

# The diffusion over time and space of energy efficiency in building

Nils Kok · Marquise McGraw · John M. Quigley

Received: 13 October 2011 / Accepted: 10 December 2011 / Published online: 28 January 2012  
© Springer-Verlag 2012

**Abstract** Awareness of global warming and the extent of greenhouse gas emissions have focused more attention upon energy efficiency in building. Moreover, the inventory of “green” office space in the United States has increased dramatically since the introduction of rating schemes that attest to the energy efficiency or sustainability of commercial buildings. In some metropolitan areas, the supply of certified office buildings has more than doubled in the last decade, and there are a few metropolitan areas where “green” office space now accounts for more than a quarter of the total office stock. In this paper, we analyze the diffusion of buildings certified for energy efficiency across US property markets. Using a panel of 48 metropolitan areas observed over the last fifteen years, we trace the diffusion of green building practices across the country. We then model the geographic patterns and dynamics of building certification, relating industry composition, changes in economic conditions, characteristics of the local

---

Financial support for this research was provided by the Royal Institute of Chartered Surveyors, the European Center for Corporate Engagement, and the University of California Energy Institute. We are grateful to William Wheaton and also to Jon Southard of CBRE Econometric Advisors for facilitating access to some of the data used in this analysis. A much condensed version of this paper appears in the *Papers and Proceedings of the American Economic Association*, 2011(2), 77–82. The present work appears with permission from the American Economic Association.

---

N. Kok  
Department of Finance, School of Business and Economics, Maastricht University,  
6200 MD Maastricht, The Netherlands  
e-mail: n.kok@maastrichtuniversity.nl

M. McGraw · J. M. Quigley (✉)  
Department of Economics, University of California-Berkeley, 549 Evans Hall,  
Berkeley, CA 94720-3880, USA  
e-mail: quigley@econ.berkeley.edu

M. McGraw  
e-mail: mmcgraw@econ.berkeley.edu

commercial property market, and the presence of human capital, to the cross-sectional variation in energy-efficient building technologies and the diffusion of those technologies over time. Understanding the determinants and the rate at which energy-efficient building practices diffuse over space and time is important for designing policies to affect resource consumption in the built environment.

**JEL Classification** D12 · Q51 · R21

## 1 Introduction

There exists an apparently intractable contradiction between the slow diffusion of energy-efficient technologies and the profitability of these measures—ranging from the adoption of energy-efficient compact fluorescent light bulbs in the residential sector (Menanteau and Lefebvre 2000) to the replacement of inefficient heating, ventilation, and air conditioning (HVAC) systems in the commercial sector. Early research on consumer choice suggested that the implicit discount rate applied to more energy-efficient appliances and durable goods was unreasonably high, approaching 20%. (See Hausman 1979; see also Metcalf and Hassett 1999.) This contradiction, termed the “energy paradox” (Jaffe and Stavins 1994), has regained currency in the recent debate on the role of buildings in carbon reduction and climate change—as the durability of real capital implies that existing structures have a substantial impact on life cycle energy consumption (Eichholtz et al. 2010a). Energy consumption in the building sector has large effects upon greenhouse gas emissions and upon energy use in the economy.<sup>1</sup>

Although the slow diffusion of more energy-efficient technologies in buildings is a widely discussed challenge to the neoclassical theory of investment—at least among engineers (Alcott and Mullainathan 2010; DeCanio and Watkins 1998)—recent trends suggest that the number of buildings in the United States that are labeled as “energy-efficient,” “sustainable,” or “green,” has surged over the past decade. Energy certificates for buildings are a testimony to improved building technologies, which are difficult for laymen to observe. As US President Barack Obama put it recently:

“...The Energy Star program [certifying sustainability] was created to promote energy efficiency by letting consumers know which appliances, which electronics, would save electricity and, therefore, would save them money over time. The program... applies this concept not only to the appliances, but also to homes and other buildings—taking energy efficiency a step further.”<sup>2</sup>

<sup>1</sup> For example, the construction and operation of buildings account for about a third of world greenhouse gas emissions, and are responsible for about forty percent of world consumption of raw materials and energy (RICS 2005). It has also been emphasized by policy makers that the built environment offers a great potential for greenhouse gas abatement and energy conservation (e.g., Stern 2008).

<sup>2</sup> Speech of President Barack Obama, Savannah Technical College, GA, March 3, 2010. See <http://projects.washingtonpost.com/obama-speeches/speech/191/>.

The Energy Star program, administered by the US Environmental Protection Agency (EPA) and the Department of Energy (DOE), was launched in 1992 as a system of voluntary labels designed to identify and promote energy-efficient products and home appliances to conserve energy. The Energy Star label was extended to commercial buildings in 1995, and the labeling program for these buildings began in 1999. Existing commercial buildings can receive an Energy Star certification if the source energy use of the building (that is, the total quantity of energy used in the building, as certified by a professional engineer) achieves a specified benchmark level;<sup>3</sup> the label is awarded to the top quarter of all comparable buildings ranked in terms of source energy efficiency. As measured by program growth, the Energy Star program for commercial buildings appears to be quite successful—as of November 2010, some 12,000 commercial buildings had received the label. More specifically, the number of office buildings certified by the Energy Star program has increased from a mere 86 (approximately 33 million square foot) in 1999 to more than 4,400 (approximately 1.3 billion square foot) in 2010.

In a parallel effort, the US Green Building Council (USGBC), a private non-profit organization, has developed the Leadership in Environmental and Energy Design (LEED) green building rating system to encourage the “adoption of sustainable green building and development practices.” The requirements for the certification of LEED buildings are substantially more complex than those for the award of an Energy Star rating, and the certification process measures six distinct components of sustainability, one of which is energy performance.<sup>4</sup> There are four different levels of LEED certification—certified, silver, gold, and platinum—and since the start of a single pilot project in 1998, the LEED system of multiple ratings has become a dominant force in the commercial and institutional building market in the United States. Many states and cities have revised their building codes to require newly constructed public buildings to meet LEED performance standards, and some municipalities include a certain minimum LEED certification for new commercial construction and for renovations. For example in Atlanta, GA, an ordinance was promulgated in late 2003 requiring all city-funded projects of more than 5,000 square feet in size, or costing at least \$2 million, to obtain a LEED Silver rating. All new city buildings in Kansas City, MO, are now required to meet criteria for LEED Silver, and Dallas, TX, requires all city buildings larger than 10,000 square feet to have at least LEED Silver certification.

Importantly, the expansion of standards for existing structures (e.g., LEED for existing buildings, LEED for operations and maintenance), means that the certification of a “sustainable” building by LEED, is no longer solely confined to new construction.

---

<sup>3</sup> The actual source energy consumption of a commercial building is compared to its predicted energy consumption, based on information collected through CBECS (the Commercial Building Energy Consumption Survey) and analyzed by DOE.

<sup>4</sup> For more information on the rating procedures and measurements, see <http://www.usgbc.org/leed>.

The growth of the LEED program is also substantial, with more than 6,500 commercial buildings (approximately 1 billion square foot) certified for sustainability by October 2010. Notwithstanding the unprecedented downturn in commercial property markets in recent years, LEED-certified buildings now account for nearly one-third of new construction in the United States, up from 2% in 2005 (McGraw-Hill Construction, 2010). And there is an impressive pipeline of LEED projects, as measured by the current registration of projects not yet completed—27,000 commercial buildings, or 6 billion square feet of office space.

