The Diffusion of Energy Efficiency in Building

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Abstract
We analyze the diffusion of buildings certified for energy efficiency across US property markets. Using a panel of 48 metropolitan areas (MSAs) observed over the last 15 years, we model the geographic patterns and dynamics of building certification, relating industry composition, changes in economic conditions, characteristics of the local 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 is important for designing policies to affect resource consumption in the built environment.

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Long Version

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I. 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 (CFLs) in the residential sector (Philippe Menanteau and Hervé 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 discount rate applied to more energy-efficient appliances and durable goods was unreasonably high, approaching twenty percent. (See Jerry A. Hausman, 1979; see also Gilbert E. Metcalf and Kevin A. Hassett, 1999.) This contradiction, termed the "energy paradox" (Adam B. Jaffe and Robert N. Stavins, 1994), has regained currency in the recent debate on the role of buildings in carbon reduction and climate change; the durability of real capital implies that the building sector has large effects upon greenhouse gas emissions and upon energy use in the economy (Piet M.A. Eichholtz, Nils Kok and John M. Quigley, 2010a).[1]

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 (Hunt Alcott and Sendhil Mullainathan, 2010, Stephen J. DeCanio and William E. Watkins, 1998) -- recent trends suggest that the number of buildings 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 President 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."[2]

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[1] 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.*, Nicholas Stern, 2008).

[2] Speech of President Barack Obama, Savannah Technical College, GA, March 3, 2010.

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;[3] 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 nonprofit 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. The LEED certification process measures six distinct components of sustainability (one of which is energy performance).[4] 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 US. 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

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[3] 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.

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

5,000 square feet in size, or costing at least $2 million, to obtain a LEED Silver rating, and all new commercial buildings in San Francisco, CA, are now required to meet criteria for LEED Gold 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.

The growth of the LEED program is also substantial, with more than 6,500 commercial buildings (approximately 1 billion square feet) 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 U.S, up from two percent in 2005 (McGraw-Hill Construction, 2010). In addition, 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 percent less energy and emit 35 percent less carbon dioxide than average unlabeled buildings.[5] 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

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[5] See for more information: http://www.energystar.gov/index.cfm?c=business.bus_index.

LEED and Energy Star certification was limited, and it consisted mostly of anecdotal evidence and industry-initiated case studies.[6]

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 (Piet M.A. Eichholtz, et al., 2010a, F. Fuerst and P. McAllister, 2011). Moreover, among rated buildings, incremental energy savings are roughly capitalized into asset values (Piet M.A. Eichholtz, Nils Kok and John M. Quigley, 2010b).

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 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 (Nancy L. Rose and Paul L. 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. (Sharon M. Oster and John M. Quigley, 1977, Lori D. Snyder, Nolan H. Miller and Robert N. Stavins, 2003).

In this paper, we analyze the spread of energy-efficient technology in the built environment. "Technology" is itself difficult to measure, but the 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

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[6] 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).

buildings, the decision to label a building may be thought of as a noisy signal of adoption of more efficient technology and 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 Wolfgang 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. We analyze the geographic patterns and dynamics of building certification, relating industry composition, energy prices, 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 II discusses the data and describes the diffusion of Energy Star and LEED buildings in the US and in a number of large MSAs. Section III 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 IV is a brief conclusion.

II. 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 US. 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.[7] 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 office space reported annually by metropolitan area, for the period 1995-August 2010. Figure 1A presents the growth in energy-efficient office space in the US. 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).[8] 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.[9] The growth in

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[7] There is some discussion of 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 percent less energy on average, per square foot, than their conventional counterparts. Despite this, it was estimated that 28–35 percent of LEED buildings used more energy than their conventional counterparts (Guy R. Newsham *et al.*, 2009).

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

[9] 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

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 ten percent of the total office market, but measured by the volume of space, the fraction is three times as high -- some thirty percent. The apparent relation 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 (Stephen J. DeCanio and William E. Watkins, 1998, Lori D. Snyder, *et al.*, 2003).

The diffusion curve for Energy-Star-labeled space follows the well-documented S-shaped pattern of innovation diffusion (Zvi Griliches, 1957), although the maximum adoption rate for Energy Star will never reach 100 percent -- recall that, by design, the Energy Star label may be awarded only to the top twenty-five percent 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 five percent of all buildings and eleven percent of the total volume of office space covered by CBRE-EA had been certified by the LEED label 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 twenty percent (with the exception of New York, at nineteen percent), even though the fraction of certified buildings is roughly ten percent in most places.

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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.

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 Section III below, 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.

Appendix Table A1 reports the adoption rates for energy efficiency labels for the twenty-five largest commercial office markets in 2010. Variations in the market penetration of sustainable and energy-efficient building technology are substantial.

III. Explaining the Diffusion of Energy Efficiency

A. Data

As noted above, there is a substantial geographic dispersion in the timing and growth of energy-efficient technology as embedded in office buildings. In this section, we relate metropolitan-area-specific variations in industry composition, economic conditions, characteristics of the local commercial property market, the availability of building professionals (*e.g.*, architects), ideology and regulation, 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.[10]

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 (Dorah Costa and Matthew E. Kahn, 2010). 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

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[10] See National Weather Service, National Centers for Environmental Prediction, Climate Prediction Center, http://www.cpc.noaa.gov/products/analysis_monitoring/cdus/degree_days/

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 (Peter C. Reiss and Matthew W. White, 2008). To evaluate this hypothesis, we measure average electricity prices by MSA by year, based on utility data reported by county.[11]

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 (Brian Roe *et al.*, 2001). Hence, we employ two measures of income: per capita personal income and the average wages and salaries reported for the MSA.[12]

Market demand by firms, industries, and labor for the adoption of energy-efficient innovations may also 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 relation between the relative size of the government and the demand for more energy-efficient space. We measure the relative importance of government in a metropolitan area by the number of people employed by local, state and federal governments, as a fraction of total employment in the MSA.

