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REVIEW PAPER

Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States

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Abstract Commissioning is arguably the single most cost-effective strategy for reducing energy, costs, and greenhouse gas emissions in buildings today. Although commissioning has earned increased recognition in recent years, it remains an enigmatic practice whose visibility severely lags its potential. The application of commissioning to new buildings ensures that they deliver or exceed the performance and energy savings promised by their design and intended operation. When applied to existing buildings, commissioning identifies deficiencies and the almost inevitable “drift” from intended performance over time, and carries out interventions to put the building back on course. More formally, commissioning is a systematic, forensic approach to quality assurance and performance risk management, rather than a technology per se. This article presents the world’s largest compilation and meta-analysis of commissioning experience and the associated literature, comprising 643 non-residential buildings, 99 million ft^2 of floorspace, \$43 million in commissioning expenditures, and the work of 37 commissioning providers. The median normalized cost to deliver commissioning is \$0.30/ft^2 (\$2009 currencies) for existing buildings and \$1.16/ft^2 for new construction (or 0.4% of the overall construction cost). The one third of projects for which data are available reveal over 10,000 energy-related deficiencies, the correction of which resulted in 16% median whole-building energy savings in existing buildings and 13% in new construction, with payback times of 1.1 and 4.2 years, respectively. Because energy savings exceed commissioning costs, the associated reductions in greenhouse gas emissions come at a “negative” cost of −\$110/tonne CO_2 for new buildings and −\$25/tonne for new construction. Cases with comprehensive commissioning attained nearly twice the overall median level of savings and five times the savings of the least-thorough projects. Significant non-energy benefits such as improved indoor air quality are also achieved. Applying the median whole-building energy-saving values to the US non-residential buildings stock corresponds to an annual energy-saving potential of \$30 billion (and 340 Mt of CO_2) by the year 2030.

Keywords Energy efficiency · Commissioning · Commercial buildings · Risk management · Quality assurance · Carbon reductions · Savings persistence

Introduction

The pursuit of discrete energy-efficient technologies is becoming increasingly commonplace. Yet, an equally important pathway to energy savings and greenhouse gas emissions reductions is virtually

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invisible to the typical building occupant, and too often even to the operators: the systems-level *commissioning* of new buildings and *retro-commissioning* 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).[2] After initial commissioning, ships are routinely inspected and serviced ("retro-commissioned") 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).[3] 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, and, finally, to a vibrant fledgling industry serving ambitious scale-up efforts today.

The translation of this concept to buildings encompasses issues as diverse as access, safety, security, mechanical, landscaping, acoustics, water use, indoor air quality, and energy performance. This article focuses on commissioning as it pertains to energy performance, although other themes (particularly indoor environment) are routinely 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 for energy savings. As a result, buildings are riddled with problems that lead to undetected energy inefficiencies (Fig. 1).

This situation is changing, albeit slowly. Commissioning is today used to ensure and maximize performance of targeted energy efficiency measures, as well as to save energy in ordinary buildings where no particular effort has previously been made to utilize energy efficiency strategies. The results are highly impressive. A growing literature documenting case studies of large-scale commissioning efforts shows attractive energy savings and payback times.

Commissioning is arguably the most potent and yet least understood strategy 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.

A US industry survey in 2005 estimated that well below 5% of existing buildings and as much as 38% of "commissionable"[4] 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 refers to energy-focused efforts. Roth et al. (2005) estimated a potential savings of \$3–17 billion/year for the top 13 measures in the USA alone (Table 1).

A national census defining how many buildings are candidates for commissioning is lacking, but practitioners say they are hard-pressed to find buildings that would not benefit from it. For example, 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).

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).

In addition to lack of awareness, commissioning is also a "stealth" energy-saving strategy in the sense

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[1] This article summarizes a more in-depth report by the author Mills (2009a).

[2] 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.

[3] A detailed historical timeline of commissioning practice in the United States is provided here: http://www.peci.org/ncbc/cx_history.html

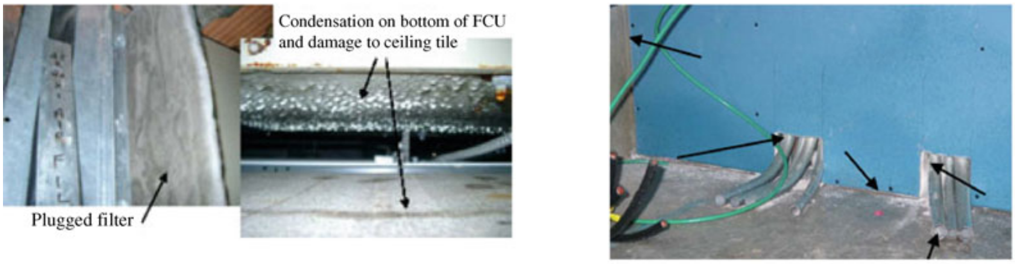
[4] The definition used here appears to be broader than just energy-driven commissioning, e.g., including safety systems. The share of buildings retro-commissioned for energy savings as thoroughly as many of those documented in this report could be lower by a factor of 10. The study assumes that one 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 is far higher.

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

Building envelope moisture entry [Aldous 2008]

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

Photosensor (for daylight harvesting) shaded by duct [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]

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

Failed window film treatment

Fig. 1 Hall of shame—visible evidence of problems addressed by commissioning

Table 1 Top faults causing energy inefficiencies in commercial buildings (top 13 of 100+ deficiencies)

	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

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 noticeable symptoms such as occupant discomfort or noise (although in some cases these are indeed important clues and corresponding "non-energy" benefits of the fixes). As a result, owners are not compelled to spend money on the commissioning process.

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 assets. Commissioning is required for buildings seeking the increasingly popular 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 operating 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 ft^2 of floorspace (Long and Crowe 2008). 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 (reducing the likelihood of claims for underperformance or errors and omissions in design and construction), and tailoring their insurance products and terms to encourage and reward it (Mills 2009b).

Commissioning is still far from mainstream. The untapped potential is huge.

Commissioning defined

Despite its 30-year history in the United States, 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 (Haasl and Heinemeier 2006a, b). As can be surmised from their 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.

Unlike an efficient light bulb, motor, or window, commissioning is not a "commodity" product (or process). Each building is unique, presenting unique problems for unique owners. Aspiration and budget can also vary; commissioning is performed at widely varying levels of effort and applied to 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 (Fig. 2). Commissioning complements these relatively familiar practices by ensuring and maintaining building energy performance (and other benefits, such as indoor environmental quality). 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.

Commissioning improves design and construction in new buildings, or "tunes" the existing system. 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 and periodically reinforced.