Presumably, buildings certified for energy efficiency or sustainability incorporate technologies that systematically reduce resource usage and operating costs. Indeed, the USGBC claims that LEED-certified buildings not only have lower operating costs but also provide healthier and safer working environments for occupants. The Energy Star program asserts that the buildings that have earned its label generally use 35% less energy and emit 35% less carbon dioxide than average unlabeled buildings.<sup>5</sup> The investment costs of achieving these benefits and savings are unclear. Although the EPA and USGBC do not charge directly for providing certification (beyond a nominal registration fee), the process may involve considerable expenses for property developers and investors. For instance, the USGBC trains and licenses third-party certification experts, who charge for their consultancy services. Beyond this, there are incremental costs associated with the design, material, equipment, and construction specifically tailored to meet LEED guidelines or to achieve the energy-efficiency standards imposed by Energy Star. Until recently, systematic evidence on the returns to investments in LEED and Energy Star certification was limited, and it consisted mostly of anecdotal evidence and industry-initiated case studies.<sup>6</sup>

There is now a small body of literature that evaluates the importance of these claims in the marketplace—mainly focusing on measurable output, rather than noisy inputs. Increased energy efficiency and other elements related to “sustainability” both contribute to increases in rents, occupancy rates, and asset values in commercial offices (Eichholtz et al. 2010a; Fuerst and MacAllister 2009, 2011). Moreover, among rated buildings, incremental energy savings are roughly capitalized into asset values (Eichholtz et al. forthcoming).

If the consequences of Energy Star and LEED building practices were transparent, rational decision making by investors suggests that the adoption of specific technologies would be diffused quickly within generic building types and local economies. But there is substantial dispersion over geography and building types in the diffusion of labeled buildings. Thus, in common with many other technical innovations, diffusion of energy-efficient building practices has varied over time and space. (See Rosenberg 1976, for an early discussion of barriers to diffusion.) This variation in diffusion and

---

<sup>5</sup> See for more information: [http://www.energystar.gov/index.cfm?c=business.bus\\_index](http://www.energystar.gov/index.cfm?c=business.bus_index).

<sup>6</sup> An exception to anecdotal case studies is the recent report by Davis Langdon, a construction consultancy, which compares the capital investment in LEED-certified buildings with investments in comparable buildings. Using a sample of 221 *public* projects (i.e., schools, hospitals, and libraries), no significant cost differences are documented (Davis Langdon 2007).

market penetration may be explained by expected cost savings from adopting energy-efficient innovations, competitive conditions that affect the appropriability of gains, and characteristics that influence the expected profitability of the adoption of the innovation (Rose and Joskow 1990). Of course, institutional characteristics, such as state or local regulation, may also play an important role in explaining the adoption of cost-reducing innovations. (See Oster and Quigley 1977; Snyder et al. 2003.)

In this paper, we analyze the spread of energy-efficient technology in the built environment. “Technology” is difficult to measure, but labels offer an indirect approach to assessing the diffusion of improved technology. Even though voluntary labeling programs do not provide direct measures of energy-efficient investments in buildings, the decision to label a building may be thought of as a noisy signal of adoption of more efficient technology and a willingness to invest to conserve energy.

This approach has parallels in the more general literature on technology diffusion, where patents are a widely used proxy for improved technology. (See Keller 2004, for a recent review.) Using labels as a measure of technology diffusion in building shares some of same drawbacks: labeling and patenting are conscious choices made by owners and investors. Some efficient buildings may not be labeled, and some valuable innovations may not be patented.

Using a detailed panel of 48 MSAs observed annually during a fifteen-year period, we trace the diffusion of buildings certified for energy efficiency and sustainability across US metropolitan areas. Then, we analyze the geographic patterns and dynamics and sustainability of building certification, relating industry composition, input prices and climate, changes in economic conditions, characteristics of the local commercial property market, and the presence of human capital, to the cross-sectional and temporal variation and local growth in more efficient office space.

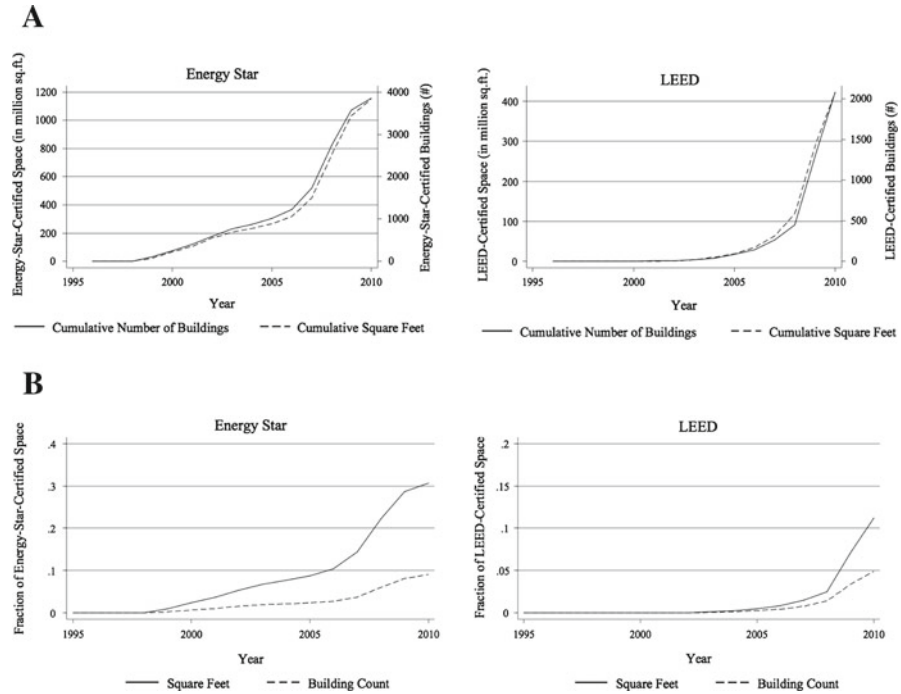
The remainder of this paper is organized as follows. Section 2 discusses the data and describes the diffusion of Energy Star and LEED buildings in the United States and in a number of large MSAs. Section 3 presents data on the economic geography of the MSAs in our sample and relates the cross-sectional dispersion in adoption rates to these measures. We then model the dynamics of diffusion directly. Section 4 is a brief conclusion.

## 2 The dynamics of energy efficiency in buildings

As a proxy for the diffusion of energy-efficient technology in building, we use the certification of Energy Star and LEED building standards across the United States. As noted previously, these systems measure different aspects of “sustainability.” An Energy Star certification is based solely upon verification of energy use by a professional engineer and upon the results of a statistical comparison of usage with “otherwise identical” buildings by DOE. LEED certification is based upon six criteria for “sustainability,” including one measuring energy use and atmospheric discharges.<sup>7</sup>

---

<sup>7</sup> There is some discussion on the importance of energy efficiency in LEED-certified buildings. A recent study, based on 100 LEED-certified buildings, finds that LEED buildings use 18–39% less energy on average, per square foot, than their conventional counterparts. Despite this, it was also estimated that 28–35% of LEED buildings used more energy than their conventional counterparts (Newsham et al. 2009).



**Fig. 1** LEED and Energy Star dynamics (1995–2010) **a.** Extent of certified office space **b.** Fraction of certified office space

The criteria are hardly mutually exclusive, and the owners of a number of buildings certified by one program apply for and receive certification by the other. We specifically focus on commercial structures rather than public buildings, as investment decision making for the latter may arise from motives other than increases in financial returns.

We accessed the data files maintained by the EPA and USGBC and aggregated the number of buildings and the volume of Energy Star and LEED-certified buildings reported annually by metropolitan area, for the period 1995–2010. Figure 1A presents the growth in energy-efficient office space in the United States. Clearly, the adoption of the Energy Star certificate is quite a recent phenomenon among commercial office buildings, with acceleration in growth since 2005. The economic downturn is reflected, perhaps, in the slower growth rate since 2008—an indication of a decline in new construction or a reduction in energy-efficient investments. The second figure reports analogous information for LEED-certified office space. The market adoption of the LEED system started somewhat later, but has been increasing rapidly during the past years, without any apparent slowdown during the recent recession in property markets.

We estimate the importance of energy-efficient office space in the private market using information on the size of commercial property markets across MSAs from CBRE Econometric Advisors (CBRE-EA).<sup>8</sup> This information includes time series measures of the stock of space, average contract rents and property prices, and the average vacancy rates for various property types including office, warehouse, apartment, retail, and hotels.

Figure 1B presents the aggregate diffusion curves of Energy Star and LEED certification for the 48 US metropolitan areas as of October 2010.<sup>9</sup> The growth in certified space is the result of three different processes: retrofits of existing buildings, the installation of more efficient technologies in newly constructed buildings, and the demolition of obsolete and inefficient buildings. Energy Star–certified buildings are currently about 10% of the total office market, but measured by the volume of space, the fraction is three times as high—some 30%. The apparent relationship between the adoption of energy-efficient technology and building size corroborates more general evidence on technology diffusion; larger companies and production facilities are more likely to adopt new technologies and to adapt more quickly to changed circumstances (DeCanio and Watkins 1998; Snyder et al. 2003).