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. (Piet M.A. Eichholtz, Nils Kok and John M. Quigley, 2010c) We define the importance of the service sector as the

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[11] See U.S. Energy Information Administration, http://www.eia.doe.gov/cneaf/electricity/page/eia861.html. Energy prices were constructed using revenue and sales data reported for each utility by the EIA. These data were mapped to counties and ultimately averaged by MSA (weighted by sales) to derive estimates of energy prices.

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

aggregate number of jobs in “financial activities,” “professional and business services,” “information,” and “other services,” as a fraction of total employment in the MSA.[13]

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 relation 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 (Piet M.A. 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. 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.

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 (Lori D. 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).[14]

Building Professionals. The design and construction of energy-efficient commercial space requires 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”

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[13] Bureau of Labor Statistics, NAICS based Quarterly Census of Employment and Wages (QCEW) data, ftp://ftp.bls.gov/pub/special.requests/cew/. We use the definitions of these sectors as provided by NAICS.
[14] All of these data were obtained from CBRE Econometric Advisors.

(LEED AP). We measure the availability of “human capital” in two ways. First, we measure the number of LEED APs registered by MSA and year. Second, we measure and aggregate the number of architecture graduates from programs accredited by the National Architecture Association Board (NAAB), within each MSA, by year. [15] The pool of local experts -- building professionals and those specifically trained in sustainable technology -- may help overcome one of the most important barriers to diffusion identified by Bronwyn Hall (2003): the lack of professional or business channels to acquire specific information about an innovation, its cost, its technical properties, and its likely impact on productivity.[16]

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” (Matthew E. Kahn, 2007, Matthew E. Kahn and Matthew J. Kotchen, 2010). 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 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.[17]

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 (Adam B. Jaffe and Karen Palmer, 1997, Jean Olsen Lanjouw and Ashoka Mody, 1996). Some cities, counties and states have adopted specific policies to stimulate “green” construction. The palette 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

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[15] See editions 5-8 of the *Guide to Architecture Schools*, Washington, DC: Association of Collegiate Schools of Architecture Press, and the 9th edition of the guide at http://www.archschools.org/guide_search/home.aspx. Our data was collected for graduates of NAAB-accredited programs in 1988,1993, 1997, 2003, and 2008.

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

[17] See CQ Press Electronic Library, http://library.cqpress.com/elections/export.php.

between the importance and type of each policy.[18] We construct a simple measure of the "intensity" of green-building-related policies by aggregating LEED-related policies by MSA by year.

B. 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 relation 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 (Brian Roe, *et al.*, 2001) and the correlation between income and the support for public environmental spending (Euel Elliott, Barry J. Seldon and James L. Regens, 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 towards the natural environment are considered more attractive employers than otherwise comparable firms without such a demonstrated attitude (Talya N. Bauer and Lynda Aiman-Smith, 1996). As human capital is increasingly viewed as a key source of value creation in modern firms (Luigi 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 relation 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 Figure 3A.

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[18] See http://www.usgbc.org/PublicPolicy/SearchPublicPolicies.aspx?PageID=1776.

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 the government is a more important tenant, the average observable energy efficiency of buildings is lower.[19]

Panel B shows the bivariate relation 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 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, and larger (absolute) payoffs of energy-efficient improvements -- as suggested in the literature on firm size as a determinant of technology diffusion (Stephen J. DeCanio and William E. Watkins, 1998, Nancy L. Rose and Paul L. Joskow, 1990). Larger size may also be associated with lower costs in the diffusion of technical knowledge, as suggested by Bronwyn H. Hall (2003).

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 relation between rents and values, and technology adoption rates may also be quite spurious, as unobservables such as age 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 relation between commercial electricity prices

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[19] 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.

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 in reducing energy consumption in commercial buildings.

Note that we find practically no relation 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 (Guy R. Newsham, Sandra Mancici and Benjamin Birt, 2009, John H. Scofield, 2009). Alternatively, there may be sufficiently strong non-financial utility for property investors and tenants in adopting sustainable building standards, as suggested by the thesis on private provision of public goods. (See Matthew J. Kotchen, 2006, for a discussion.)

Panel E indicates the dispersion of energy-efficient buildings and 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 skilled labor simply sorts into places where demand and compensation for their specific skills 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 (Dora L. Costa and Matthew E. Kahn, 2011), in general perceptions of environmental issues (Matthew E. Kahn and Matthew J. Kotchen, 2010), and in the actual “green” consumption behavior of consumers (Matthew E. Kahn, 2007).

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 Adam B. Jaffe and Karen Palmer (1997), who document a positive effect of environmental compliance on R&D expenditures. 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 U.S. metropolitan property markets observed in one year – and they ignore the presence of other observables that may explain the variation in the adoption of energy efficiency in building.

C. 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:

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

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 time necessary to complete property renovations and new property development. To address the fact that the pattern of diffusion of energy efficiency and "sustainability" technology 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:

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

Third, to account for possible endogeneity of the independent variables, we report more general results following the Arellano-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.

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.

The differences in the regression results reported in Panel A and Panel B may be implied by differences in the criteria employed for the award of Energy Star and LEED certification. Energy Star certification is based only upon 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 of lesser importance. 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 (Brian 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.[20]

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 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

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[20] 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.