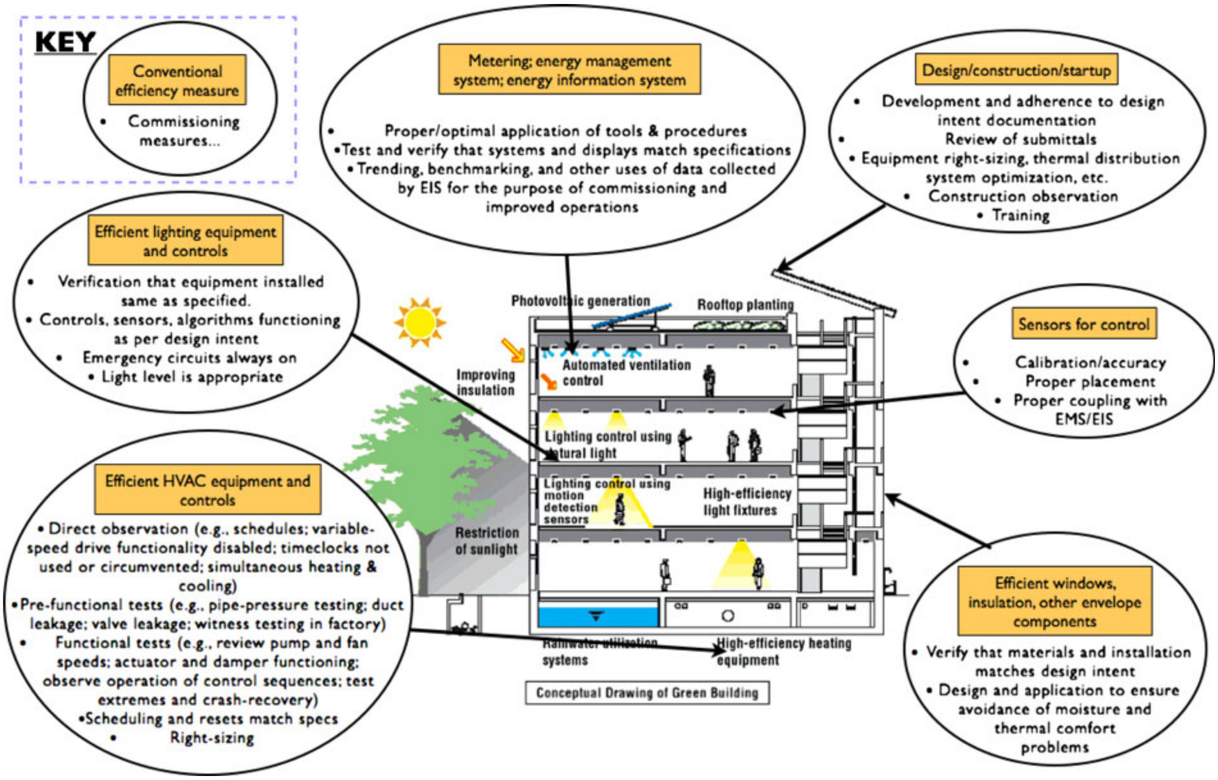


Fig. 2 Illustrative relationships between commissioning and energy efficiency measures

Although the focus includes individual pieces of energy-using equipment, it is also a decidedly holistic approach emphasizing the connections between components into systems.[5] Thus, "softer" elements are addressed, such as control logic or even the effectiveness of control system 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-saving strategies in that it does not blindly 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 physically and financially 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 simplified methods and that promised energy savings would always materialize. Many studies and estimates of savings potential still assume that everything 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 conventional 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-saving 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 to money, and regulators strengthen their oversight. Meanwhile, new technologies for saving energy have an intrinsic degree of risk simply due to the lack of historical 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 (Mills 2009b), 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 cite concerns ranging from unfulfilled energy warranties or receipt of promised green ratings, to business interruptions, to liabilities posed by exotic materials and equipment that do not have the same track record as (less efficient) standard practices, to "crisis management" situations when high-profile buildings embarrassingly fail. A landmark lawsuit has been brought for non-attainment of $600,000 in anticipated tax credits (Beverly 2010).

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

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

Commissioning approaches that incorporate in-depth monitoring and verification can offer significantly enhanced risk-management benefits by notifying operators when savings diminish. This provides added security for owners, energy efficiency program implementers, and their regulatory agencies that the savings are real and last over time (Jump 2007).

Irrespective of the degree of monitoring and verification, to not commission at all is to invite a multitude of risks and underattainment of energy-saving goals. It can further 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).

Commissioning is also a tool for managing non-energy risks. Indeed, prevention of indoor air quality problems, premature equipment failure, and litigation over non-attainment of design intent 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 non-standardized quantitative information on the costs of commissioning and resulting energy savings in actual buildings. However, the underlying methods, assumptions, completeness, and level of data quality vary widely and are not always revealed. The goal of this article is to qualify these disparate data sources and provide 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.[6] 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 intercomparisons.[7]

Data sources and analysis methods

In this article, 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, enlisted commissioning providers to extract previously unpublished data from prior projects around the country, and incorporated an evaluation of "monitoring-based commissioning" at 21 University of California and California State University sites (Mills and Mathew 2009), and combed the commissioning literature for individual or sets of candidate projects and obtained supplemental information by contacting authors, utility partners, or building owners.

As with any evaluation activity, data quality control and quality assurance are essential. Our experience with conducting 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.[8]

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[6] This assessment focuses on experience in the United States. An international overview has been conducted by the International Energy Agency (under Annex 47). Applicable US projects are included in the LBNL database. See http://www.iea-annex47.org/eng/index.html

[7] 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 lb/kWh), natural gas (112.49 lb per million BTUs). Economic assumptions: costs normalized to 2009 price levels ("US$2009"). Energy prices per US 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), and 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: 5 years. General inflation correction using gross domestic product deflators from the US 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.

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

Many case studies we encountered did not qualify for inclusion, lacking 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 including 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 conventional retrofit capital costs and savings were included, and we omit these cases as well. For such projects, other useful data may still be available and included in the secondary analyses (e.g., types of problems found or measures implemented).

To facilitate comparisons, the raw data are normalized to a standard US 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[9] in existing buildings and 77 in new construction, spanning 26 states, representing a total of 643 buildings, 99 million ft^2, and \$43 million invested in the commissioning work (Table 2).

Our sample includes data representing 37 commissioning providers covering about half of the floor area in the database, with only 1% known to be performed in-house. The provider is unknown for the balance of the projects. The California Commissioning Collaborative presently recognizes 67 providers across the United States.[10]

Caveats and conservatisms

The prime caveats in assessing commissioning project performance are verification of measure implementation, persistence of savings (discussed below), and lack of valuation of non-energy benefits.

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, but not lighting or other loads or fuels). Thus, energy savings attained in those cases are less than they might otherwise be with a more comprehensive approach. In some cases a commissioning program design (e.g., low caps on rebate levels) can intrinsically limit the level of effort applied to achieving savings, or can decouple incentives from the level of savings achieved.

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.

With these caveats in mind, 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 far more complex than that applied to conventional energy efficiency investments.

Commissioning can be said to have both costs and benefits. Benefits can include energy savings, reductions in other utilities, and lower 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), along with documentation, training, and other bundled services. Commissioning can influence the type and number of project 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).

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[9] A "project" can contain one or more buildings.

[10] As of September 16, 2010. See http://www.cacx.org/resources/provider_list.html. Some providers in our study are not on this list.

Table 2 Sample by 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	–	–	–

In some cases floor area is apportioned among more than one building type

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

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 property owner and occupant 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 had they gone unaddressed, 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, but they provide a far more robust and 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 3 provides a high-level summary of the characteristics of our sample, the investment made in commissioning, as well as the energy and economic outcomes. Figure 3 gives key results for building types for which we have more than five examples in the database.