The diffusion curve for Energy Star–labeled space follows the well-documented S-shaped pattern of innovation diffusion (Griliches 1957), although the maximum adoption rate for Energy Star will never reach 100%—recall that, by design, the Energy Star label may be awarded only to the top 25% of buildings in the US as ranked by energy efficiency.

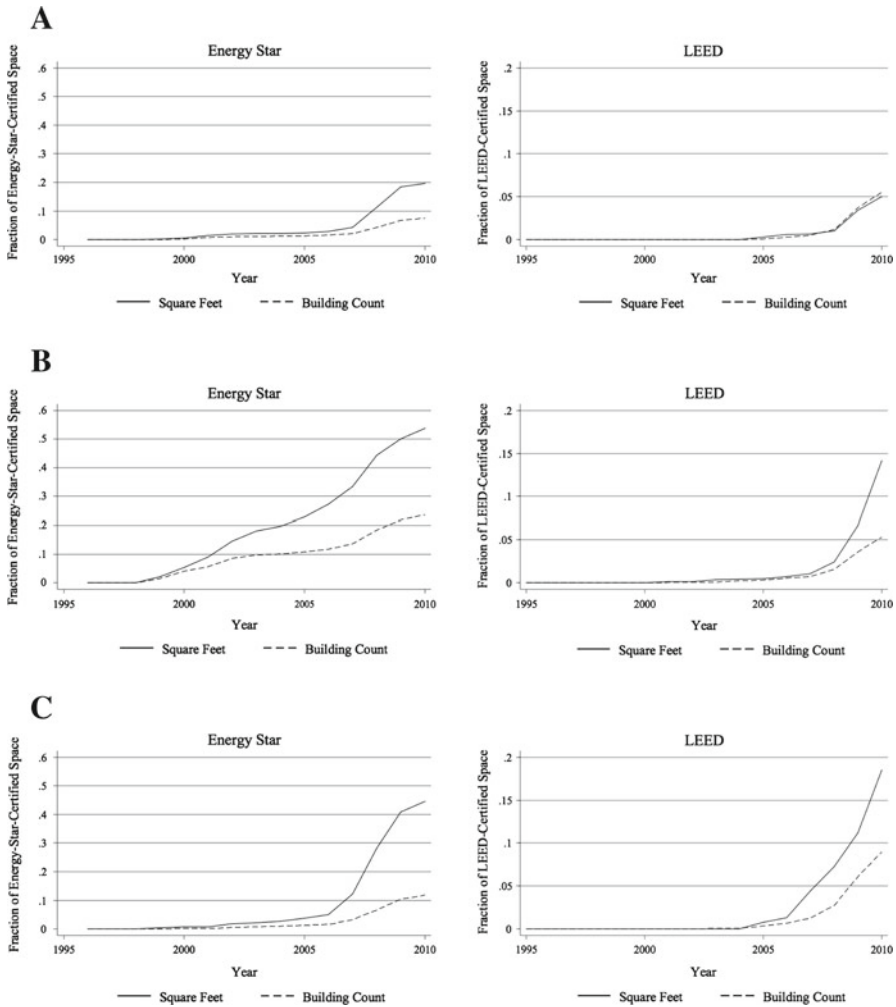
The right-hand figure shows that the diffusion of LEED-certified space is still in early stages, although some 5% of all buildings and 11% of the total volume of office space covered by CBRE-EA had been certified by the USGBC as of October 2010. The later start of the LEED system and its initial focus on new construction help explain the relatively slow diffusion rate.

Figure 2 reports the diffusion curves for a selection of US metropolitan areas. The timing of adoption and growth in space designated as energy efficient differs quite substantially across metropolitan areas. More than half of the total office stock in Los Angeles (as monitored by CBRE-EA) has been awarded an Energy Star label, with labeling starting as early as 1999. In most of the selected MSAs, the fraction of Energy Star–rated office space is well above 20% (with the exception of New York, at 19%), even though the fraction of certified buildings is roughly 10% in most places.

---

<sup>8</sup> CBRE Econometric Advisors (CBRE-EA), a subsidiary of CB Richard Ellis, is a major provider of research services to owners and investors in the US and Canadian commercial real estate markets. We utilize information from their “Building Stock Database.” For more information see: <https://www.cbre-ea.com>.

<sup>9</sup> We note that the CBRE Building Stock Database is confined to buildings that are considered “competitive”—this criterion is related to building size and differs by market. For example, most markets have a building size of 10,000 sq. ft. as one of the criteria for “competitive,” but in New York it is higher, at 50,000 sq. ft. As a result, the estimated fractions of energy efficient space presented in this paper are biased upwards, by at least by some small amount. An impediment to time series research on real estate markets is the lack of reliable, systematic time-series information. To our knowledge, the CBRE database is the only consistent source of this information.



**Fig. 2** LEED and Energy Star dynamics, fraction of certified office space across selected metropolitan markets (1995–2010) a. New York b. Los Angeles c. Chicago d. Washington e. Dallas f. Phoenix

There is also substantial variation between the initial start and the consequent growth in the diffusion of LEED labels across different markets. Clearly, Chicago and Phoenix are early adopters of the LEED system (as a fraction of the total market), whereas the adoption of LEED-certified space started much later in areas like New York and Dallas. In Sect. 3, we explore these differences in timing, which may be related to local economic geography, politics, and regulation. In addition, of course, areas with more recent development are also more likely to have higher fractions of “green” space.



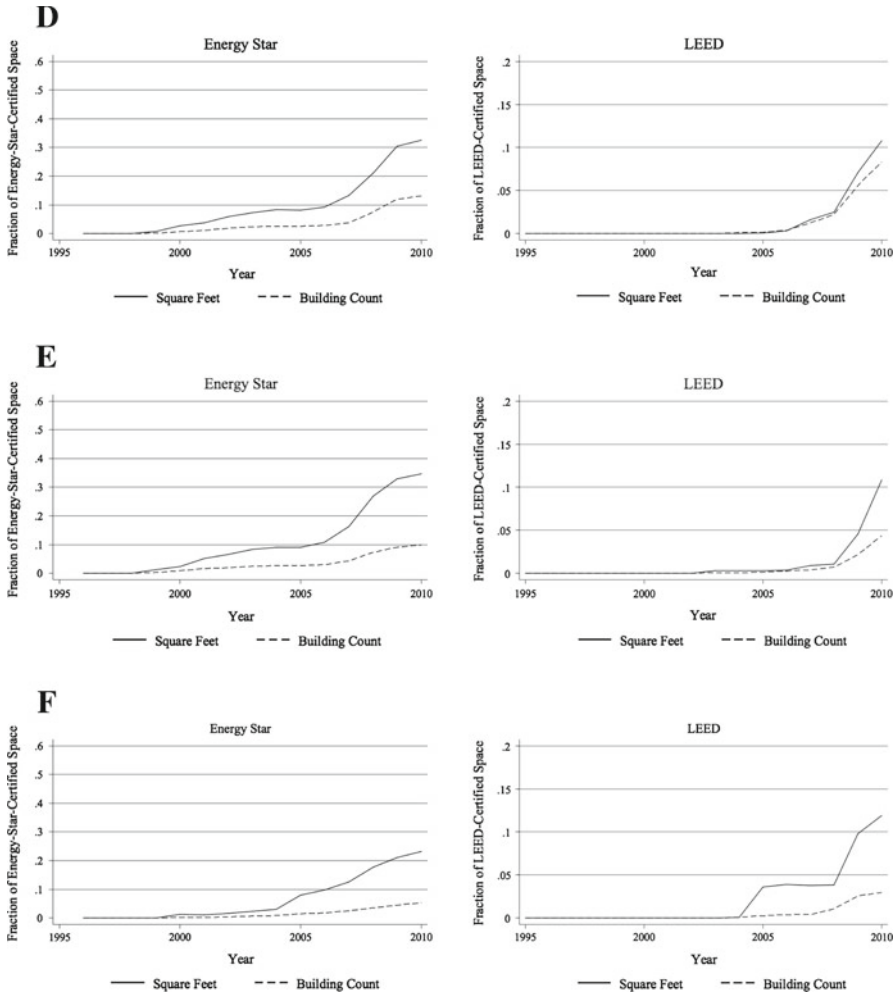


Fig. 2 continued

### 3 Explaining the diffusion of energy efficiency

#### 3.1 Data

As noted above, there is a substantial geographic dispersion in the timing and growth of energy-efficient technology as embedded in office buildings. This variation in diffusion may be explained by: variations across buildings and property markets in the expected cost savings from adopting energy-efficient innovations; variations in local economic conditions that affect the appropriability of gains; and other characteristics that influence the expected profitability of the adoption of the energy-efficient innovations. Of course, political and institutional characteristics, such as regulation and ideology, may also play an important role in explaining the adoption of energy-efficient

