy benefit from commissioning—and one of the largest in terms of economic value—is helping to right-size mechanical systems, thereby saving on capital costs during original construction or future retrofit/replacement.

We documented a dramatic example of this in the Advanced Light Source facility at Lawrence Berkeley National Laboratory (Box B) in which a huge cost savings was garnered by scaling back a new chiller from over 450 tons to 350 tons (thanks to the energy savings from commissioning). The corresponding one-time savings were four times the entire commissioning project cost.

Leading commissioning practitioners have gone as far as to say that all the costs of new-construction commissioning *should* be recovered through cost savings in project delivery (with energy savings being icing on the cake). Dorgan et al. (no date) cite seven examples in which these non-energy benefits amount to 1.7 to 22 times the cost of commissioning, with a combined value of over $2.2 million in savings before energy savings are even counted.

Dorgan et al. cite four examples in high-tech buildings in which new-construction commissioning saved $319,000, $400,000, $425,000, and $500,000 in project delivery costs, for a science center, hospital, vivarium, and science building, respectively (before energy savings were even counted). These benefits resulted from:

- Eliminating change orders
- Eliminating requests for information (RFIs)
- Proper system/component selection
- Reducing contracgtor callbacks and accelerated date of proper operation

Commissioning Continuity

We identified a rare opportunity to follow a high-tech building through both its initial commissioning process (during design, construction, and startup) and then its subsequent commissioning as an existing building. The data tell an important story of the importance of embedding commissioning throughout a building's lifecycle (Box C). This took place at Lawrence Berkeley National Laboratory's Molecular Foundry facility, a complex high-tech building containing laboratory spaces as well as data processing and cleanroom environments.

Considerable energy savings were garnered during new-construction phase, with a payback time of 0.4 years. A comparable level of savings was subsequently obtained when new commissioning opportunities arose after occupancy, and with an even shorter payback time of 0.2 years (Box C).

Box B. High-Tech Case Study: The Advanced Light Source

Project Summary:

- Floor area: 118,573 square feet
- Project cost: $32,000
- System commissioned: Chillers
- Energy savings: 45.7% (weather-normalized)
- Payback time (commissioning cost/annual energy savings) less than one year
- Avoided capital cost thanks to chiller replacement downsizing from 450 to 350 Tons: $120,000 (based on $1,200/tonne), i.e., four times the cost of the commissioning project

Drivers: Observed simultaneous heating and cooling

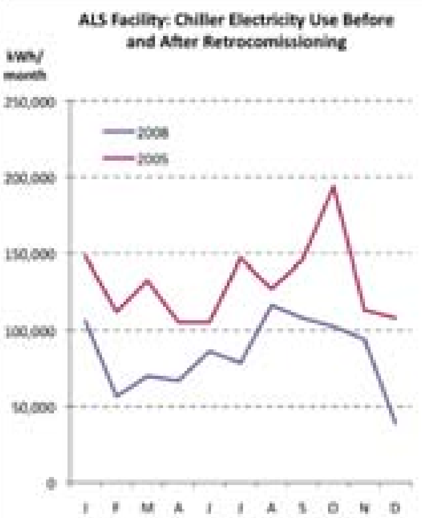
Deficiencies Identified through Commissioning:
- A false cooling load induced by the facility's temperature-stabilization reheat system.

- The main air handling units (AHUs), which provide outside air and cooling for the main experimental area, were not functioning properly. Cooling valves in all AHUs were frozen in full-cooling position, causing simultaneous heating and cooling throughout the facility. Outside air dampers not functioning.

- The central plant cooling and heating system's control programming did not optimize energy-efficiency performance or equipment longevity.

Measures Implemented through Commissioning:
- Fixed/replaced heating valve controllers and leaking valves; adjusted automated control parameters

- AHUs' cooling control valves and dampers repaired



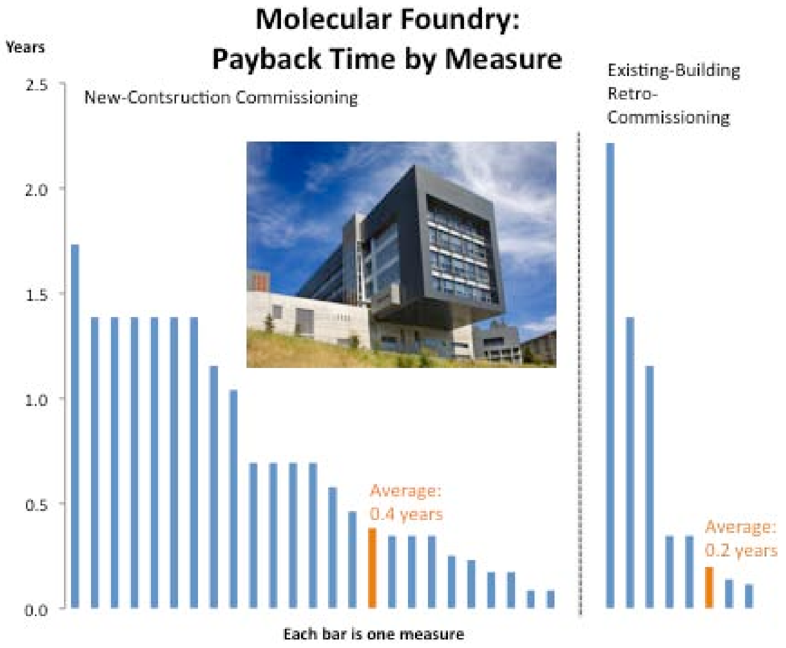
Outcomes

Energy Savings – Chiller plant cooling capacity requirements were reduced by 50 to 70 tons (10%–15%, weather corrected), which corresponded to a 45.7% (weather corrected) reduction in energy use.