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” is negatively related to the diffusion of energy-efficient space. Our proxy measures the number 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 efficiency innovations, but there is no evidence of spillover effects of these specific regulations and incentives leading to more efficient building performance.[21]

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 (Bronwyn Hall, 2003). Also, local

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[21] 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.

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.

IV. Conclusions

Despite much discussion about the “energy paradox” in the built environment, the diffusion of energy efficiency and “green” in technology in commercial building has been widespread and rapid. This paper documents this diffusion over time and across U.S. property markets. By 2010, about thirty percent of all commercial office space in the 48 largest metropolitan areas was certified for energy efficiency by Energy Star. About eleven percent 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 property markets across the US that face dire economic conditions, such as Dallas, Detroit and Tampa; these areas will 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 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, although the consequences of this growth on the energy demand from the built environment remains unclear.

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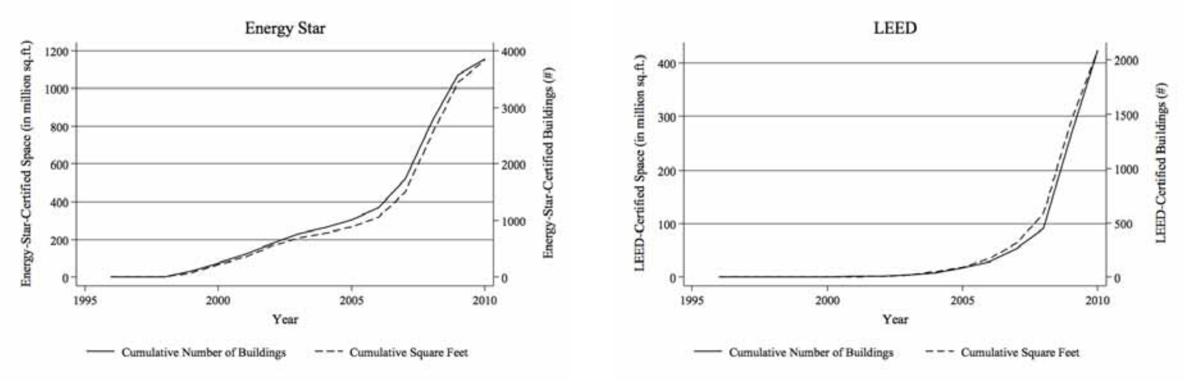
Figure 1
LEED and Energy Star Dynamics
(1995-2010)

A. Extent of Certified Office Space



B. Fraction of Certified Office Space

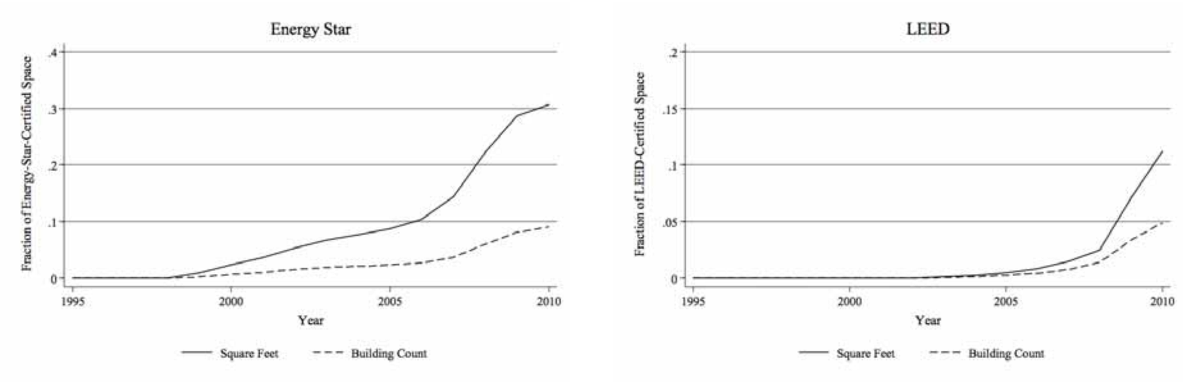
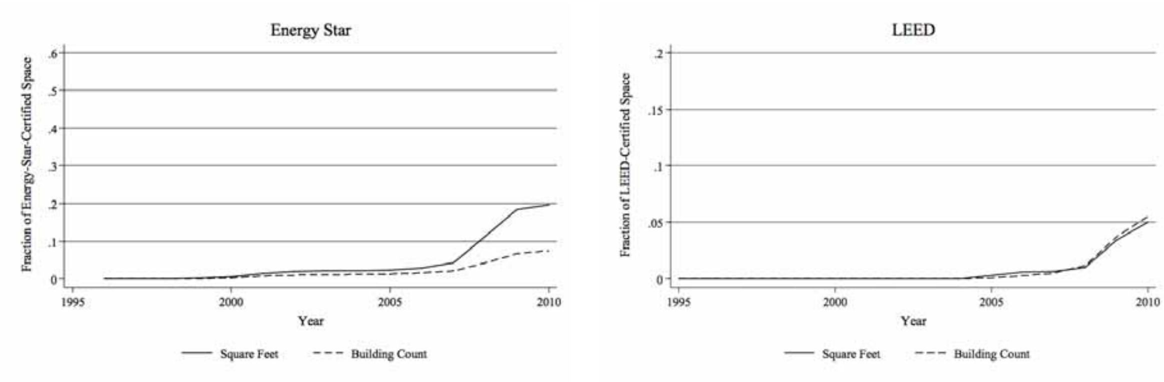
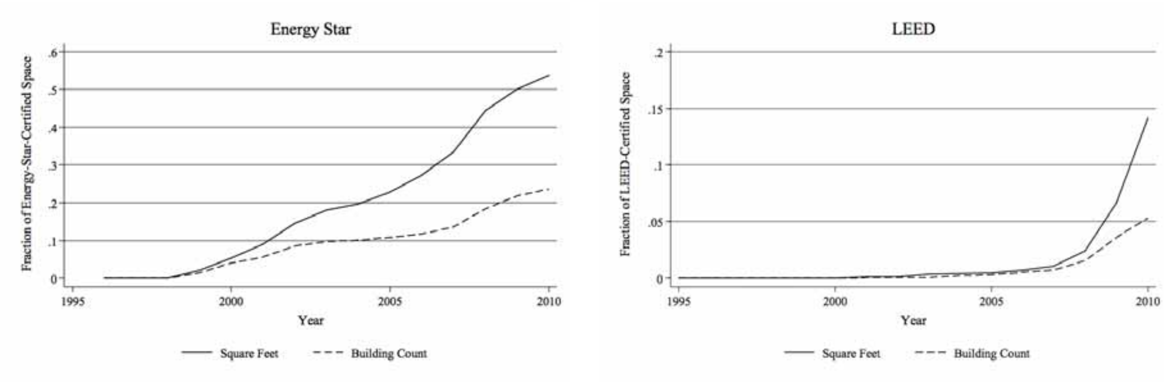