innovations. In this section, we relate metropolitan-specific variations in industry composition, economic conditions, characteristics of the local commercial property market, and the availability of building professionals (e.g., architects), to the cross-sectional variation and growth in certified space, using the following measures:

*Climatic conditions.* We expect that areas with more adverse climatic conditions will be more likely to adopt energy-efficient building practices, as the expected economic payoff of these technologies is larger. We employ data on cooling and heating degree-days by MSA as a general proxy for weather.<sup>10</sup>

*Energy prices.* There is a strong presumption, and a modicum of empirical evidence, that construction practices are more energy-efficient during periods of higher energy prices (Brounen et al. 2011.) We expect that the adoption of technologies leading to Energy Star and LEED certification increases with the price and the expected future price of electricity (which is the major part of the energy-mix consumed in commercial buildings), as the economic return to equivalent investments improves with higher energy prices, *ceteris paribus*. Moreover, Energy Star certification is based directly on the quantities of energy consumed. Assuming a price elasticity of energy demand in commercial space that is comparable to residential dwellings, we would expect significantly lower energy consumption in more expensive areas (Reiss and White 2008). We exploit average electricity prices by MSA by year, based on utility data reported by county.<sup>11</sup>

*General economic conditions and industry composition.* The financial payoff from energy efficiency should be related to conditions in the property market, but more-or-less independent of other general economic conditions in a metropolitan area. However, it is sometimes argued that “green” is a luxury good, or one which provides a “warm glow,” and thus the adoption of more sustainable building technologies may be related to local prosperity (Roe et al. 2001). We employ two measures of income: per capita personal income, and the average wages and salaries both reported for the MSA.<sup>12</sup>

Market demand by firms, industries, and labor for the adoption of energy-efficient innovations may influence the speed of diffusion. Many local jurisdictions have mandated “green” procurement policies that sometimes include the commercial space rented by the public sector. We expect a positive relationship between the relative size of the government and the demand for more energy-efficient space. We measure the relative importance of government in each metropolitan area by the number of people employed by local, state, and federal governments, as a fraction of total employment in the MSA.

Also, it is argued that some of the ancillary (but hard-to-measure) benefits of “green” building, such as improved employee productivity through superior indoor air quality, may benefit the space-intensive service sector in particular. (See Eichholtz et al. 2010b,

<sup>10</sup> See National Weather Service, National Center for Environmental Prediction, Climate Prediction Center, [http://www.cpc.noaa.gov/products/analysis\\_monitoring/cdus/degree\\_days/](http://www.cpc.noaa.gov/products/analysis_monitoring/cdus/degree_days/).

<sup>11</sup> See US Energy Information Administration, <http://www.eia.doe.gov/ceanf/electricity/page/eia861.html>.

<sup>12</sup> Bureau of Economic Analysis, Regional Data Products, Regional Economic Information DVD, <http://www.bea.gov/regional/docs/reis2008dvd.cfm>.

for a discussion.) We define the importance of the service sector as the aggregate number of jobs in “financial activities,” “professional and business services,” “information,” and “other services,” as a fraction of total employment in the MSA.<sup>13</sup>

*Property market conditions.* The characteristics of the property market surely affect the diffusion of energy-efficiency technologies in building. First, as noted above, several studies have documented a price premium for office space certified by the EPA or by the USGBC. However, there seems to be an inverse relationship between location rents and the size of this premium. This may suggest that the signal conveyed by energy labels is more valuable in markets with weaker fundamentals (Eichholtz et al. 2010a).

Second, we expect that the adoption of Energy Star and LEED certificates is positively related to new construction in a metropolitan area, as local building codes and federal energy-efficiency requirements progress and as building technology makes investments in energy efficiency more attractive. As market professionals report, new construction starts are dependent on the “stage” of the property cycle, i.e., upon market fundamentals such as the vacancy rate and rental levels, and their rates of change.

Finally, the adoption of energy efficiency in commercial real estate may also be a function of size, as suggested strongly by the findings on technology diffusion in other industries (Snyder et al. 2003).

We measure the characteristics of the local property market by: the total office stock, the average vacancy rate (vacant space as a percentage of the property type), the average rental price (that is, the lease for office space in the average building, corrected for the hedonic characteristics of properties), and the average property price (estimated for a 100,000 square foot building and derived from the average rent, the vacancy rate and the prevailing capitalization rate in the MSA).<sup>14</sup>

*Building Professionals.* The design and construction of energy-efficient commercial space require specific technical knowledge, supplied by architects and engineers among others. In fact, the human infrastructure developed around the LEED program is quite substantial; as of November 2010, more than 150,000 designers, contractors, and consultants had earned the designation “LEED Accredited Professional” (LEED AP). We measure the availability of “human capital” by the number of LEED APs registered by MSA and year and by the number of architecture graduates within the MSA from schools with NAAB-accredited programs.<sup>15</sup> The pool of local experts—building professionals and those specifically trained in sustainable technology—may help overcome one of the most important barriers to the diffusion of technology identified by Hall (2004): the availability of professional or business channels to acquire specific information about an innovation, its cost, its technical properties, are likely to affect adoption and productivity.<sup>16</sup>

<sup>13</sup> Bureau of Labor Statistics, NAICS based Quarterly Census of Employment and Wages (QCEW) data, <ftp://ftp.bls.gov/pub/special.requests/cew/>.

<sup>14</sup> All of these data were obtained from CBRE Econometric Advisors.

<sup>15</sup> See editions 5–8 of the *Guide to Architecture Schools*, Washington, DC: Association of Collegiate Schools of Architecture Press.

<sup>16</sup> See Green Building Certification Institute, <http://www.gbci.org/>, and National Architecture Association Board, <http://www.naab.org/>.

*Political Ideology.* There is a growing literature on the role of ideology in consumer choice. In particular, there is strong evidence that “green” consumers are predisposed to adopt environmental innovations, and that they are more responsive to energy conservation “nudges” (Kahn 2007; Costa and Kahn 2010a). In a similar spirit, one may expect political ideology to influence the adoption of energy efficiency and “green” technologies in commercial building across US metropolitan areas. We measure the dominant political preferences in each MSA by the percentage vote for Ronald Reagan in 1984 and the percentage vote for George H.W. Bush in 1988 by MSA.<sup>17</sup>

*Regulation and Incentives.* Government policies, such as regulation and incentives, may also play an important role in explaining the growth in adoption of energy-efficient innovations (see Jaffe and Palmer 1997). Some cities, counties, and states have adopted specific policies to stimulate “green” construction. The pattern is diverse, and policies range from “fast-tracking” building permits for LEED-certified developments, to subsidies and tax credits for energy-efficiency innovations, to specified minimum LEED performance standards. The US Green Building Council registers policies related to “green” building, at the city, county, and state level, even though it does not distinguish between the importance or the type of policy.<sup>18</sup> We construct a simple measure of the “intensity” of green building-related policies by aggregating LEED-related government policies by MSA by year.