O&M Improvements – The system was documented, and the staff was trained and became more able to operate the building.

Capital-cost Savings – The original chiller plant included a variable-speed 450-ton unit and an old, unreliable 350-ton unit. The commissioning project lowered chilled water needs so significantly that the 450-ton chiller went into a "surge" mode of operation that, and if allowed to continue, would damage the chiller. The operators/users believed that a new chiller with an even greater capacity than the 450-ton unit needed to be installed in place of the old 350-ton unit. However, due to the energy reductions achieved during the project, a chiller-replacement project was completed to install a new variable-speed 350-ton chiller to replace the old 350-ton unit. The new 350-ton unit provides the majority of annual chilled water needs, thus becoming the "baseload" chiller instead of the larger, less-efficient 450-ton unit.

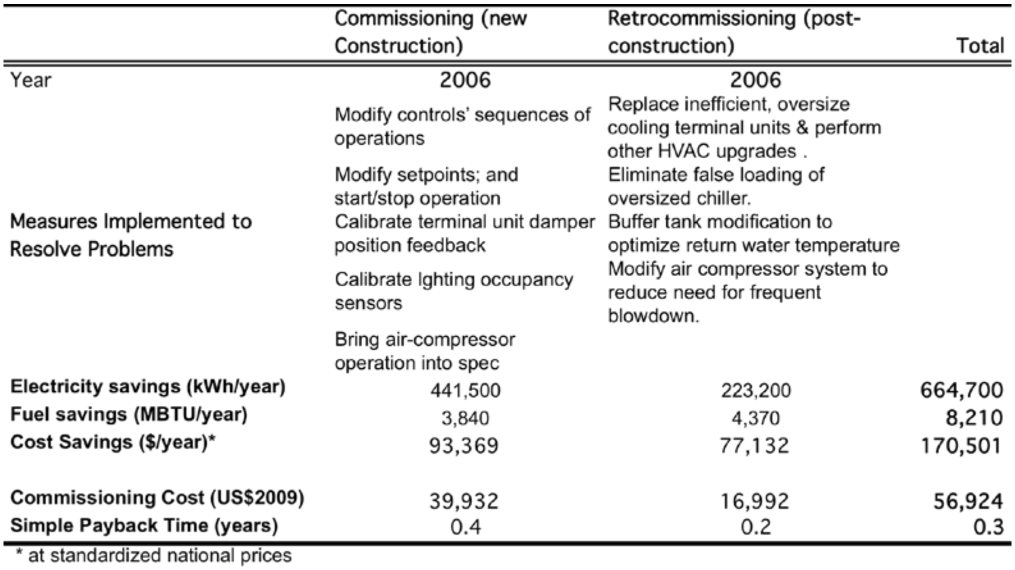
Box C. Two Tales of One Building



The Molecular Foundry at Lawrence Berkeley National Laboratory is a 91,000-ft^2 high-tech research facility. As is often heard anecdotally, even though commissioned during construction, this building was immediately a candidate for commissioning upon completion and occupancy.

During the construction phase, problems where found in the HVAC system and plant, air-handling and distribution, terminal units, and lighting. Forty-eight specific deficiencies were discovered during the new-construction phase of the commissioning. When commissioning was performed, an additional fourteen deficiencies were discovered and corrected.

Both the phases were highly cost-effective, with the new-construction commissioning averaging a 0.4-year payback time and the existing-building building commissioning phase averaging 0.2 years.



	Commissioning (new Construction)	Retrocommissioning (post-construction)	Total
Year	2006	2006	
Measures Implemented to Resolve Problems	Modify controls' sequences of operations Modify setpoints; and start/stop operation Calibrate terminal unit damper position feedback Calibrate lghting occupancy sensors Bring air-compressor operation into spec	Replace inefficient, oversize cooling terminal units & perform other HVAC upgrades . Eliminate false loading of oversized chiller. Buffer tank modification to optimize return water temperature Modify air compressor system to reduce need for frequent blowdown.	
Electricity savings (kWh/year)	441,500	223,200	664,700
Fuel savings (MBTU/year)	3,840	4,370	8,210
Cost Savings ($/year)*	93,369	77,132	170,501
Commissioning Cost (US$2009)	39,932	16,992	56,924
Simple Payback Time (years)	0.4	0.2	0.3

* at standardized national prices

Persistence of Energy Savings

Concern is often voiced about the durability or "persistence" of energy savings from commissioning projects. The literature on the subject remains sparse, and the periods over which persistence has been tracked are mostly under five years. In a rare example of longer-term analysis, a large existing office building in Colorado originally commissioned in 1996 was reexamined in 2003, and it was found that most of the original measures were still in place and that 86% of peak-demand savings and 83% of electricity consumption savings had persisted (Selch and Bradford 2005). These eroded savings were recovered at the time by re-commissioning the original measures.