Figure 2
LEED and Energy Star Dynamics
Fraction of Certified Office Space Across US MSAs
(1995-2010)

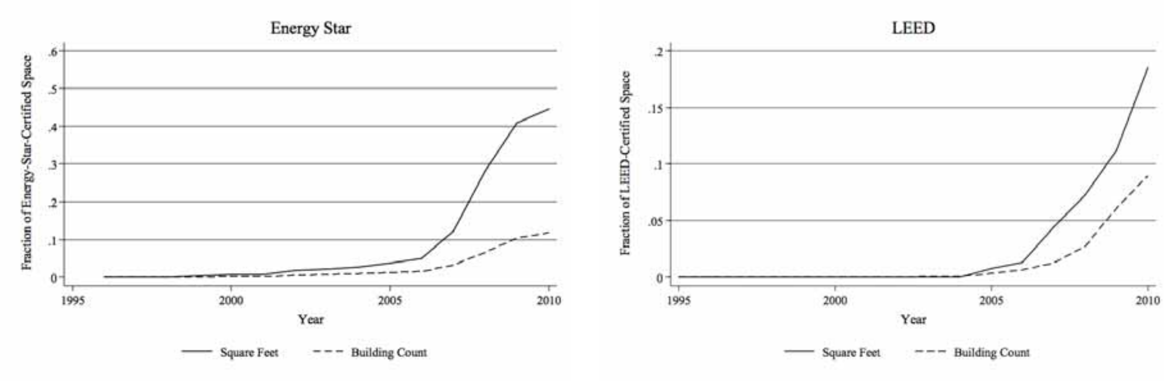
A. New York



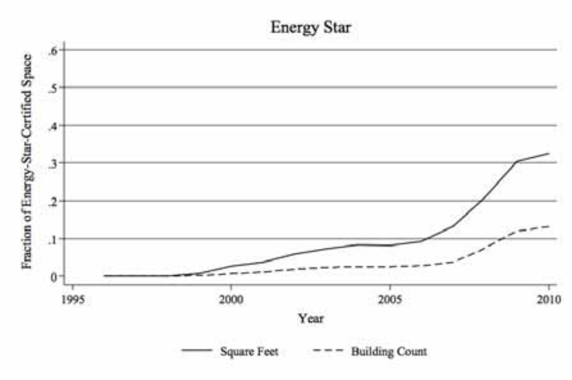
B. Los Angeles

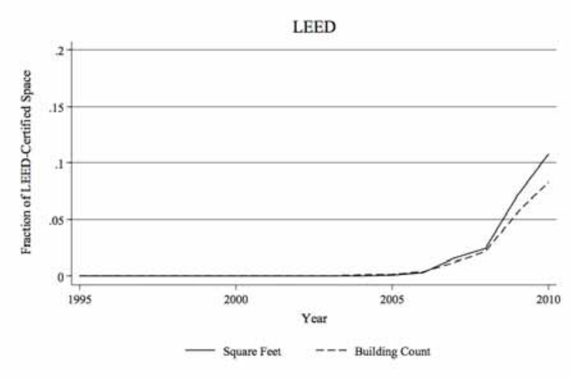


C. Chicago