### 3.2 Cross-sectional evidence on the diffusion of energy efficiency

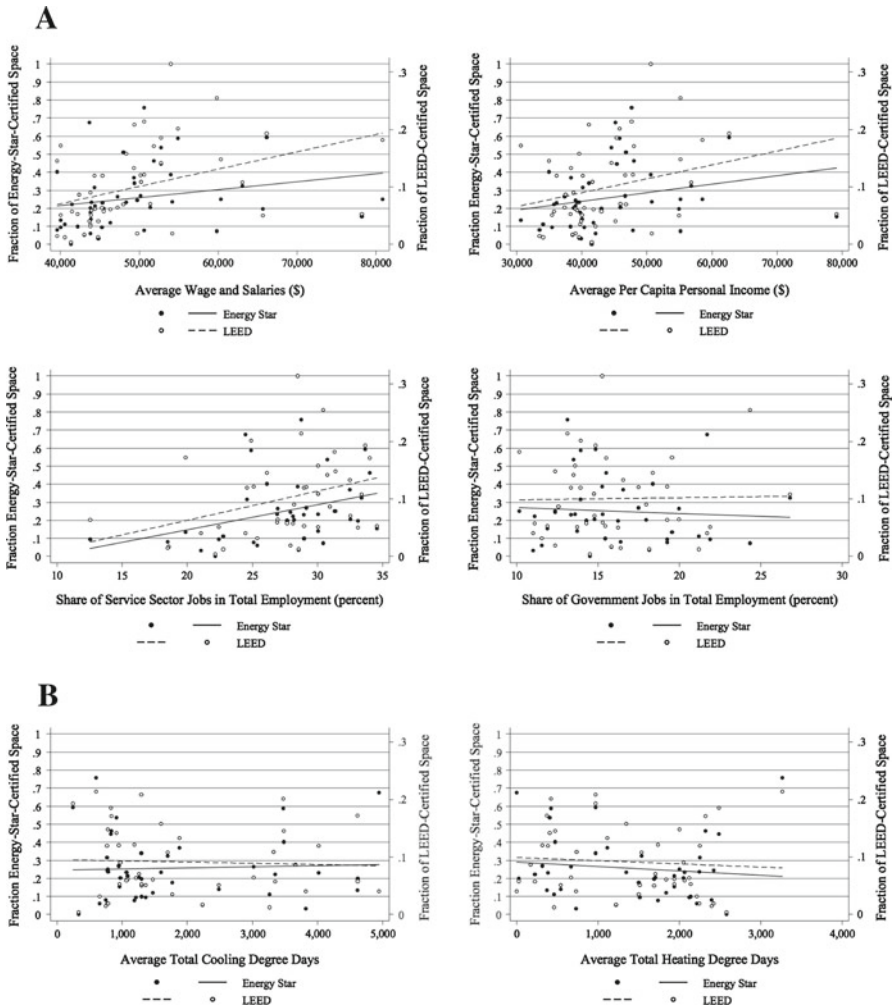
We first relate the 2010 cross-section measures of the diffusion of energy-efficient technology—the fraction of space certified by Energy Star or LEED—to lagged values of the various measures of local economic conditions. Figure 3 presents a series of scatter plots reporting the bivariate relationship between these variables and the adoption of sustainable building technologies. The figures indicate the cross-sectional variation in the diffusion of Energy Star-certified space and LEED-certified space, as a fraction of the total office stock, as well as a fitted regression line.

Panel A presents measures of general economic conditions and industry composition. Both measures of personal income are positively related to the adoption of energy-efficient (Energy Star) and sustainable (LEED) construction practices. The scatter diagrams are consistent with empirical evidence reporting the positive association between income and the willingness to pay for environmental goods (Roe et al. 2001) and the correlation between income and the support for public environmental spending (Elliott et al. 1997).

If higher incomes are related to value-added per employee, companies may also be more like to adopt “green” space—it is claimed that firms demonstrating a positive attitude toward the natural environment are considered more attractive employers than otherwise comparable firms without such a demonstrated attitude (Bauer and Aiman-Smith 1996). As human capital is increasingly viewed as a key source of value creation

<sup>17</sup> See CQ Press Electronic Library, <http://library.cqpress.com/elections/export.php>.

<sup>18</sup> See <http://www.usgbc.org/PublicPolicy/SearchPublicPolicies.aspx?PageID=1776>.



**Fig. 3** Correlates of the diffusion of energy efficiency in building, 2010 **a.** Income and employment **b.** Climatic conditions **c.** Property market characteristics **d.** Energy prices **e.** Building professionals **f.** Ideology **g.** Government policies on green building

in modern firms (Zingales 2000), “green” real estate may be a visible signal of a firm’s environmental policy and might thus contribute to a firm’s success in attracting better workers.

This argument may also explain the positive relationship between the share of jobs in the service sector and the adoption of energy efficiency in commercial buildings, reported in the lower-left graph of Fig. 3a.

The importance of the government in the metropolitan job market seems unrelated to the adoption of LEED-certified space and also to the adoption of energy-efficient technologies in the office market. The scatter diagram suggests that in markets where

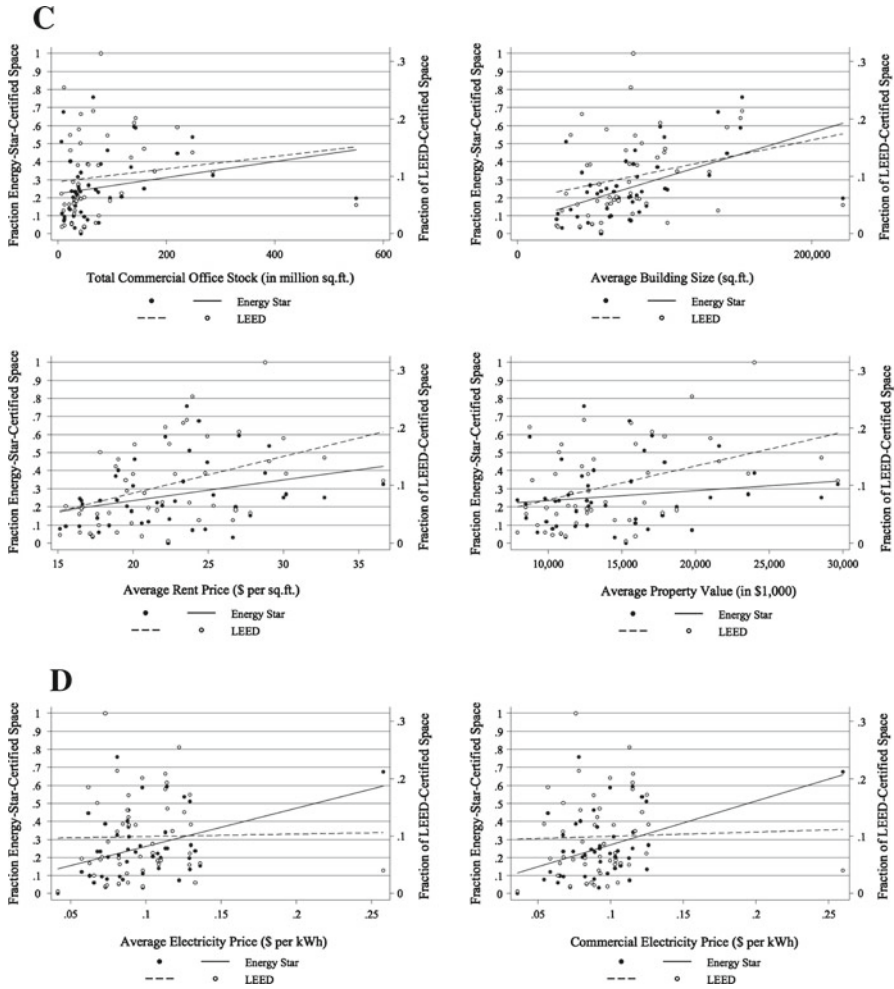


Fig. 3 continued

the government is a more important tenant, the average observable energy efficiency of buildings is lower.<sup>19</sup>

Panel B shows the bivariate relationship between climatic conditions and the adoption of Energy Star and LEED certificates across MSAs. One would expect the economic payoff from energy-efficiency investments to be positively related to heating and cooling degree-days, but surprisingly, the energy efficiency of building technology seems unrelated to more challenging climatic circumstances.