To our knowledge, we have assembled the largest available collection of persistence data for commissioned existing buildings. For a subset of 36 buildings, energy-savings data (total or for particular fuels) was available for two or more consecutive years following the project, allowing us to observe the persistence/durability of savings (Figure 18). Each project is represented in the figure by a grey line for the corresponding type(s) of energy for which persistence data were collected. The heavy red curves show the median trends for each type of energy.

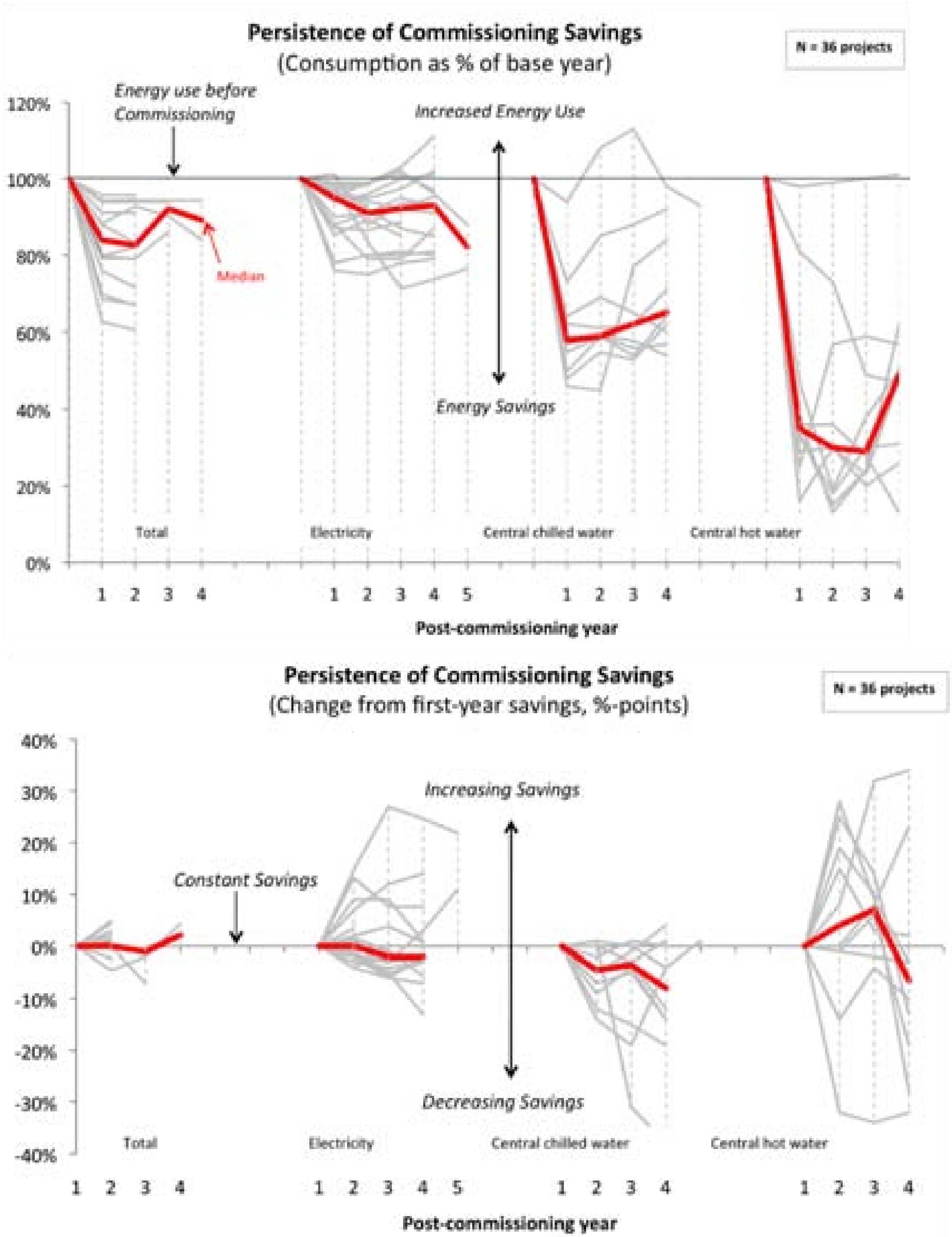
The first important observation is that savings in many cases increase in the second year, presumably a product of refinements in the commissioning or incomplete implementation in the first year. Savings from "static" commissioning measures can be expected to diminish over time. Indeed, the erosion of savings or other factors that tend to bring a building "out of tune" are the rationale for commissioning in the first place.

While some projects exhibit an erosion of savings over time, many do not. In fact, the tendency for the sample as a whole is for level or even slightly increasing savings over time. This perhaps counterintuitive outcome may be explained by the fact that comprehensive commissioning includes training, and, in some cases, installation of permanent metering and feedback systems. These improvements "live on" after the commissioning engineers leave the site, and, if properly utilized, can maintain and even help deepen savings. Many measures implemented in new-construction commissioning will tend to be very durable, e.g., properly sizing HVAC equipment.