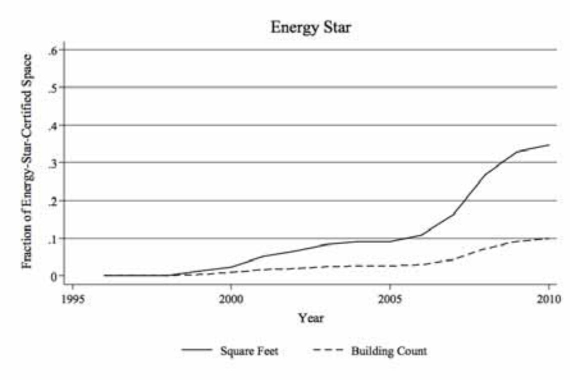


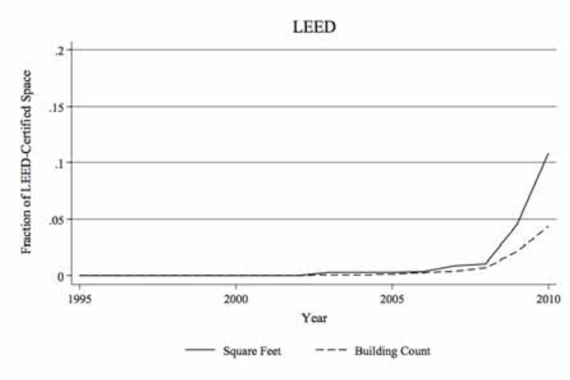
D. Washington



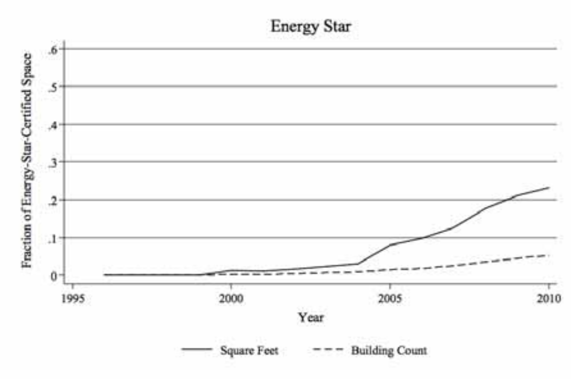


E. Dallas





F. Phoenix



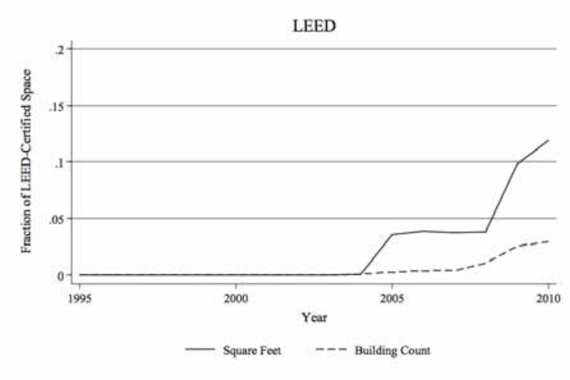
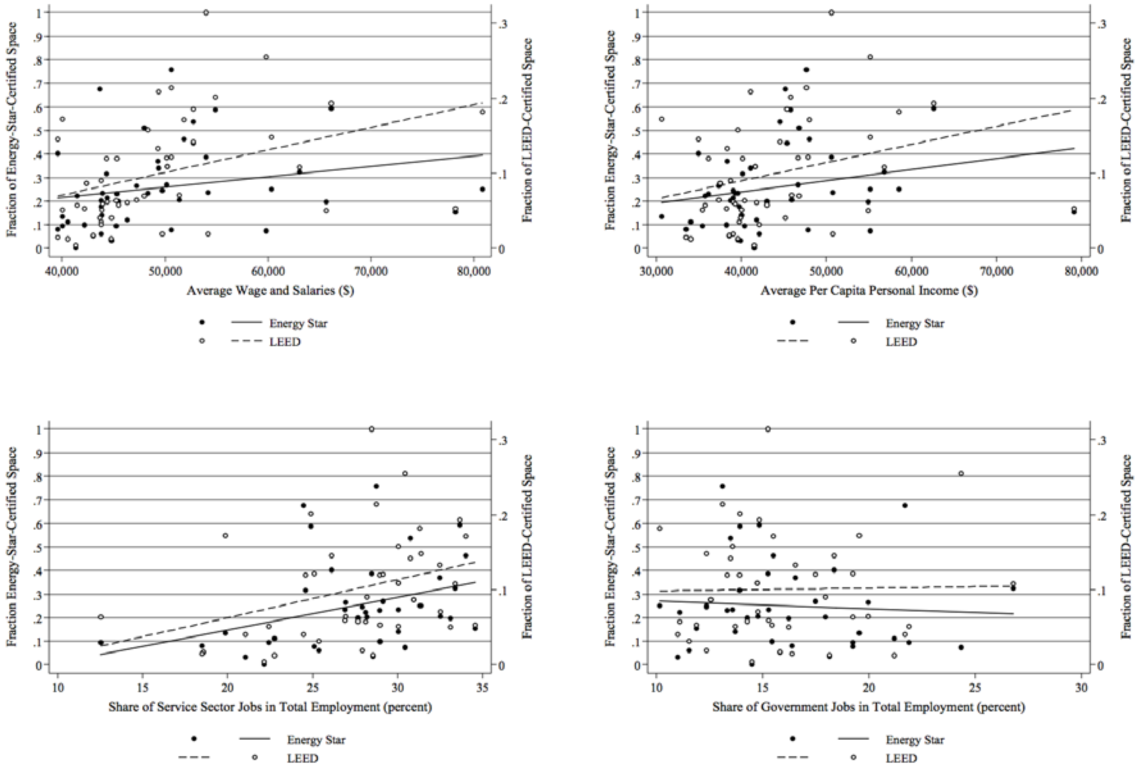
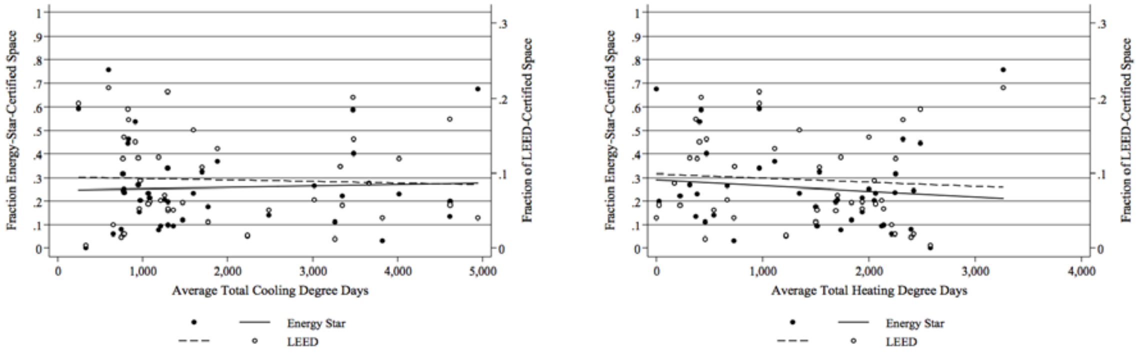