In Panel C, local property market characteristics are related to the diffusion of energy efficiency in commercial buildings. Larger property markets have higher fractions of

<sup>19</sup> Note, however, that a large share of space occupied by local, state and federal government is in illiquid, owner-occupied buildings, which are not reported in our data.

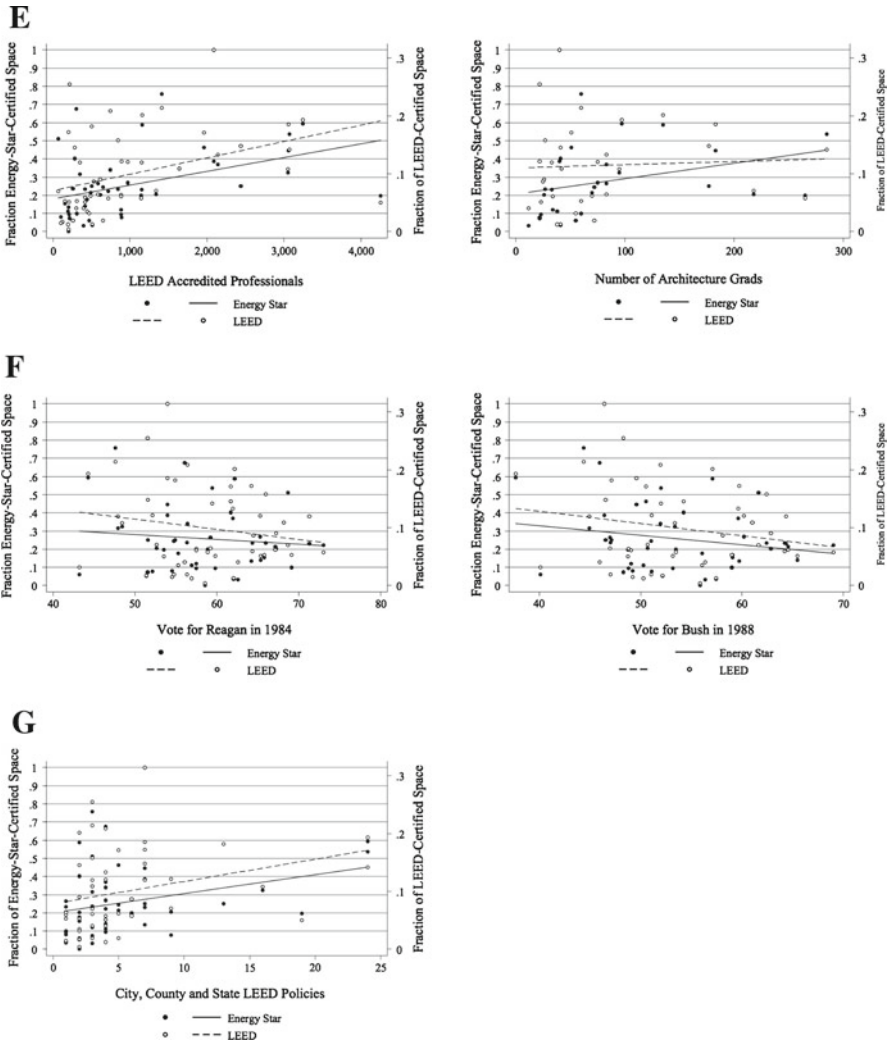


Fig. 3 continued

energy-efficient and “green” space, and the average volume of commercial property available is positively related to the diffusion of Energy Star and LEED certificates. The effect of size may be associated with distributing fixed costs over a wider base, as well as larger (absolute) payoffs of energy-efficient improvements—as suggested in the literature on firm size as a determinant of technology diffusion (DeCanio and Watkins 1998; Rose and Joskow 1990). Larger size may also be associated with lower costs in the diffusion of technical knowledge, as suggested by Hall (2004).

The adoption of energy-efficient and “green” technology in building is positively related to average office rents and values. These results are an indication that investments in energy-efficient technologies are more likely under more favorable property

market fundamentals. We note that the relationship between rents and values, and technology adoption rates may also be quite spurious, as unobservables such as vintage and building quality are positively related to rents, prices, and the adoption of energy labels.

Panel D presents the simple correlation between commercial electricity prices in local markets and the diffusion of technologies resulting in Energy Star and LEED certification. There is a strong and positive association between commercial electricity prices and the adoption of energy-efficient technologies, which is consistent with conventional investment theory—the economic return to energy-efficient investments improves with higher energy prices, *ceteris paribus*. A case in point is Hawaii, the outlier at the top right of the graph. Electricity prices in Hawaii are consistently the highest in the country, and building owners in Hawaii have expended considerable efforts to reduce energy consumption in commercial buildings.

Note that we find practically no relationship, at least no simple and direct relationship, between energy prices and the adoption of “sustainable” building standards. The LEED standard signals more than energy efficiency alone—if it measures energy efficiency at all (Newsham et al. 2009; Scofield 2009). Alternatively, there may be sufficiently strong non-financial utility for property investors and tenants motivating the adoption of sustainable building standards, as suggested by hypotheses about the voluntary private provision of public goods (see Matthew J. Kotchen 2006, for a discussion.)

Panel E relates the dispersion of energy-efficient buildings to the presence of trained building professionals across MSAs. Both Energy Star and LEED certification are positively related to the number of architects and engineers that are officially accredited by the Green Building Certification Institute (GBCI)—this form of professional training is specific to “green” building technology. (Alternatively, it is certainly possible that this skilled labor simply sorts into places where demand and compensation for the specific skill is highest.)

In Panel F, we relate political preferences in the metropolitan area to the adoption of energy-efficient technology in commercial buildings. Our measures of ideology, the percentage vote for Reagan in 1984, and the percentage vote for Bush in 1988 are negatively related to the adoption of environmental technologies. This finding confirms recent research on consumer choice and environmental ideology. This research has documented the extent to which political preferences are moderating factors in the effectiveness of energy efficiency outreach programs by utilities (Costa and Kahn 2010a), in general perceptions of environmental issues (Kahn and Kotchen 2010), and in the “green” consumption behavior of consumers as well.

Panel G relates “green” building policies to the adoption of energy efficiency and “sustainability” in commercial real estate. Quite clearly, there is a positive correlation between policies and the diffusion of “green” space—public regulation and incentives stimulate more energy-efficient building. This is consistent with the work of Jaffe and Palmer (1997), who document a positive effect of environmental compliance on R&D expenditures (offering some support for the “Porter hypothesis” on environmental regulation and economic performance). Interestingly, our proxy for environmental regulation and policies is also associated with higher fractions of energy-efficient space, even though the measure is based on LEED-related policies only.



Of course, all these inferences above are drawn from a perilously small sample—48 observations on US metropolitan property markets observed in 1 year—and they ignore the presence of other observables that may explain the variation in the adoption of energy efficiency in building.

### 3.3 Dynamic evidence on the diffusion of energy efficiency

We exploit the dynamics in the dispersion of energy-efficient office space across metropolitan areas. First, we model the dynamic relationship between the diffusion of labeled office space over time and geographical markets in a straightforward manner:

$$Fraction_{it} = \alpha + \beta \mathbf{X}_{it-2} + \varepsilon_{it}, \quad (1)$$

where  $Fraction_{it}$  is the fraction of certified office space,  $\mathbf{X}_{it-2}$  is a vector of metropolitan incomes, energy prices, and property market characteristics. We use a two-year lag of the explanatory variables to account for the real time necessary to complete property renovations and new property development. To address the fact that the pattern of diffusion of energy efficiency and “sustainability” in buildings is highly autocorrelated, we estimate equation (1) using a simple model of first-order serial correlation, AR(1), estimated efficiently by feasible generalized least squares (FGLS).

Second, we model the dispersion of energy-efficiency labels across time and space using first differences, which controls for time-invariant unobserved effects specific to MSAs:

$$\Delta Fraction_{it} = \alpha + \beta \Delta \mathbf{X}_{it-2} + \varepsilon_{it} \quad (2)$$

Third, to account for possible endogeneity of the independent variables, we report more general results following the [Arellano and Bond \(1991\)](#) procedure, where all covariates are instrumented by their own lagged values in a GMM estimation.