To the extent that savings increase over time, our project cost-benefit estimates miss some of the true savings. This means that effective payback times could be even shorter than we have estimated.

The data underscore the importance of benchmarking performance over time and revisiting the need to commission with some frequency.

Figure 18. *Two views of the persistence commissioning energy savings: 36 projects.*



Note: The upper panel plots the energy use in each post-commissioning year, with the pre-commissioning value set at 100%. The lower panel plots the change in percentage savings for each year (starting with year 2 versus year 1). Note that the decline in "Total" savings in year three is attributed to the discontinuation of some of the "better" data series after two years.

Trust, But Verify

As with most other energy-efficiency measures, commissioning savings are often roughly estimated or out-and-out stipulated based on little more than best guesses.

The imperative for measurement has increased as energy prices soar, concerns intensify about securing reductions in greenhouse gas emissions, and demand-side programs come under closer scrutiny and expectations that savings be measured and verified. In addition, there are strong engineering arguments that better due-diligence during and after the commissioning project can identify deficiencies that would otherwise go undetected. Thus, a measurement-based paradigm certainly does not imply that savings will necessarily prove lower than estimates.

In a previously referenced example of the value of measurement, a data center was believed to be attaining 14% savings (Nodal 2008). Upon conducting a number of measurements within the commissioning process, it was discovered that there were actually no savings. Proper adjustments not only recovered the "lost" savings but actually *increased* them by a third, to a total savings of 19.2%.

In another example, the commissioning of an existing hospital was projected to garner annual savings of just over $56,000. A first-order calculation and inspection led to a revised savings estimate of under $53,000. The subsequent application of full "retrofit isolation" measurement technique, per the International Performance Measurement and Verification Protocols (IPMVP), identified additional savings opportunities, bringing the verified total to nearly $74,000—a 31% increase over the original estimate. The additional effort came at a price, but overall payback times remained well below one year (Chitwood et al. 2007).

The aforementioned issue of savings persistence has also contributed to the healthy interest in applying a higher level of measurement-based approach to commissioning than is typically the case. Program operators, however, have articulated various barriers, which include lack of staff, monitoring data that are useful and understandable, empowering those doing the monitoring to act on the results (to intervene if the data suggest that savings are being forfeit), and lack of information on the cost-effectiveness of monitoring (Long and Crowe 2008).

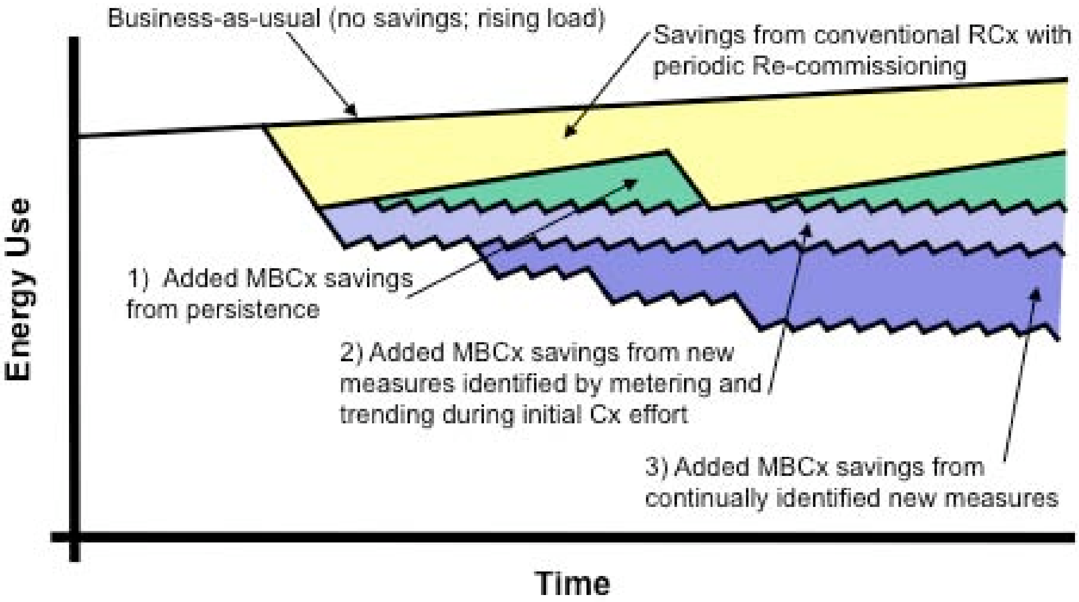
Monitoring is a tool for benchmarking and identifying savings opportunities that may otherwise go undetected. One of Xcel Energy's most successful commissioning projects attributes its high peak-demand savings (221 kW) to the presence of a sophisticated energy monitoring and control system that was used to implement "creative control strategies at little cost" (Mueller et al. 2004).

The field has responded to this opportunity through increased use of monitoring, e.g., as practiced early on within various research-based projects by Texas A&M University and increasingly in projects within the University of California and California State University systems.