We found median whole-building energy savings of 16% for existing buildings and 13% for new construction. Fuel savings for existing buildings were

Table 3 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[a]	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)[b]			
Total project cost (US$2009)	43,484,002	28,562,970	14,921,031
US$2009/project		49,075	86,546
US$2009/ft^2		0.30	1.16
Cost as % of construction cost			0.4%
Outcomes			
Number of deficiencies identified[c]	10,180	6,652	3,528
Number of measures[c]	5,795	4,104	1,691
Energy savings			
Total primary energy		16%	13%
Electricity		9%	–
Peak electrical demand		5%	–
Fuel		16%	–
Combined central thermal		31%	–
Central hot water		12%	–
Central chilled water		16%	–
Cental steam		19%	–
Payback time (years)[d]		1.1	4.2
Cost–benefit ratio[d]		4.5	1.1
Cash-on-cash return[d]		91%	23%
Cost of conserved carbon ($/tonne)[d]		−110	−25

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 is available vary by row

–no data

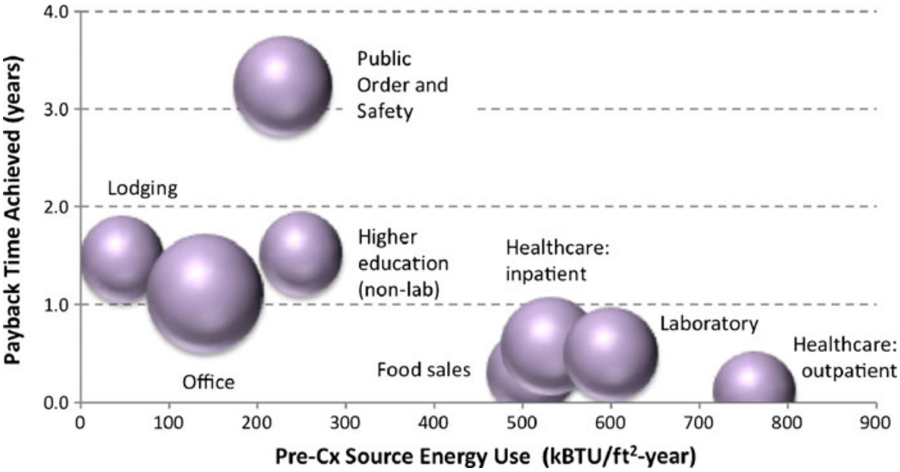
[a] The provider is known for 55% of the floor area treated in existing building projects and 43% in the new construction projects

[b] Gross costs (excluding non-energy impacts)

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

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

Fig. 3 Results by building type. Circle diameter is proportional to percent energy cost savings (e.g., "Office" = 22%). Public order and safety includes prisons



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%—even thought they were often not the main focus of the commissioning projects.

Deficiencies and their resolutions

The initial benefit from commissioning is the unearthing of problems in a 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, and the burden of responding to occupant complaints.

Information on a wide diversity of deficiencies and measures implemented to resolve them was available for 122 (about one third) of the projects in this study, and we have mapped them to a consistent framework (Fig. 4). We identified 6,652 deficiencies for existing buildings and 3,528 for new construction.

For existing buildings, deficiencies were by far most common in air-handling and distribution systems. For new construction, they 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 heating, ventilating, and air conditioning (HVAC systems)) and that most commissioning providers are specialists in mechanical systems.

Energy, economy, and environment

Approximately $43 million (inflation-adjusted 2009 USD) was spent on commissioning the projects in our database. The median investments per existing building were $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/ft^2 (inflation-adjusted to US $2009 currencies). The corresponding median 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 (Fig. 5), but with large variance. In the case of new construction, pricing appears to be more proportional to total project cost (Fig. 6). The nature of activities required for new construction commissioning may be less dependent on project 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.

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.

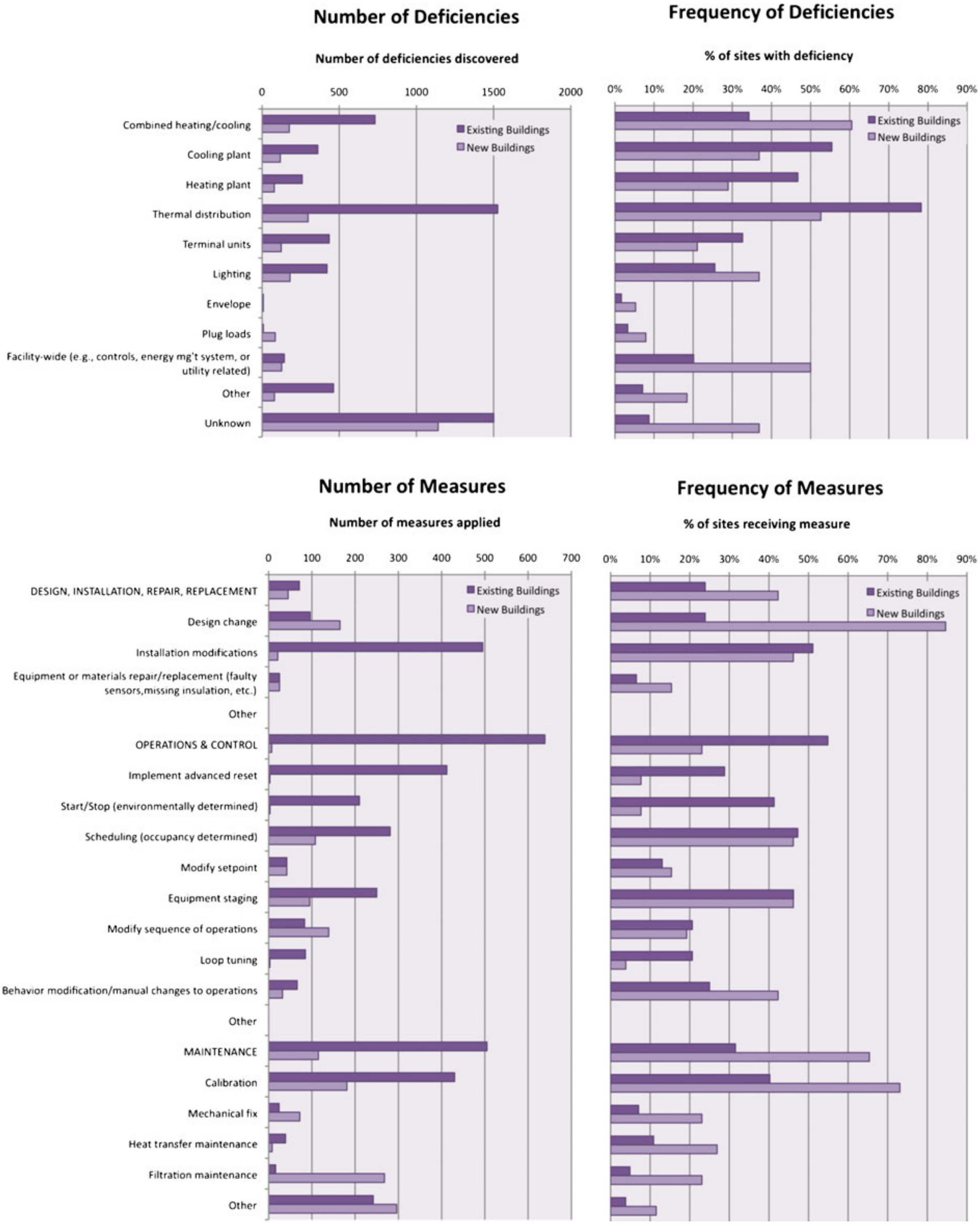


Fig. 4 Types of problems (*Deficiences*) and their solutions (*Measures*)