Table 1 summarizes the relationship between the diffusion of energy-efficient office space and a few presumed key economic determinants of the adoption of energy-efficient buildings: income, energy prices, and a crude summary of property market characteristics. Panel A presents predictions about the diffusion of Energy Star certification across the 48 MSAs; Panel B presents predictions about the diffusion of LEED certification. Columns (1) and (2) report the relationship in levels; the dependent variable is the fraction of space certified as energy efficient by MSA and year, Columns (3) and (4) present the same models in first differences (to control for time-invariant unobservables in the diffusion of energy labels in the office sector), and Columns (5) and (6) report more general results using the Arellano-Bond GMM estimation.

Panel A shows that income is important in explaining the diffusion of Energy Star-certified buildings over space and time. In areas with higher income levels and stronger income growth, adoption of energy-efficient building practices, as reflected in the fraction of labeled space, is significantly higher. In five of the six regressions explaining the diffusion of Energy Star certification over space, the price of commercial electricity is highly significant, with an estimated price elasticity of about 0.6. The measure of the relative size of the property market is significant in two of the six specifications, but coefficients are ambiguous.

**Table 1** Basic regression results (dependent variable: fraction of certified commercial office space)

	Levels		First differences		Arellano-Bond	
	Linear	Log-log	Linear	Log-log	Linear	Log-log
<i>A. Energy star</i>						
Income (\$ thousands)	0.005*** [0.001]	4.750*** [0.273]	0.005*** [0.001]	3.395*** [0.710]	0.003*** [0.000]	3.450*** [0.388]
Average electricity price (\$ per kWh)	0.913*** [0.133]	0.558*** [0.166]	0.538*** [0.113]	0.105 [0.174]	0.317** [0.140]	0.623*** [0.192]
Office space/worker (sq. ft.)	0.000 [0.000]	-0.238*** [0.084]	-0.000 [0.000]	0.037 [0.032]	0.000** [0.000]	-0.021 [0.072]
Fraction rated space <sub>t-1</sub>	-	-	-	-	-0.135*** [0.017]	-36.466*** [4.424]
Constant	-0.357*** [0.041]	-50.430*** [3.021]	0.002 [0.002]	-0.080 [0.166]	0.898*** [0.025]	0.409*** [0.045]
Observations	768	493	768	445	768	397
Wald Chi <sup>2</sup>	72.30	396.8	63.25	24.29	7,842	4,376
AR(1) coefficient	1.022	0.837	0.398	0.064	-	-
Sargan test	-	-	-	-	320.0	127.5
<i>B. LEED</i>						
Income (\$ thousands)	-0.003*** [0.000]	8.726*** [0.903]	-0.000 [0.000]	1.252 [2.787]	0.001*** [0.000]	10.112*** [1.016]
Average electricity price (\$ per kWh)	-0.027 [0.046]	0.416 [0.456]	-0.050 [0.033]	-0.584 [0.641]	0.123 [0.099]	1.070 [0.794]
Office space/worker (sq. ft.)	-0.000 [0.000]	-0.111 [0.160]	-0.000** [0.000]	-0.213** [0.098]	-0.000 [0.000]	-0.340 [0.239]
Fraction rated space <sub>t-1</sub>	-	-	-	-	1.223*** [0.042]	0.307*** [0.045]
Constant	0.064*** [0.008]	-95.938*** [10.192]	0.005*** [0.001]	1.697*** [0.514]	-0.055*** [0.010]	-106.616*** [11.698]
Observations	768	290	768	239	768	194
Wald Chi <sup>2</sup>	136.4	141.3	7,311	5,607	1,533	952.1
AR(1) coefficient	1.145	0.843	0.753	0.095	-	-
Sargan test	-	-	-	-	245.5	92.50

Surprisingly, the results documented in Panel B suggest that the price of energy is essentially irrelevant to the geographical and temporal variation in the diffusion of LEED-certified office space. The measures of income are significant in four of the six specifications, and the diffusion of LEED certification appears to be highly income elastic. The measure of property market conditions is significant in the first

differences models only—in markets with a larger supply of office space per employee in the service sector, the adoption of energy-efficient technologies is higher.

These differences in the regression results may be implied by differences in the criteria employed for the award of Energy Star and LEED certification. Energy Star certification is awarded exclusively for energy efficiency in building operation; this is clearly more important in property markets in which the price of energy is higher. LEED certification is based on a variety of aesthetic features of building, and energy efficiency is less important. These features are apparently more important in metropolitan areas where incomes are higher, which may be related to the positive association between income and the willingness to pay for environmental goods (Roe et al. 2001). Also, the ancillary benefits of LEED certification may be more valuable in areas where incomes, and thus the average value-added per employee, are higher. Energy prices are not particularly important in explaining the cross-sectional diffusion of LEED-labeled buildings.

Table 2 presents a series of models in which several additional variables are included as regressors. The variable measuring personal income is excluded from these models, because it is strongly related to some of the other variables. (Likewise, correlation across covariates inhibits estimation of fully specified models.) Columns (1) through (4) report results for the diffusion of Energy Star-certified space, and Columns (5) through (8) report results for the adoption of LEED certification in office buildings.<sup>20</sup>

Column (1) provides some evidence that Energy Star certification has increased in markets with lower unemployment rates. Higher demand for office space, leading to more favorable conditions in the property market (and more new construction), clearly affects the diffusion of energy-efficient technologies in building. This is also reflected in the positive and significant (albeit weakly significant) coefficient for the share of service sector jobs in the local economy—more white-collar jobs means higher demand for office space and higher adoption rates of energy-efficient technologies in the commercial office sector across space and time.

Of course, we can also measure the conditions in the commercial property market directly. Column (2) includes the (lagged) vacancy rate and average property values across MSAs and over time. The adoption of energy-efficient and “green” building practices is more likely in more healthy property markets, with lower vacancy rates and higher average property values. The expected payoff from investments in energy efficiency increases with lower volatility in occupancy rates, and the dollar amount of the value increment that “green” buildings may command in the marketplace is more significant if property prices are higher. Naturally, lower vacancy rates will also trigger new construction, which may also increase the fraction of “green” space.

In column (3), we evaluate the impact of climatic conditions and building professionals on the diffusion of Energy Star certification. The energy efficiency of building technology is unrelated to more extreme climatic circumstances, even though the return to energy-efficiency investments is expected to be positively related to heating and cooling degree-days. The presence and growth of “human capital” are negatively related to the diffusion of energy-efficient space. Our proxy measures the number

<sup>20</sup> Results are reported for linear GMM models only. Logarithmic results and results from GLS estimations accord largely with the findings reported here, and are available upon request.

**Table 2** Arellano-Bond GMM Regression Results (dependent variable: fraction of certified commercial space)

	Energy star			LEED				
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Unemployment rate (percent)	-0.631*** [0.113]				-0.269*** [0.074]			
Share of government jobs (percent)	-0.070 [0.049]				-0.016 [0.031]			
Share of service sector jobs (percent)	0.097* [0.057]				0.022 [0.036]			
Commercial vacancy rate (percent)		-0.001*				-0.000**		
Average commercial property value (\$ million)		[0.000]				[0.000]		
Cooling degree-days (thousands)		0.002*** [0.001]				0.001*** [0.000]		
Heating degree-days (thousands)			0.005 [0.008]				0.007** [0.004]	
LEED-accredited professionals (Share of total population)			-0.009 [0.008]				0.000 [0.004]	
Local policies encouraging LEED (count)			-60.783* [33.691]				117.362*** [23.366]	
				0.001 [0.001]				0.003*** [0.000]

Table 2 continued

	Energy Star				LEED			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Average electricity price, (\$ per kWh)	0.421*** [0.147]	0.358** [0.151]	0.395** [0.189]	0.437*** [0.148]	0.260** [0.101]	0.208** [0.102]	0.100 [0.105]	0.174* [0.095]
Office space/worker (sq. ft.)	0.050*** [0.018]	0.024* [0.013]	0.028* [0.015]	0.025** [0.012]	0.001 [0.011]	-0.006 [0.008]	-0.005 [0.007]	-0.004 [0.007]
Constant	-0.016 [0.024]	-0.031** [0.014]	-0.019 [0.024]	-0.026** [0.011]	-0.008 [0.016]	-0.021** [0.010]	-0.020 [0.012]	-0.011 [0.008]
Observations	768	749	473	768	768	749	473	768
Wald Chi <sup>2</sup>	6,648	6,421	3,894	6,487	1,258	1,290	1,144	1,590
Sargan Test	307.0	309.7	209.9	327.7	245.3	237.4	164.8	242.7

of LEED-accredited professionals (standardized by total population), and this certification is apparently unrelated to engineering knowledge on energy efficiency in commercial buildings.