The Monitoring-based Commissioning Paradigm

An emerging formalization of measurement in the commissioning process is known as monitoring-based commissioning (MBCx). As discussed by Mills and Mathew (2009), monitoring-based commissioning can also be thought of as monitoring-enhanced building operation that incorporates three components: (1) permanent energy information systems (EIS) and diagnostic tools at the whole-building and sub-system level; (2) commissioning based on the information from these tools and savings accounting emphasizing measurement as opposed to estimation or assumptions; and (3) ongoing commissioning to ensure efficient building operations. MBCx is thus a measurement-based paradigm that affords better risk management and also helps to identify problems and opportunities that are missed with periodic commissioning. The fundamental goal is to garner more and more persistent energy savings (Figure 19).

Figure 19. *MBCx provides three streams of additional energy savings relative to conventional commissioning of an existing facility.*



An initial outline of the theory and practice, coupled with an evaluation of 13 projects was performed by Brown et al. (2006), followed by an evaluation of 21 projects by Mills and Mathew (2009). These projects have been integrated into our meta-analysis database. The analysis was based on in-depth benchmarking of a portfolio of MBCx energy savings for buildings located throughout the University of California and California State University systems. A total of 1120 deficiency-intervention combinations were identified (Mills and Mathew 2009). From these interventions flowed significant and highly cost-effective energy savings. For the MBCx cohort, source energy savings of 10% were achieved, with a range of 2% to 25%. Peak electrical demand savings were 0.2 watts per square foot per year (W/ft^2-year) (4%), with a range of 3% to 11%. Costs ranged from

$0.37/ft^2 to 1.62/ft^2, with a median value of $1.00/ft^2 for buildings that implemented MBCx projects. Half of the projects were in buildings containing complex and energy-intensive laboratory space, with the higher costs associated with these projects. Median energy cost savings were $0.25/ft^2, for a median simple payback time of 2.5 years. The greatest absolute energy savings and shortest payback times were achieved in the subset of laboratory-type facilities.

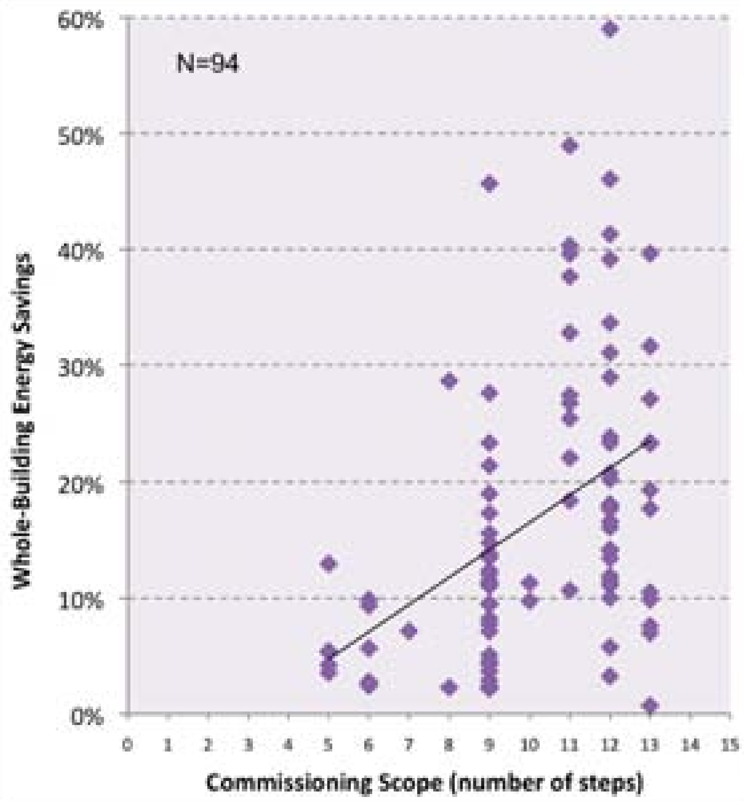
An evaluation of California utility-funded commissioning programs attributed higher savings to those that were monitoring-based (PECI and Summit Building Engineers 2007).

Best Practices

When viewed in terms of outcomes, the best practices we have observed result in zero- or negative net cost as non-energy benefits more than offset commissioning fees. The resulting payback times are in effect instantaneous, combined with energy savings surpassing 50% whole-building energy use.

Such large energy savings of course depend on thorough commissioning and the presence of serious problems at the outset, but it is clear that in more than half the cases in our database saved above our median value of 16%, and higher savings were correlated strongly with the breadth of the commissioning undertaking (Figure 20).

Figure 20. *Depth of commissioning versus savings achieved (existing buildings).*



Projects with a comprehensive approach to commissioning attained nearly twice the overall median level of savings and five-times the savings of the least-thorough projects. Comprehensiveness is measured in terms of the number of pre-defined steps/phases included in the commissioning process.[13]

In terms of application, it is critical that commissioning be well integrated with the rest of the building lifecycle and associated services. These include design and design-intent documentation at the early stages of the project cycle, through benchmarking performance to identify baseline performance and savings opportunities, and a monitoring-based paradigm for identifying and quantifying opportunities on an ongoing basis.