Figure 3
Correlates of the Diffusion of Energy Efficiency in Building, 2010

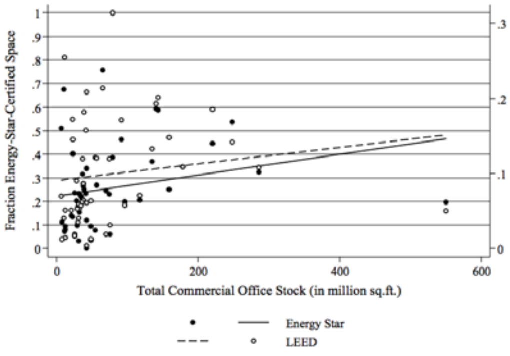
A. Income and Employment

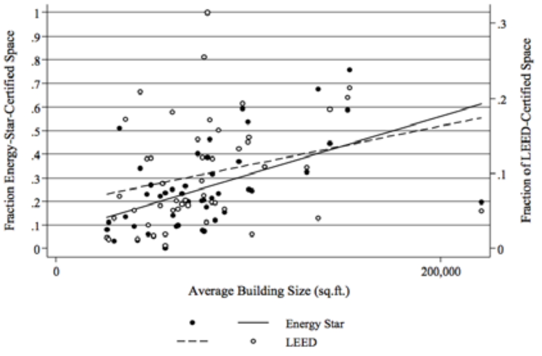


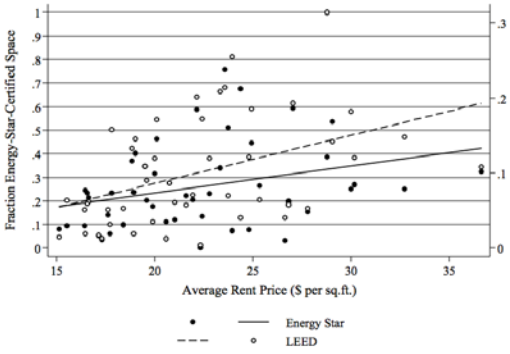
B. Climatic Conditions

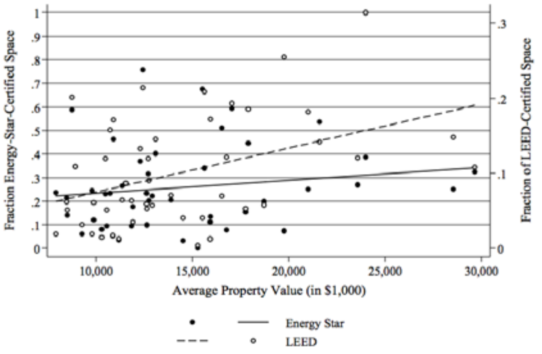


C. Property Market Characteristics

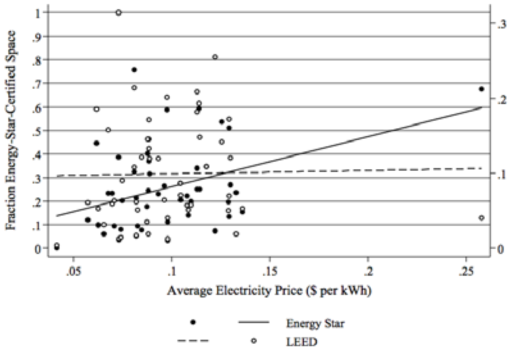


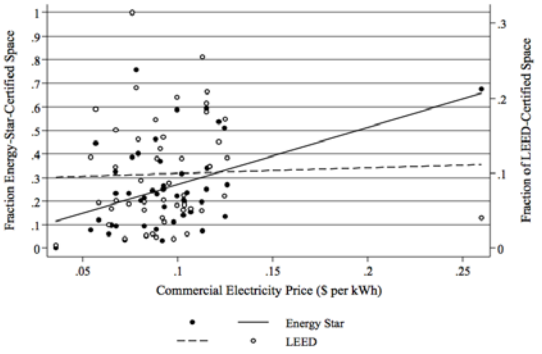




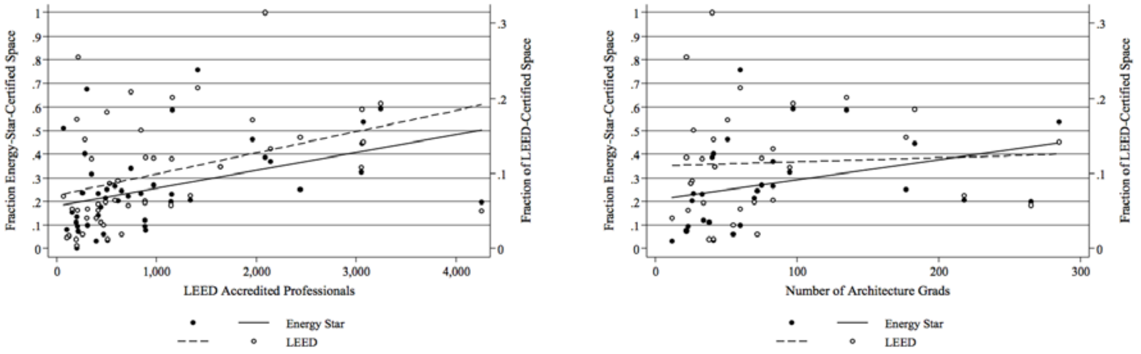


D. Energy Prices

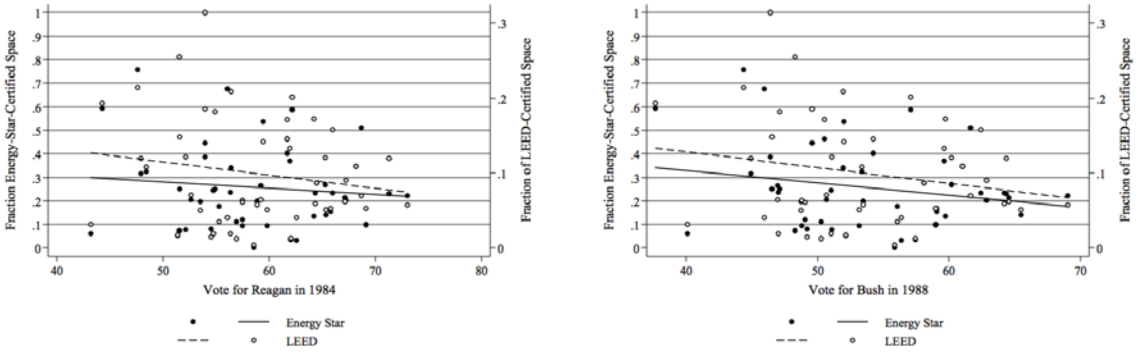




E. Building Professionals



F. Ideology



G. Government Policies on Green Building

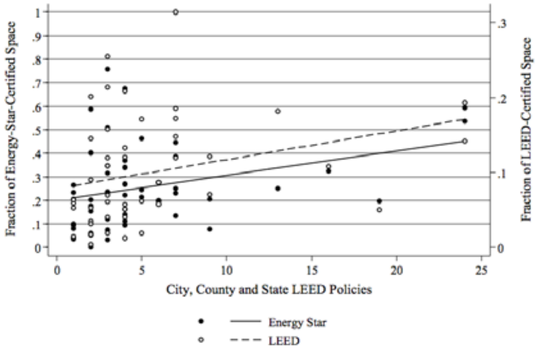


Table 1
Basic Regression Results
(dependent variable: fraction of certified commercial office space)

A. Energy Star

	Levels		First Differences		Arellano-Bond	
	linear	log-log	linear	log-log	linear	log-log
Income	0.005***	4.750***	0.005***	3.395***	0.003***	3.450***
($ thousands)	[0.001]	[0.273]	[0.001]	[0.710]	[0.000]	[0.388]
Average Electricity Price	0.913***	0.558***	0.538***	0.105	0.317**	0.623***
($ per kWh)	[0.133]	[0.166]	[0.113]	[0.174]	[0.140]	[0.192]
Office Space/Worker	0.004	-0.238***	-0.001	0.037	0.023**	-0.021
(sq. ft.)	[0.006]	[0.084]	[0.005]	[0.032]	[0.012]	[0.072]
Fraction Rated Space$_{t-1}$	-	-	-	-	0.898***	0.409***
					[0.025]	[0.045]
Constant	-0.357***	-52.073***	0.002	0.177***	-0.135***	-36.466***
	[0.041]	[3.092]	[0.002]	[0.066]	[0.017]	[4.424]
Observations	768	493	768	445	768	397
Wald Chi^2	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

B. LEED

	Levels		First Differences		Arellano-Bond	
	linear	log-log	linear	log-log	linear	log-log
Income	-0.003***	8.726***	-0.000	1.252	0.001***	10.112***
($ thousands)	[0.000]	[0.903]	[0.000]	[2.787]	[0.000]	[1.016]
Average Electricity Price	-0.027	0.416	-0.050	-0.584	0.123	1.070