Column (4) relates the presence of LEED-related policies to the adoption of energy-efficient innovations, but there is no evidence of spillover effects of these specific regulations or of these incentives leading to more efficient building performance.<sup>21</sup>

Columns (5) through (8) present similar models to explain the diffusion of LEED-certified buildings across space and time. In common with the analysis for Energy Star, the adoption of LEED certification seems to be a consequence of income and property market fundamentals. Areas with higher wages and salaries have higher levels and stronger growth in “green” construction or retrofits. Higher vacancy rates and lower property values hamper to the diffusion of “green” building innovations.

Importantly, the number of building professionals trained to perform LEED audits has a positive effect on the growth of green space, as reported in Column (7). This finding supports the notion that the presence of professional or business channels to acquire specific information about an innovation and its technical properties is one of the most important determinants of technology diffusion (Hall 2004). Also, local policies designed to stimulate more “sustainable” building practices have a significantly positive effect on the diffusion of LEED-certified space, although we cannot distinguish between the effectiveness of regulations or other incentives.

## 4 Conclusions

Despite much discussion about the “energy paradox” in the built environment, the diffusion of energy efficiency and “sustainability” in building technology has been widespread and rapid. This paper documents this diffusion over time and across US property markets. By 2010, about 30% of all commercial office space in the 48 largest metropolitan areas was certified for energy efficiency by Energy Star. About 11% of office space was certified as sustainable by LEED. But there is considerable variation across metropolitan areas. In Los Angeles, for example, more than half of all commercial office space has been certified for energy efficiency.

The diffusion has been more rapid in metropolitan areas with higher incomes, and in those with sound property market fundamentals (for example, lower vacancy rates and higher property values). These findings have implications for those property markets across the United States that are faced with more dire economic conditions, such as Dallas, Detroit, and Tampa; these areas are expected to lag behind in the energy efficiency of their commercial office stock.

Importantly, the diffusion of energy-efficient technology in buildings is more responsive to energy prices than is the diffusion of buildings certified for “sustainability.” Commercial property markets—and, more specifically, building owners—seem to evaluate the impact of resource consumption upon the profitability of investment in real capital. This lends considerable support to the efficiency of energy investment

---

<sup>21</sup> There is an extensive discussion of reasons for inclusion of LEED performance standards in conventional building codes. But the voluntary LEED system was never intended to serve as government code.

decisions in the business sector, certainly compared to the “energy paradox” decried in the residential sector.

Finally, the diffusion of “green” space is facilitated by factors such as trained building professionals and governmental policies. LEED policies and the LEED professional education program seem to be effective in stimulating the growth of “green” space, but the consequences of this growth on the energy efficiency of the built environment remains unclear.

**Acknowledgments** Kok is supported by a VENI grant of the Dutch Organization for Scientific Research (NWO).

## References

- Alcott H, Mullainathan S (2010) Behavior and energy policy. *Science* 327:1204–1205
- Arellano M, Bond S (1991) Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *Rev Econ Stud* 58(2):277–297
- Bauer TN, Aiman-Smith L (1996) Green career choices: the influences of ecological stance on recruiting. *J Bus Psychol* 10(3):445–458
- Brounen D, Kok N, Quigley JM (2011) Residential energy use and conservation: economics and demographics. *Eur Econ Rev* (forthcoming)
- Costa DL, Kahn ME (2010a) Energy conservation ‘Nudges’ environmentalist ideology: evidence from a randomized residential electricity field experiment. NBER Working Paper #15939
- Costa DL, Kahn ME (2010b) Why Has California’s electricity consumption been so flat since the 1980s? A microeconomic approach. NBER Working Paper #15978
- DeCanio SJ, Watkins WE (1998) Investment in energy efficiency: do the characteristics of firms matter? *Rev Econ Stat* 80(1):95–107
- Eichholtz PMA, Kok N, Quigley JM (2010a) Doing well by doing good: green office buildings. *Am Econ Rev* 100(5):2494–2511
- Eichholtz PMA, Kok N, Quigley JM (2010b) Who rents green? Ecological responsiveness and corporate real estate. Working Paper. UC Berkeley, Berkeley
- Eichholtz PMA, Kok N, Quigley JM (2013) The economics of green building. *Rev Econ Stat* (forthcoming)
- Elliott E, Seldon BJ, Regens JL (1997) Political and economic determinants of individuals’ support for environmental spending. *J Environ Manag* 57:15–27
- Fuerst F, McAllister P (2009) New evidence on the green building rent and price premium. Working Paper. University of Reading
- Fuerst F, McAllister P (2011) Green noise or green value? Measuring the effects of environmental certification on office values. *Real Estate Econ* 39(1):45–69
- Griliches Z (1957) Hybrid corn: an exploration in the economics of technical change. *Econometrica* 25(4):501–522
- Hall BH (2004) Innovation and diffusion. In: Fagenberg J, Mowray D, Nelson RR (eds) *Handbook of innovation*. Oxford University Press, Oxford, pp 459–485
- Hausman JA (1979) Individual discount rates and the purchase and utilization of energy-using durables. *Bell J Econ* 10:33–54
- Jaffe AB, Palmer K (1997) Environmental regulation and innovation: a panel data study. *Rev Econ Stat* 79(4):610–619
- Jaffe AB, Stavins RN (1994) The energy paradox and the diffusion of conservation technology. *Resour Energy Econ* 16:91–122
- Kahn ME (2007) Do greens drive hummers or hybrids? Environmental ideology as a determinant of consumer choice. *J Environ Econ Manag* 54:129–145
- Kahn ME, Kotchen MJ (2010) Environmental concern and the business cycle: the chilling effect of recession. NBER Working Paper #16241
- Keller W (2004) International technology diffusion. *J Econ Lit* 42(3):752–782
- Menanteau P, Lefebvre H (2000) Competing technologies and the diffusion of innovations: the emergence of energy-efficient lamps in the residential sector. *Res Policy* 29(3):375–389

- Metcalf GE, Hassett KA (1999) Measuring the savings from home improvement investments: evidence from monthly billing data. *Rev Econ Stat* 81(3):516–528
- Newsham GR, Mancini S, Birt B (2009) Do LEED-certified buildings save energy? Yes, but.... *Energy Build* 41:897–905
- Oster SM, Quigley JM (1977) Regulatory barriers to the diffusion of innovation: some evidence from building codes. *Bell J Econ* 8(2):361–377
- Reiss PC, White MW (2008) What changes energy consumption? Prices and public pressures. *RAND J Econ* 39(3):636–663
- Roe B, Teisl MF, Levy A, Russell M (2001) Us consumers' willingness to pay for green electricity. *Energy Policy* 29(11):917–925
- Rose NL, Joskow PL (1990) The diffusion of new technologies: evidence from the electric utility industry. *RAND J Econ* 21(3):354–373
- Rosenberg N (1976) *Perspectives on technology*. Cambridge University Press, Cambridge
- Royal Institute of Chartered Surveyors (2005) *Green value*. RICS, London
- Scofield JH (2009) Do LEED-certified buildings save energy? Not really.... *Energy Build* 41:1386–1390
- Snyder LD, Miller NH, Stavins RN (2003) The effects of environmental regulation on technology diffusion: the case of chlorine manufacturing. *Am Econ Rev* 93(2):431–435
- Stern N (2008) The economics of climate change. *Am Econ Rev* 98(2):1–37
- Zingales L (2000) In search of new foundations. *J Finance* 55(4):1623–1653