Within the commissioning process are a wide number of steps and documentation and training (Box A), which should be but are rarely all exercised in practice. For new and existing buildings alike, periodic recommissioning is often called for. For new construction this dictates introducing the commissioning agent at the very outset of the design and planning process and keeping them on board well through startup and into the warranty period. This is often not the case in practice, i.e., in only about one-quarter of our projects was commissioning begun during the design phase, and in only one-third of the cases did it include construction observation.

To have maximum impact, commissioning must address the whole building. Many of our case studies are selective in their focus, e.g., addressing space-conditioning systems to the exclusion of service water heating, lighting, plug loads, and envelopes.

Lastly, much better practices are needed in the documentation of commissioning projects and creation of case studies. The current literature is fraught with ambiguities and non-standard definitions. When quality control protocols are applied along with benchmarking analyses[14] that require very specific data—as is done in this report—much of the existing literature is not usable. Areas requiring clear definition include factors such as correlating floor area to commissioning cost, extent of end uses and fuels included in savings estimates, weather-normalization of pre-/post-commissioning data, specific costs included and excluded, and clarity as to whether measures and savings have been verified.

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[13] Details available at http://cx.lbl.gov/documents/2009-study/supplemental-information.pdf

[14] A quality control/quality assurance checklist is provided in Mills and Mathew (2009).

The Ultimate Potential for Commissioning

Applying our median whole-building energy savings value (i.e. not best practices) to the stock of U.S. non-residential buildings corresponds to an annual energy-savings potential of $30 billion by the year 2030, which in turn corresponds to annual greenhouse gas emissions of about 340 megatons of CO_2 each year.[15] Commissioning is thus a formidable efficiency "measure" in its own right. In some cases it enables the achievement and maximizes the impact of other more traditional measures. In other cases, it provides savings independently of other measures. Like other energy-efficiency measures, it has a cost, associated savings, and a given "lifetime," or period of persistence.

Scores of studies have been conducted on the potential for energy savings. Few, if any, have rigorously included the costs and benefits of building commissioning. However, many such studies examine the "technical potential," other measures which, rather, implicitly assumes that all measures work perfectly and, typically, that they fully penetrate the targeted stock of buildings. This would require considerable commissioning effort and generate equally considerable rewards.

To put the potential for commissioning in context, Figure 21 shows the significant carbon reductions that commissioning of U.S. commercial buildings would represent in context with a prominent study of the potential for a wide range of other strategies. This exercise reveals that not only is commissioning among the very most cost-effective strategies for reducing greenhouse gas emissions, but it is also a large absolute source of savings, as indicated by the width of the step in the figure.

Thorough potential studies must also incorporate the role of commissioning in extending the persistence of other energy-efficiency measures, as well as the finite persistence of commissioning itself. Commissioning is also a delivery mechanism for operator training, which supports maintenance and extension of the savings potential of virtually all other carbon-abatement strategies in buildings.

Projections of commissioning cost-benefits should also consider trends in costs and impacts. Delivery costs will be driven in large part by trends in labor prices, although as this relatively young industry moves up the learning curve, delivery will become more time-efficient. New technologies such as advanced metering, wireless sensors, and "automated commissioning" electronics stand to considerably reduce the costs. The value of energy savings will be pegged to energy prices, which will rise in the long term.

Non-energy benefits should also be incorporated in potentials studies. As borne out by the data presented in this report, they are significant and today generally not monetized;