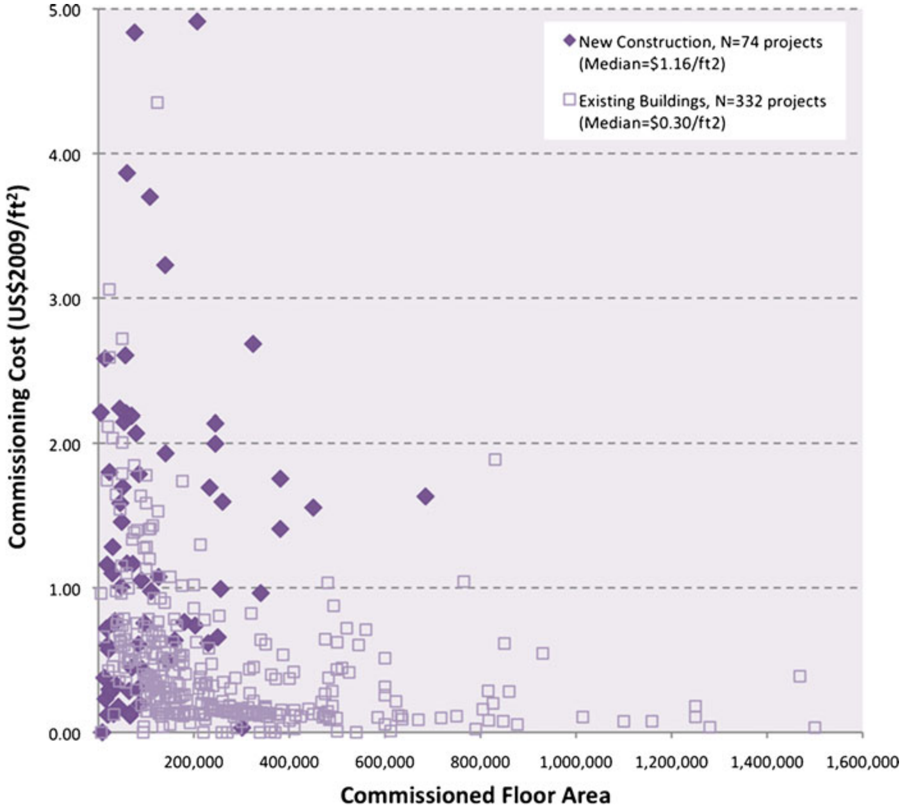


Fig. 5 Commissioning cost as a function of building size

We have seen this done in other studies, and often not disclosed to the reader. For the 32 cases where we had disaggregated 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%.

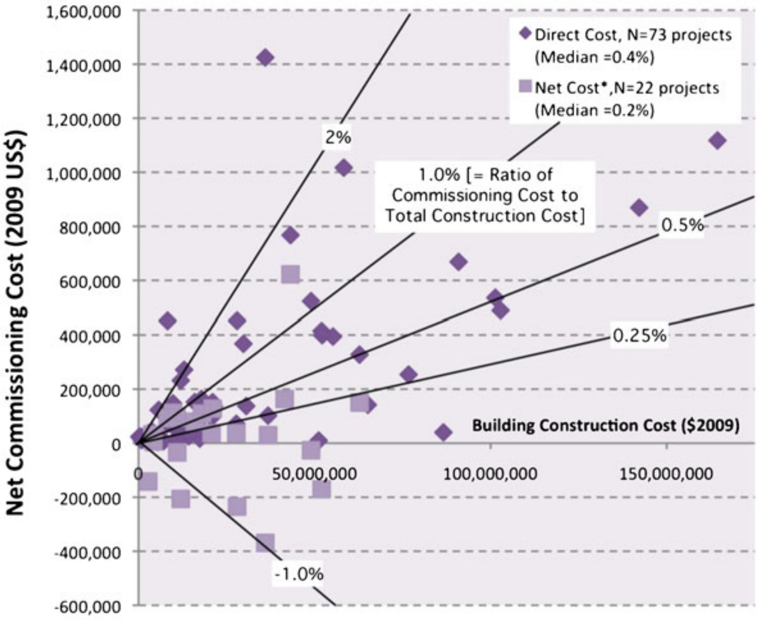


Fig. 6 New construction commissioning cost as a fraction of total construction cost. *Net Cost* includes first-cost savings where applicable

The seven panels in Fig. 7 benchmark the core energy savings and cost–benefit findings from our compilation, indicating 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 than indicated here 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 electrical demand reductions (Franconi et al. 2005; Lenihan 2007; Mills and Mathew 2009). Within our database, 54 existing building projects include savings in peak demand (median value 5.4%, with the upper quartile at 12%), and another 11 new construction projects report peak-demand savings but without pre/post values (and thus the percentage savings cannot be determined).

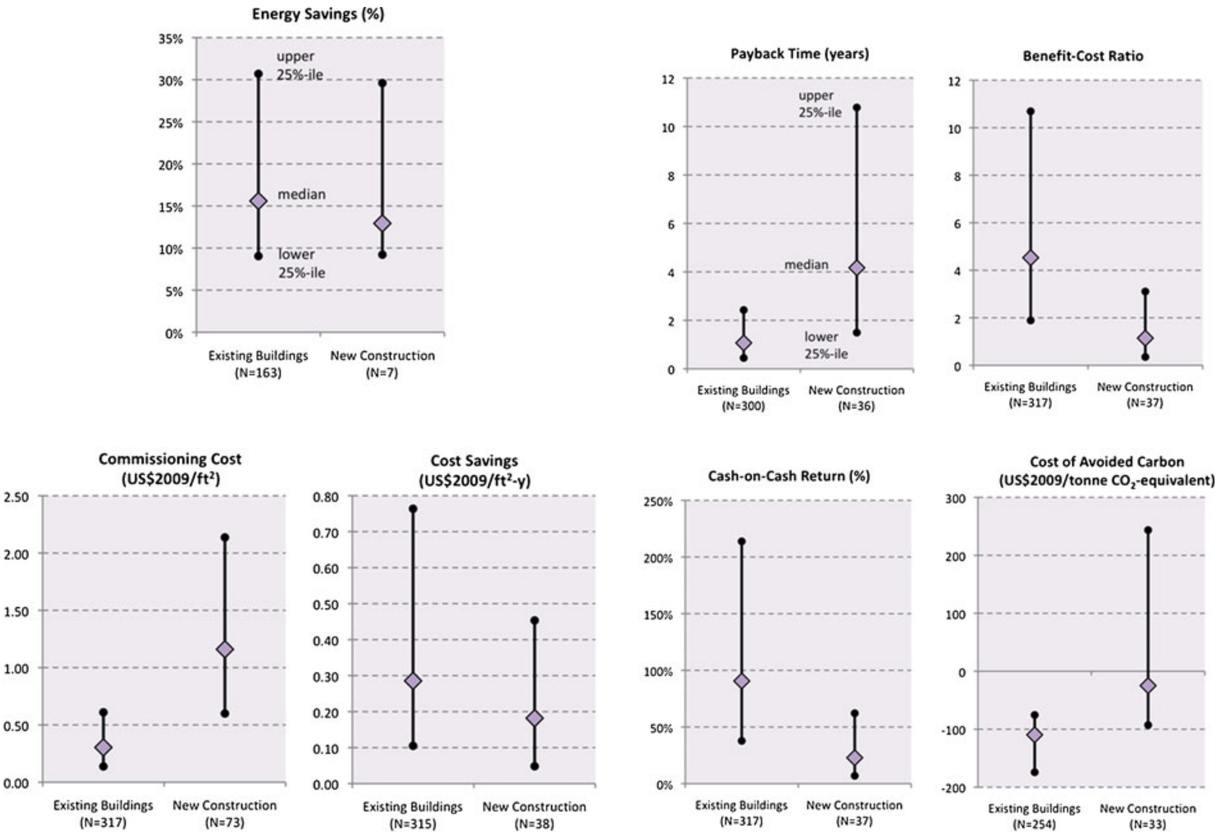


Fig. 7 Benchmarks for energy savings and cost-effectiveness. *Cash-on-cash return* is the ratio of first-year cost savings from the project divided by project cost, expressed as a percentage return (inverse of the payback time). If the return is equal to or greater than alternative investment returns (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. *Cost of avoided carbon* 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

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, the benefit–cost ratio, the cash-on-cash return, and the cost of avoided carbon.