($ per kWh)	[0.046]	[0.456]	[0.033]	[0.641]	[0.099]	[0.794]
Office Space/Worker	-0.001	-0.111	-0.004**	-0.213**	-0.004	-0.340
(sq. ft.)	[0.002]	[0.160]	[0.002]	[0.098]	[0.007]	[0.239]
Fraction Rated Space$_{t-1}$	-	-	-	-	1.223***	0.307***
					[0.042]	[0.045]
Constant	0.064***	-96.705***	0.005***	0.226	-0.055***	-108.965***
	[0.008]	[10.192]	[0.001]	[0.201]	[0.010]	[11.698]
Observations	768	290	768	239	768	194
Wald Chi^2	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

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	-0.631***				-0.269***			
(percent)	[0.113]				[0.074]			
Share of Government Jobs	-0.070				-0.016			
(percent)	[0.049]				[0.031]			
Share of Service Sector Jobs	0.097*				0.022			
(percent)	[0.057]				[0.036]			
Commercial Vacancy Rate		-0.001*				-0.000**		
(percent)		[0.000]				[0.000]		
Average Commercial Property Value		0.002***				0.001***		
($ million)		[0.001]				[0.000]		
Cooling Degree Days			0.005				0.007**	
(thousands)			[0.008]				[0.004]	
Heating Degree Days			-0.009				0.000	
(thousands)			[0.008]				[0.004]	
LEED Accredited Professionals			-60.783*				117.362***	
(Share of total population)			[33.691]				[23.366]	
Local Policies Encouraging LEED				0.001				0.003***
(count)				[0.001]				[0.000]
Average Electricity Price$_t$	0.421***	0.358**	0.395**	0.437***	0.260**	0.208**	0.100	0.174*
($ per kWh)	[0.147]	[0.151]	[0.189]	[0.148]	[0.101]	[0.102]	[0.105]	[0.095]
Office Space/Worker	0.050***	0.024*	0.028*	0.025**	0.001	-0.006	-0.005	-0.004
(sq. ft.)	[0.018]	[0.013]	[0.015]	[0.012]	[0.011]	[0.008]	[0.007]	[0.007]
Constant	-0.016	-0.031**	-0.019	-0.026**	-0.008	-0.021**	-0.020	-0.011
	[0.024]	[0.014]	[0.024]	[0.011]	[0.016]	[0.010]	[0.012]	[0.008]
Observations	768	749	473	768	768	749	473	768
Wald Chi^2	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