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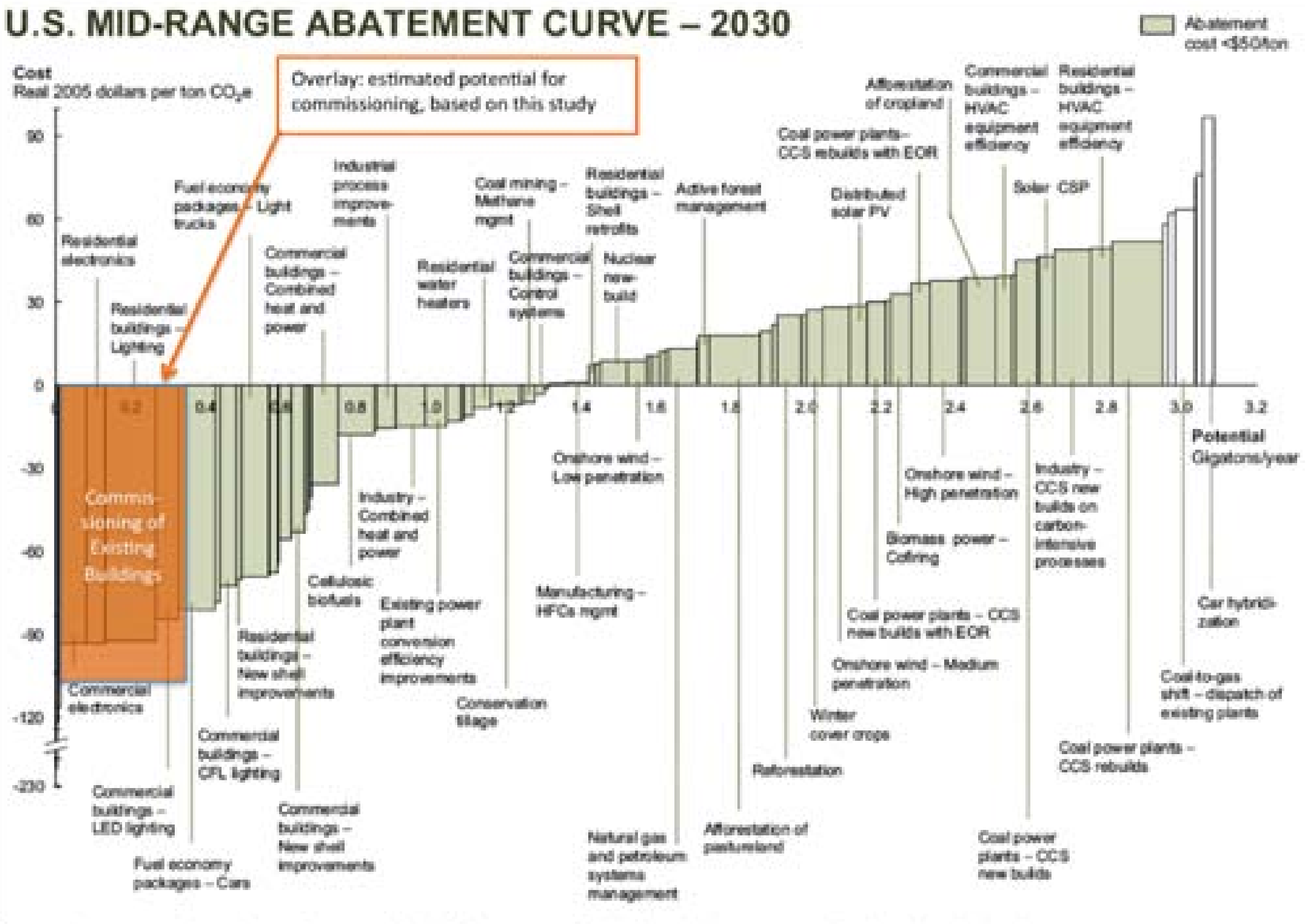
[15] We assume energy consumption per DOE/EIA (2003), demand growth per the U.S. Energy Information Administration's *Annual Energy Outlook* (2007), median commissioning energy savings of 16% (per this study) and the energy price default values used in preparing this report.

this may change in the future. One certain example of this final point will be when a cost/value is assigned to greenhouse gas emissions.

Figure 21. *Potential U.S. carbon savings from commissioning in context with other options.*



Sources: Green curve based on Mckinsey and the Conference Board (2007), and Orange step overlay based on this study.

Notes. The overlaid orange bar is derived from the analysis in this report and superimposed for reference over the green carbon "abatement curve" published by McKinsey (McKinsey & Company and the Conference Board (2007). The full abatement curve indicates the potential emissions savings potential for a range of measures, ranked by the annualized net cost per ton of emissions reductions (y-axis), i.e., the cost of commissioning minus the value of the resulting energy savings over the measure life. The horizontal width of each step is the potential emissions reduction attributed to each measure for the particular scenario considered. The height of the orange step reflects the median cost of avoided carbon for commissioning derived in this report, and the width represents a potential 16% reduction (median value from this report) in commercial-building emissions projected for the year 2030. To estimate the baseline emissions in 2030, commercial buildings emissions from 2005 are scaled by the projected growth in commercial floor area (EIA 2006). The mid-range scenario is described as one that "involves concerted action across the economy."

Research Frontiers

Those who study and evaluate commissioning have a wealth of interesting technical and market-based issues to address. These include: garnering greater insight into the mechanics of savings persistence, optimal application of measurement and monitoring, decreasing the cost of delivering and reaching difficult market segments, and filling in gaps in the types of facilities for which good case-study data are available. Commissioning is becoming more specialized towards individual systems, although certain end uses (e.g., plug loads) are less well addressed than the heating, ventilating, and air-conditioning systems with which most commisisoning practitioners are most familiar. Few studies have examined the commissioning of central plants, and few have reached outside the commercial buildings sector to address industrial facilities or multifamily residential buildings.

Most of the rigorously documented commissioning projects appear to be limited to the United States. It is important to expand the practice of commissioning project data collection and evaluation to other parts of the world.

Numerous emerging technologies are entering the marketplace. Among these are solid-state lighting systems, integrated daylight-dimming and automated window shading systems, electric demand control methods and technologies, wireless controls, and a host of smart-grid strategies. Each will bring new risks along with opportunities for energy savings. In one example—a chilled-beam cooling project at a major research laboratory—about 30% of the 100 condensation sensors failed (Mantai 2009). It is critical that the practice of commissioning keep pace with the introduction of new technologies in order for their energy-savings potential to be realized.

With the new imperative of climate change, more effort must also be focused on tailoring commissioning services to the reduction of greenhouse gas emissions. As carbon savings achieve greater economic value, verifying and ensuring the persistence of reductions will become an increasingly important role for the commissioning provider. Little has yet been done on the related but broader theme of green-buildings (e.g. water use and green materials/practices) commissioning and quality assurance.