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 when applying the same methodology to a smaller sample of projects in 2004 (Mills et al. 2004). The variations between the two studies have no practical significance in terms of the attractiveness of commissioning compared to other energy efficiency measures.

We observed a wide range of costs and savings. We found that commissioning was cost-effective for each individual measure for which we have data (Fig. 8). Payback times at the project level (multiple measures) varied but were highly attractive in most cases (Fig. 9). 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).

It is notable that payback times showed little correlation with per-commissioning energy intensities or how much 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. Unfortunately, many utility programs that promote and incentivize commissioning exclude smaller buildings. For example, the 2003 Xcel Energy program excluded buildings below 75,000 ft^2 (and preferred ones over 250,000 ft^2) (Mueller et al. 2004).

Project costs and energy savings can be cross-referenced with the forms of energy saved (e.g., electricity versus fuel) to determine the cost of greenhouse gas reductions achieved. 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. This metric has been used to rank various emission-reduction strategies in “carbon-abatement curves,” as will be discussed below.

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”).

Indeed, perceived non-energy benefits are in many cases the primary reason—or the *only* reason—for embarking on commissioning projects. For example, 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 (Fig. 10). Ensuring system performance per se is a 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, while equip-

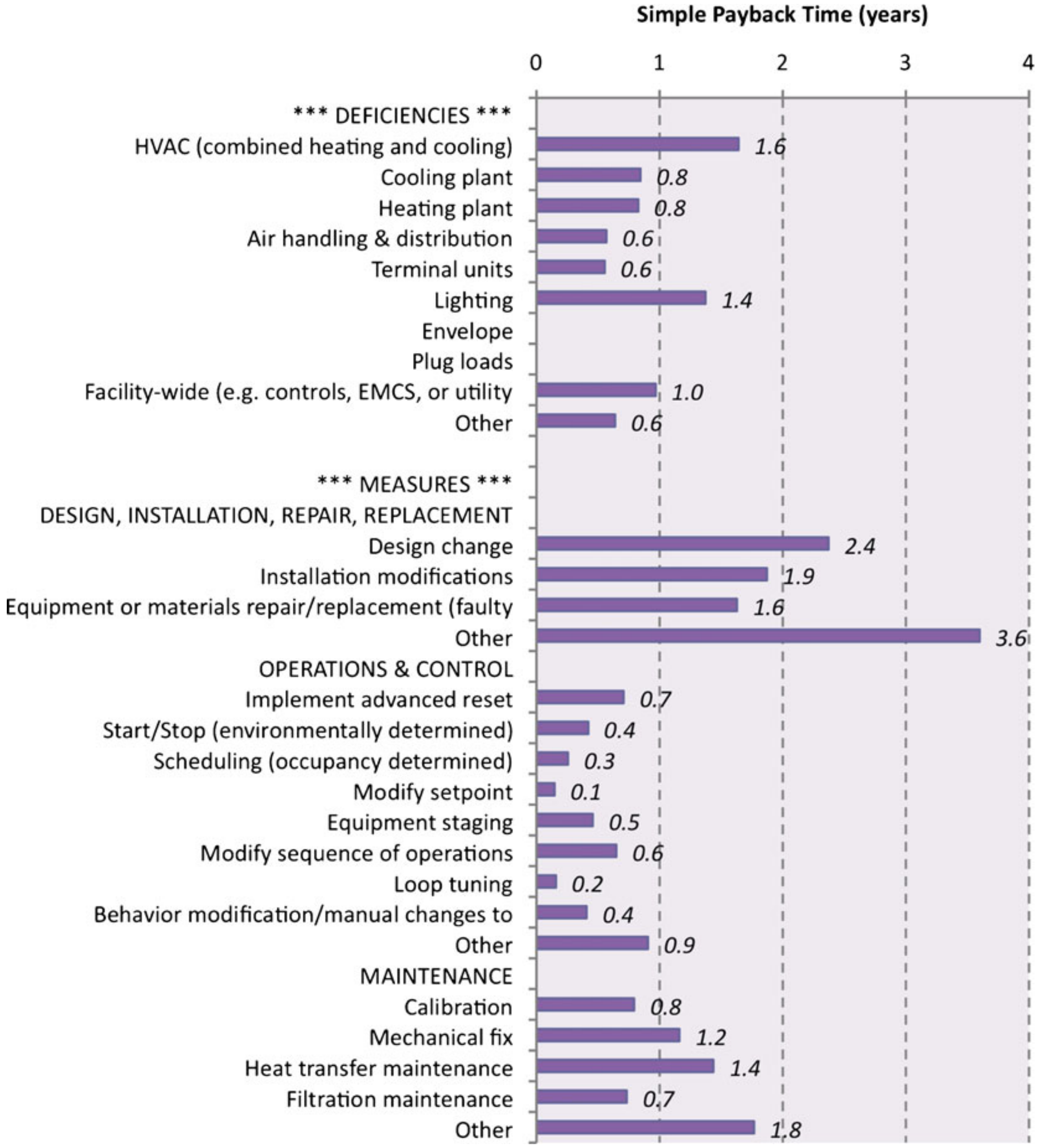


Fig. 8 Payback times by type of problem (*Deficiencies*) and by resolution (*Measures*)

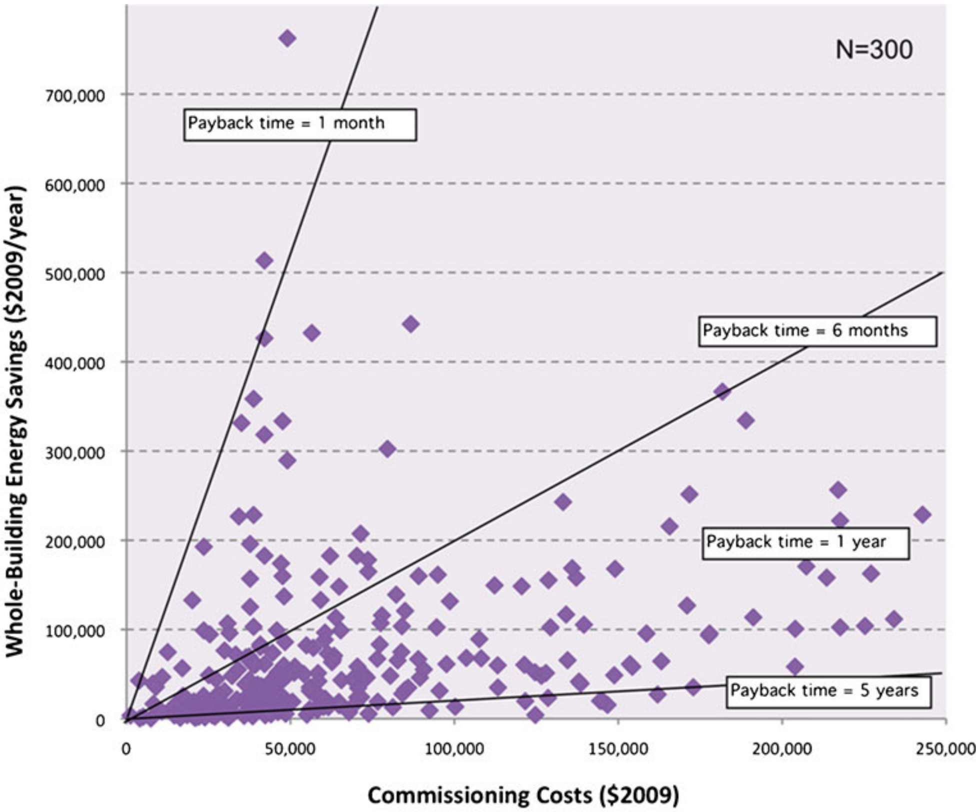
ment life is the most-cited benefit for new construction, followed by improved thermal comfort.