Appendix Table 1A
Fraction of Certified Office Space Across US MSAs
(2010)

A. Energy-Star-Certified Office Space

Metropolitan Area	Total Office Stock (million sq.ft.)	Number of Energy-Star-Certified Buildings	Fraction of Energy-Star-Certified Buildings	Energy-Star-Certified Space (million sq.ft.)	Fraction of Energy-Star-Certified Space
New York- New Jersey-Long Island	554.73	188	7.51	109.32	19.71
Washington-Arlington-Alexandria	294.85	295	13.18	95.92	32.53
Los Angeles-Long Beach-Santa Ana	251.31	593	23.61	135.09	53.76
Chicago-Joliet-Naperville	224.40	185	11.85	100.02	44.57
Dallas-Fort Worth-Arlington	181.60	165	9.84	63.07	34.73
Boston-Cambridge-Quincy	161.65	121	7.51	40.68	25.16
Houston-Sugar Land-Baytown	147.88	214	21.75	86.78	58.68
San Francisco-Oakland-Fremont	142.15	313	21.47	84.21	59.24
Atlanta-Sandy Springs-Marietta	138.92	142	9.81	51.36	36.97
Philadelphia-Camden-Wilmington	118.56	76	4.92	24.29	20.49
Miami-Fort Lauderdale-Pompano Beach	100.44	96	6.72	19.93	19.84
Denver-Aurora-Broomfield	93.48	176	15.15	43.31	46.33
Seattle-Tacoma-Bellevue	82.85	105	10.21	32.09	38.73
Phoenix-Mesa-Glendale	77.82	86	5.34	18.06	23.20
Pittsburgh	76.74	17	1.07	4.60	5.99
Detroit-Warren-Livonia	69.86	47	6.85	17.15	24.55
Minneapolis-St. Paul-Bloomington	65.35	119	27.80	49.59	75.88
Baltimore-Towson	57.56	19	2.57	4.52	7.85
San Diego-Carlsbad-San Marcos	57.25	105	9.04	15.41	26.92
Raleigh-Cary	49.95	12	1.03	1.76	3.52
Kansas City	49.14	24	3.05	4.70	9.57
Sacramento-Arden-Arcade-Roseville	44.70	110	11.09	15.20	34.00
Charlotte-Gastonia-Rock Hill	44.34	56	11.18	10.32	23.27
St. Louis	43.49	17	3.22	5.20	11.96
Portland-South Portland-Biddeford	43.22	3	0.40	0.04	0.08

Appendix Table 1A (continued)
Fraction of Certified Office Space Across US MSAs
(2010)

B. LEED-Certified Office Space

Metropolitan Area	Total Office Stock (million sq.ft.)	Number of LEED-Certified Buildings	Fraction of LEED-Certified Buildings	LEED-Certified Space (million sq.ft.)	Fraction of LEED-Certified Space
New York- New Jersey-Long Island	554.73	138	5.51	27.86	5.02
Washington-Arlington-Alexandria	294.85	186	8.31	31.84	10.80
Los Angeles-Long Beach-Santa Ana	251.31	133	5.29	35.63	14.18
Chicago-Joliet-Naperville	224.40	140	8.97	41.57	18.53
Dallas-Fort Worth-Arlington	181.60	73	4.36	19.76	10.88
Boston-Cambridge-Quincy	161.65	111	6.89	23.95	14.82
Houston-Sugar Land-Baytown	147.88	76	7.72	29.82	20.16
San Francisco-Oakland-Fremont	142.15	143	9.81	27.46	19.32
Atlanta-Sandy Springs-Marietta	138.92	91	6.29	18.52	13.33
Philadelphia-Camden-Wilmington	118.56	71	4.59	8.38	7.07
Miami-Fort Lauderdale-Pompano Beach	100.44	37	2.59	5.81	5.79
Denver-Aurora-Broomfield	93.48	79	6.80	16.04	17.16
Seattle-Tacoma-Bellevue	82.85	105	10.21	26.03	31.42
Phoenix-Mesa-Glendale	77.82	48	2.98	9.29	11.94
Pittsburgh	76.74	30	1.90	2.40	3.12
Detroit-Warren-Livonia	69.86	17	2.48	1.36	1.94
Minneapolis-St. Paul-Bloomington	65.35	58	13.55	14.01	21.44
Baltimore-Towson	57.56	43	5.82	6.99	12.14
San Diego-Carlsbad-San Marcos	57.25	43	3.70	6.89	12.03
Raleigh-Cary	49.95	7	0.60	0.65	1.30
Kansas City	49.14	20	2.54	3.13	6.38
Sacramento-Arden-Arcade-Roseville	44.70	35	3.53	9.34	20.90
Charlotte-Gastonia-Rock Hill	44.34	45	8.98	6.99	15.77
St. Louis	43.49	32	6.06	2.65	6.08
Portland-South Portland-Biddeford	43.22	7	0.93	0.16	0.37