There is currently rising interest in the “softer” fields of energy research focusing on human decision-making and behavior by end users and intermediaries. These questions are central to both the uptake and practice of commissioning. While awareness of commissioning is low among building owners, it is equally low among energy policymakers (most of whom are not even familiar with the term).

Commissioning America in a Decade

Since our 2004 review of commissioning experience, the field has bourgeoned with large increases in the number of projects and the scale of coordinated deployment programs. The next tier of growth may prove more challenging, but will also be more rewarding. Given the need to reduced greenhouse-gas emissions, there is an unprecedented urgency to capture and retain energy savings wherever they can be found. With the high cost-effectiveness of commissioning, the practice will continue to be looked to as part of the solution. Reaching a more meaningful scale will require resolution of various barriers.

Leading commissioning practitioners and other stakeholders were convened at a "Town Hall" meeting in conjunction with the 2008 National Conference on Building Commissioning. The group set out to identify key issues and needs faced by the industry (PECI 2008), and it identified four high-level issues and challenges:[16]

1. **Professionalism:** inadequately trained workforce, insufficient communication within commissioning teams, and uneven quality in the practice
2. **Value Proposition:** low awareness among owners (and concern about persistence of savings), combined with split incentives where owners do not benefit from commissioning services that reduce tenants' energy bills
3. **Standardization:** need for standardization in methods and definitions, while avoiding counterproductive commoditization (where price competes with value)
4. **Fragmentation:** splintered activities and competition among a growing number of trade groups and certification programs

Addressing these issues will be no small challenge, and it will require a well-engineered mix of discipline in the training of commissioning providers and practice of the art, together with awareness-building within the broader end-user/customer community, most of whom have still never heard of commissioning, or, when they do, are skeptical as to its need or value.

The National Energy Management Institute estimated that the current market for commissioning *new* buildings grew from $121 million per year in 2001 to $788 million in 2005, and projected it would reach $1.3 billion 2008 (NEMI 2005).[17]

The vast preponderence of near-term energy savings, are to be had in existing buildings. The NEMI study estimated that the market for commissioning *existing* buildings grew relatively slowly from $175 million in 2002 to $200 million 2005. NEMI estimates that this level of effort corresponded to 2.3 million labor-hours were spent on commissioning existing buildings, or about 1,150 full-time equivalent workers.[18] At a stipulated retrocommissioning cost of $0.30/ft^2 (based on this study) to deliver retrocommissioning,

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[16] Similar findings emerged from a major survey of industry players sponsored by NEMI (2005).

[17] It is not clear whether the NEMI findings are limited to commissioning that includes an energy focus or more broadly at all forms of commissioning.

[18] NEMI states that there are 1.5 million "field-labor" hours per year, which constitute 65% of the total labor. They utilize a billing rate for the work of $65/hour.

the $200 million spent corresponds to about 660 million square feet currently treated each year and even if this is being achieved today it represents less than 1% of the U.S. non-residential building stock.

If, as a thought experiment, a goal was to commission all existing U.S. commercial building floorspace (clearly an upper limit of the need), it would take the existing workforce about 100 years to do so (assuming current practices). Thus, to achieve the goal in a decade would require a 10-fold increase in the workforce (to about 12,000 workers). While this may sound like a large number, consider that as of 2006 there were 292,000 heating, air-conditioning, and refrigeration mechanics and installers; 80,000 electrical and electronics repairers for commercial and industrial equipment; 226,000 mechanical engineers; and 511,000 engineering technicians in the United States.[19]

The corresponding industry would have a sales volume of $2 billion per year for existing buildings commissioning. In addition, there should be some degree of recommissioning to ensure persistence of savings. If done every five years, then the preceding numbers would double to 24,000 workers and a $4 billion market size.

There is clearly more potential demand for commissioning than the existing workforce can meet. One study estimates that only 20% of the existing providers have capacity to take on new projects at any one point in time (PECI and Summit Building Engineering 2007). As commissioning is a highly specialized skill, requiring keen sensibilities, it is not an overnight project to train more providers. An assessment of the record and capacity of workforce development institutions to train providers of energy services identified commissioning as one of the areas in which current programs were deficient, and concluded more generally that:

> *"Workforce development needs of the energy efficiency industry are acute. Employers are not finding sufficiently skilled job applicants in today's market and the anticipated growth of the industry will only increase the severity of the problem in the short term. Educational institutions, at all levels, are not keeping pace with the growth and needs of the energy efficiency industry. ... The job creation potential in the energy efficiency industry appears to be very significant and is likely the leading sector in the clean energy field for job growth potential. The industry has need and opportunity for talented and creative thinkers, both in technical and non- technical areas, which will drive the development of a new energy economy ..."* (NEEC 2008)

"Commissioning America" in a decade is an ambitious goal, but "do-able" and very consistent with this country's apirations to simultaneously address energy and environmental issues while creating jobs and stimulating sustainable economic activity.

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[19] U.S. Bureau of Labor Statistics, http://www.bls.gov/oco/

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