In 38 cases, the non-energy impacts were quantified. As seen in Fig. 11, 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. For this sub-sample, the actual net median commissioning project cost was reduced 49% from the nominal level.

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

Fig. 9 Commissioning costs, savings, and payback times: ▶ existing buildings (*above*) and new construction (*below*)


N=300
Payback time = 1 month
Payback time = 6 months
Payback time = 1 year
Payback time = 5 years
Whole-Building Energy Savings ($2009/year)
0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
Commissioning Costs ($2009)
0
50,000
100,000
150,000
200,000
250,000

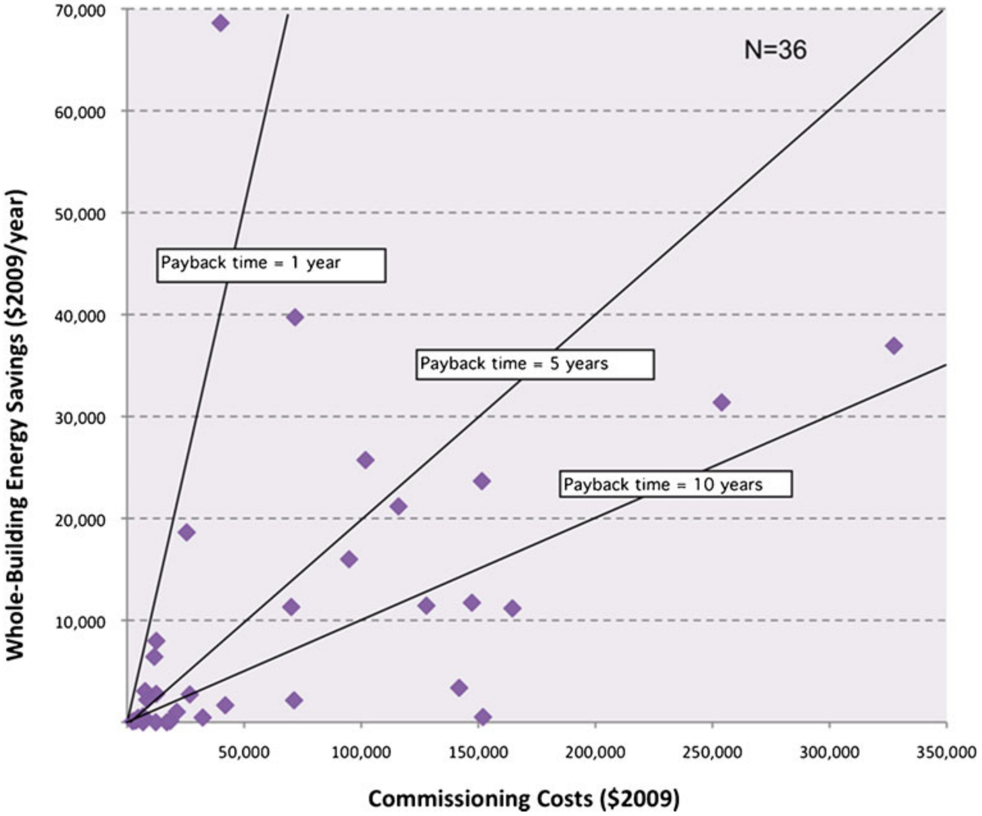
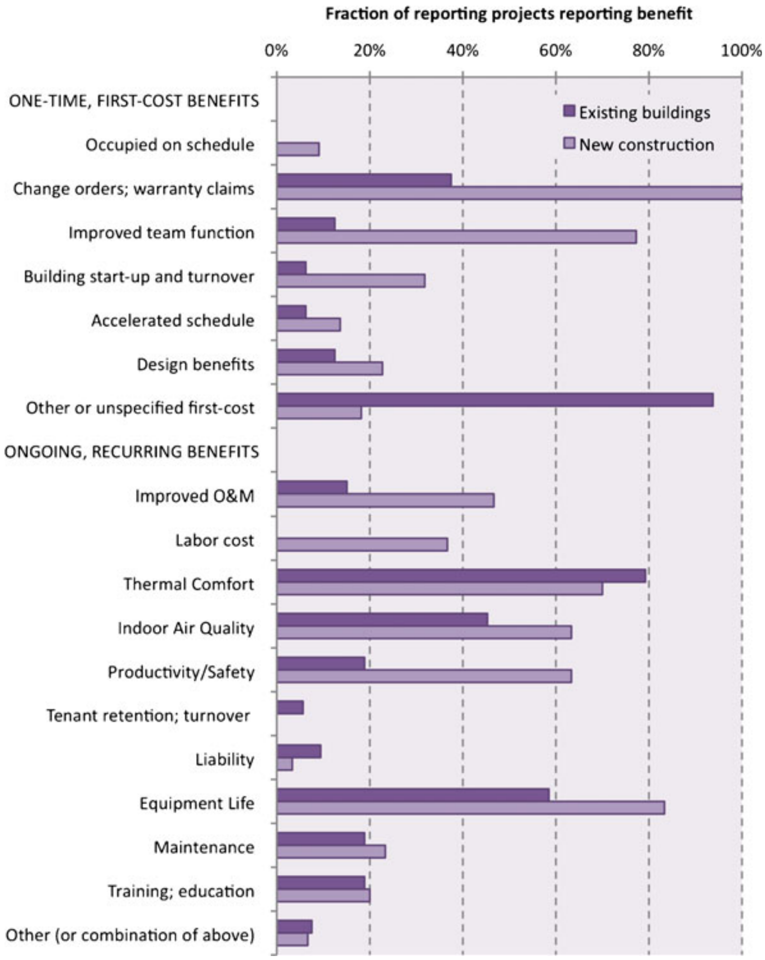

N=36
Payback time = 1 year
Payback time = 5 years
Payback time = 10 years
Whole-Building Energy Savings ($2009/year)
10,000
20,000
30,000
40,000
50,000
60,000
70,000
Commissioning Costs ($2009)
50,000
100,000
150,000
200,000
250,000
300,000
350,000

Fig. 10 Non-energy benefits observed following commissioning



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. 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 2009c).

High-tech facilities 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 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.

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 cites the special importance of fume hoods and

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

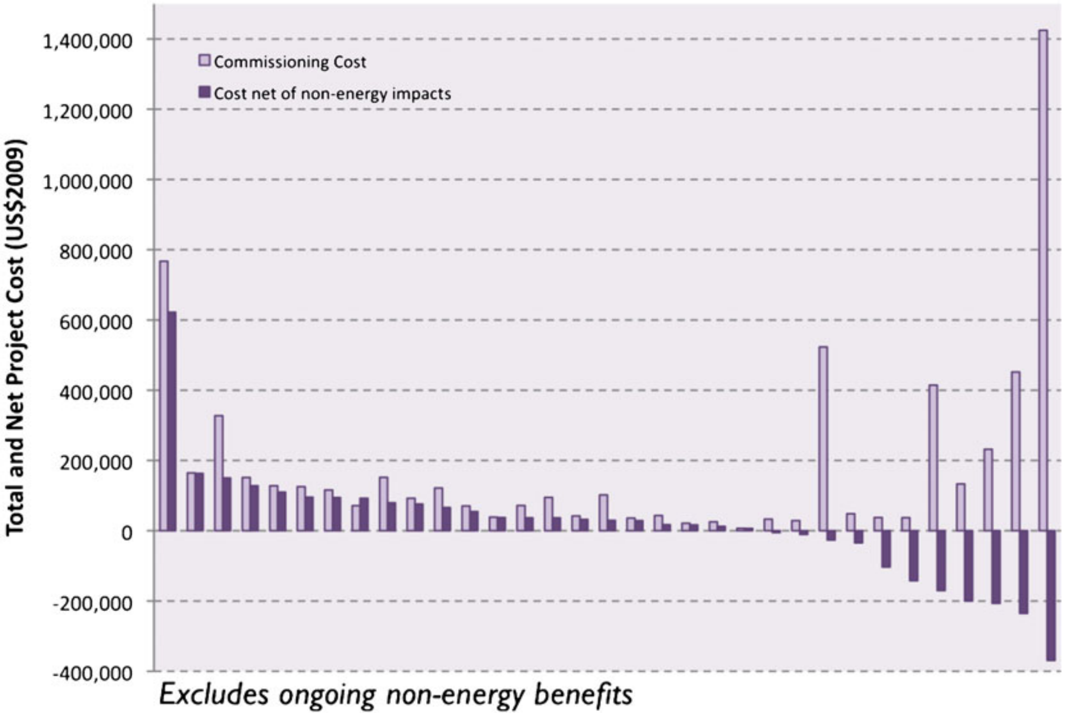

Fig. 11 First-cost savings often offset part or all nominal commissioning project costs

specialty pressure- or volume-controlled HVAC systems used for safety purposes.[12]

While problems identified in the commissioning of high-tech facilities can manifest 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.

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. Our database contains data for 115 high-tech facilities, representing 19 million ft^2 of floor area. Percentage energy savings tended to be somewhat higher than other building types, while absolute savings were significantly higher because of initial energy intensities. Payback times were also among the lowest of any building type we evaluated.

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.

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. One data center analyzed for this report (Nodal 2008) had a pre-commissioning energy intensity of over 900 kWh/ft^2/year (or almost \$100/ft^2/year), which is about 100 times the energy cost of a typical office building. Just the savings ultimately achieved by commissioning this one

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

facility—173 kWh/ ft^2/year—is 10 times the median pre-commissioning energy use for the non-high-tech buildings in our database.

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 to 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, no date), inspections of the envelope of a cleanroom in the final stages of construction found that 6% of the prodigious amount of circulated, conditioned 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 $5,000 per day (at energy prices that are very low by today's standards—$0.039/kWh and $4.4/therm).

Commissioning captured $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 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.

The value of first-cost savings can eclipse 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 in which a huge cost savings was garnered by scaling back a new chiller from over 450 to 350 t (thanks to the energy savings from commissioning). The corresponding one-time savings ($120,000) 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. (The value of the commissioning process: Costs and benefits) 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. The primary source of these benefits is in right-sizing equipment during the design phase of a project.

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
- Proper system/component selection
- Reducing contractor callbacks and accelerated date of proper operation

Two tales of one building

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.

The project was located at Lawrence Berkeley National Laboratory's Molecular Foundry facility, a complex 91,000 ft^2 high-tech building containing laboratory spaces as well as data processing and cleanroom environments. During the construction phase, problems were 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 14 deficiencies were discovered and corrected.

Considerable energy savings were garnered during the 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. The overall commissioning cost of \$57,000 was recovered three times during the first year.

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 5 years. The International Energy Agency has recently reviewed experience with the persistence of commissioning savings (Freidman et al. 2010), and found that for the cases reviewed 3 to 20 years after commissioning, savings remaining ranged from 50% to 100% for all but a handful of buildings.

In a rare example of longer-term analysis, a large existing office building in Colorado originally commissioned in 1996 was re-examined 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-saving 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 (Fig. 12).

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

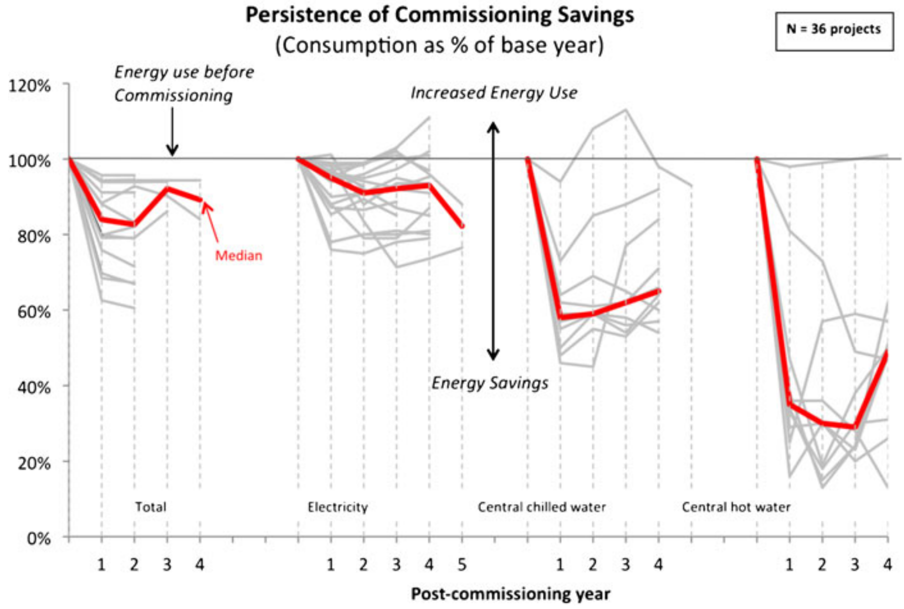

Fig. 12 The persistence commissioning energy savings: 36 projects. Each project is represented in the figure by a *gray line* for the corresponding type(s) of energy for which persistence data were collected. The *heavy red curves* show the median trends by type of energy. The decline in *Total* savings in year 3 is attributed to the discontinuation of some of the "better" data series after 2 years

performance over time and revisiting the need to commission with some frequency.

Trust, but verify

As with most other energy efficiency measures, commissioning savings are often roughly estimated or even stipulated based on engineering estimates rather than measurements.

The imperative for measurement and verification has increased as energy prices soar, concerns intensify about assigning credible reductions in greenhouse gas emissions, and demand-side programs come under closer scrutiny and expectations that savings be validated. 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 prove lower than estimates.

In one 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, 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 1 year (Chitwood et al. 2007).

The aforementioned issue of savings persistence has also contributed to the healthy interest in applying a more rigorous 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 commissioning 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.

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 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 (Fig. 13).

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 the presence of serious problems at the outset, thorough commissioning, and an owner's willingness to invest in the process. By definition, half the cases in our database saved above our median value of 16%, and in excess of 30% savings for the upper quartile. Attaining savings at the higher end of the range can be expected to require relatively significant effort, and this is indeed borne out in Fig. 14, which correlates savings with the comprehensiveness of the commissioning intervention, measured in terms of the number of pre-defined steps/phases included in the commissioning process.[13] Projects with a comprehensive approach attained nearly twice the overall median level of savings and five times the savings of the least-thorough projects.

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, 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 involving 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, however, 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-assessment/LBNL-Cx-Cost-Benefit-Pres.pdf

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

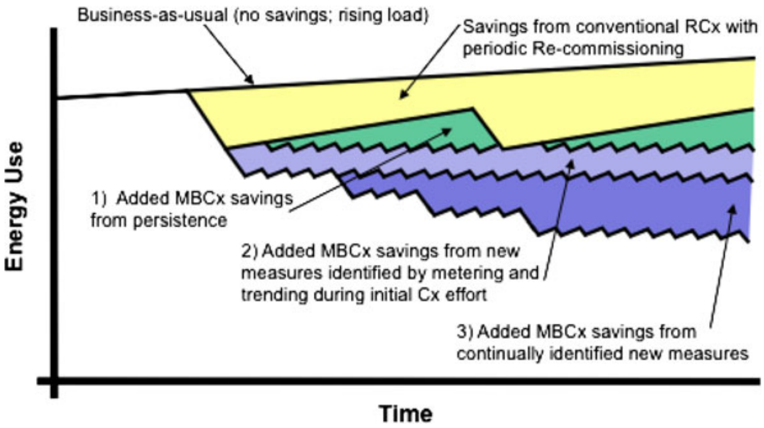

Fig. 13 Monitoring-based Commissioning (*MBCx*) provides three streams of additional energy savings relative to conventional commissioning of an existing facility

The national-scale potential for commissioning

Applying our median whole-building energy-saving value (i.e., not best practices) to the stock of US non-residential buildings corresponds to an annual energy-saving potential of $30 billion by the year 2030, which in turn corresponds to annual greenhouse gas emissions of about 340 Mt of CO_2 each year (or 110 "Rosenfelds", per Koomey et al. (2010)).[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, Fig. 15 shows the significant carbon reductions that commissioning of US 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; 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.

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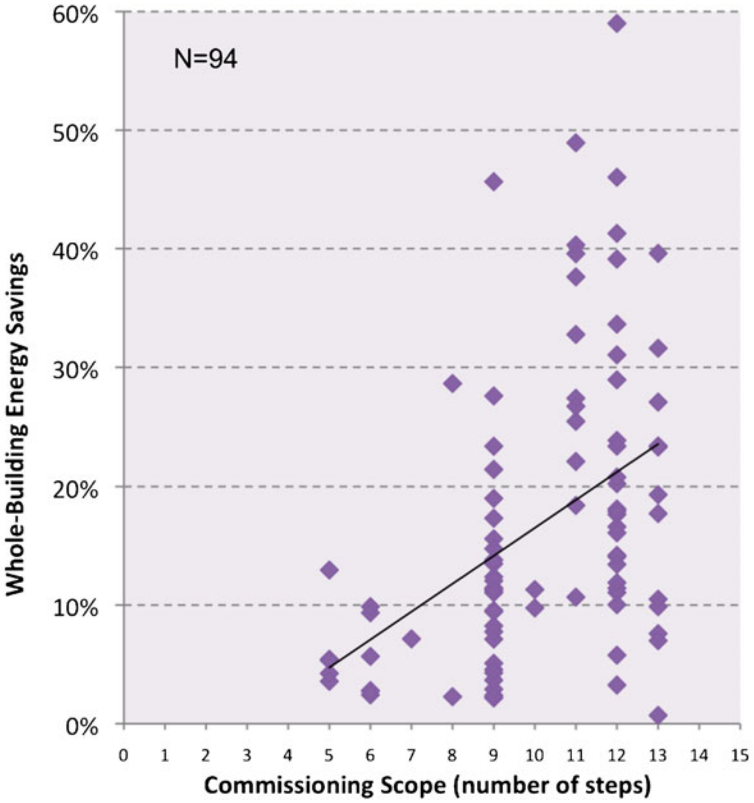
[15] We assume energy consumption per DOE/EIA (2003), demand growth per the US Energy Information Administration's *Annual Energy Outlook* (2007), median commissioning energy savings of 16% (per this study) and the energy price default values used in preparing this report.

Fig. 14 Depth of commissioning versus savings achieved (existing buildings)



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 commissioning 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 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-saving 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

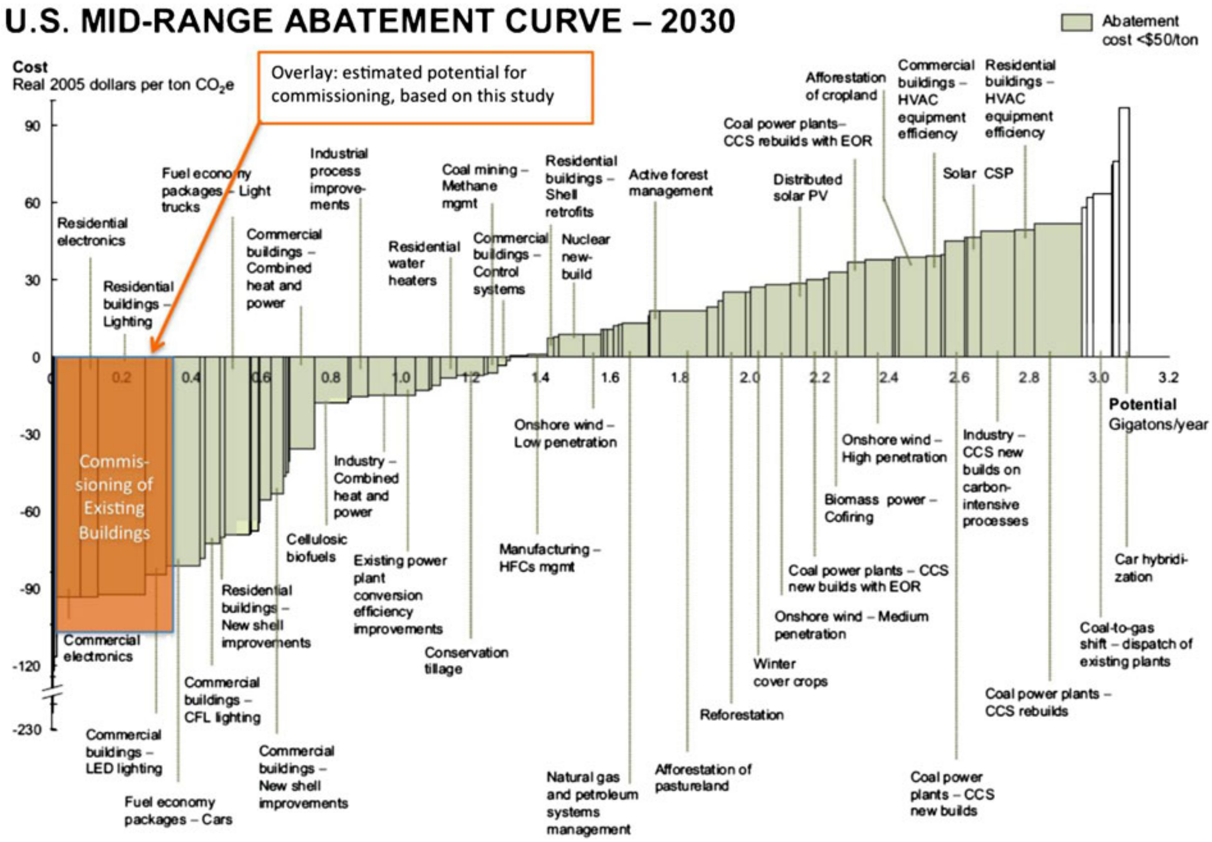


Fig. 15 Potential US carbon savings from commissioning in context with other options. The *overlaid orange bar* is derived from the analysis in this report and superimposed for reference over the green carbon "abatement curve" published by McKinsey (McKinsey and Company and the Conference Board 2007). 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 the measure minus the value of the resulting energy savings over the measure life. The horizontal width of the each step (*x-axis*) 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 building 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"

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 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 preponderance 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 cost of $0.30/ft^2 (based on this study) to deliver commissioning in existing buildings, the $200 million spent corresponds to about 660 million ft^2 currently treated each year and even if this is being achieved today it represents less than 1% of the US non-residential building stock.

If, as a thought experiment, a goal was to commission all existing US 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 tenfold 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 5 years, then the preceding numbers would double to 24,000 workers and a $4 billion annual 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 the 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 (NEEC 2008).

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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/h.

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

"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 sustainable economic activity.

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