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Carbon emissions from the commercial building sector: The role of climate, quality, and incentives☆

Matthew E. Kahn [a,d], Nils Kok [b,*], John M. Quigley [c]

[a] University of California, Los Angeles, United States
[b] Maastricht University, Netherlands
[c] University of California, Berkeley, CA, United States
[d] NBER, United States

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ABSTRACT

Commercial buildings play a major role in determining U.S. greenhouse gas emissions, yet surprisingly little is known about the environmental performance of different buildings at a point in time or how the same buildings perform over time. By exploiting a unique panel of commercial buildings from a major electric utility, we study the association between a building's electricity consumption and the physical attributes of buildings, lease incentive terms, indicators of human capital, and climatic conditions. We find that buildings that are newer and of higher quality consume more electricity, contrasting evidence for the residential sector. However, using our panel data set, we document that newer buildings are most resilient when exposed to hotter weather. Those buildings that have a building manager on-site and whose tenants face a positive marginal cost for electricity also demonstrate a better environmental performance.

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1. Introduction

Economic research investigating urban greenhouse gas production has mainly focused on the transportation sector's consumption of gasoline, the residential sector's energy consumption, and the power generation sector's carbon emissions (Glaeser and Kahn, 2010; Ito, 2014; Kotchen and Mansur, in press). But in the service economy, most work activity takes place in commercial buildings and a significant amount of shopping activity occurs in the commercial sector's structures. The commercial sector is thus a major user of natural resources — its share of total U.S. energy consumption was 18% in 2013.[1]

Electricity is the most important source of energy used in the commercial building stock, and the sector's share of electricity consumption has been rising over time.[2] Given that 40% of U.S. electricity consumption is generated using coal and 29% using natural gas, there is a significant unpriced greenhouse gas externality associated with electricity consumption.[3]

Despite the importance of the commercial property sector as a consumer of electricity, and thus as a major producer of urban carbon emissions, we know very little about the environmental performance of its buildings, and the effectiveness of energy policies addressing the externalities from commercial buildings. Lack of access to good data has limited our knowledge of the core facts — for instance, the most comprehensive source of data, the Department of Energy's Commercial

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* Corresponding author at: Maastricht University, School of Business and Economics, PO BOX 6161, 6200MD, Maastricht, Netherlands. Tel.: +31 433883838; fax: +31 43 3884875.

E-mail addresses: mkahn@ioe.ucla.edu (M.E. Kahn), n.kok@maastrichtuniversity.nl (N. Kok).

[1] See http://www.eia.gov/totalenergy/data/browser/xls.cfm?tbl=T02.01&freq=m.

[2] According to the Energy Information Agency (EIA), in 2013 about 79% of the total energy consumption in commercial buildings was from electricity (18% was from natural gas). Forty years ago, electricity represented 54% of the total energy consumption in the commercial stock. See http://www.eia.gov/totalenergy/data/browser/xls.cfm?tbl=T02.01&freq=m.

[3] See http://www.eia.gov/totalenergy/data/browser/xls.cfm?tbl=T07.02B&freq=m.

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Buildings Energy Consumption Survey (CBECS), was last conducted in 2003; this nationally representative data set offers cross-sectional information on the energy consumption of just 5,000 buildings. There is a small body of research about commercial building energy consumption, mostly conducted by engineers, exploring either aggregate consumption data at the state or national level (Horowitz, 2004), or analyzing small samples of buildings (see Hirst and Jackson, 1977, for an early analysis; see also Ham et al., 1997).[4]

In this paper, we exploit access to a unique dataset to study the electricity consumption of a large sample of commercial buildings located in a county in the Western U.S. Using our cross-sectional data, we investigate the determinants of commercial building energy consumption, exploring the association between building quality and lease incentive terms, and building electricity consumption. Our results show that the higher quality, newer vintages of commercial buildings actually consume *more* electricity than older buildings. This finding contrasts evidence on energy consumption trends for residential structures (Costa and Kahn, 2011). In comparing the environmental performance of newer and older buildings, we discuss relevant regulatory building codes.

Second, we examine the split incentive problem between the commercial building's tenant and its landlord. If incentives determine electricity consumption, then the structure of contracts has direct implications for the sector's greenhouse gas production. Lease contracts can be structured as all-inclusive, “full gross” contracts, or excluding utility cost (“triple net”) contracts, providing a standard principal–agent problem (Sappington, 1991) where the occupant chooses how much effort to exert on saving resources. The “full gross” contract provides the weakest incentives for a tenant to conserve on electricity consumption but incentivizes the building owner to make investments in energy efficiency. In contrast, the “triple net” lease incentivizes the tenant to economize on electricity (and thus greenhouse gas production) but provides weaker incentives for the building owner. We document that tenants whose utilities are bundled into the rent consume more electricity than observationally identical tenants who pay their own bills — similar to findings for residential housing (Levinson and Niemann, 2004). While most studies have pointed to the disincentives for landlords to make optimal investments in energy efficient appliances (Davis, 2010), we focus on the incentives for tenants to conserve on energy consumption, as provided by the lease framework.

By exploiting our data's monthly panel structure, we then test what types of buildings are most resilient when exposed to hotter weather. There is a growing consensus that carbon emissions will alter the earth's climate, most notably by causing temperatures and weather variability to increase. This has significant and direct implications for the average energy consumption in buildings (Dêschenes and Greenstone, 2011), but it may also affect the maximum, or peak demand for electricity from buildings (Chong, 2012). Our results highlight what types of commercial real estate increase their electricity consumption the most during hot summers. Such estimates are relevant for predicting grid resilience (a local public good) in the face of increased summer temperature.

Contrasting results for average consumption levels, we document that newer buildings increase their electricity consumption less on hotter days as compared to the average building — they are more resilient to temperature shocks. Using the data on the leasing arrangements of space within buildings, we document that tenants who face a zero marginal cost of energy consume relatively more electricity on hotter days. This finding highlights the important role that occupant behavior plays in determining a building's electricity consumption dynamics. On hotter days, there will be greater demand for air-conditioning and this demand will be even higher in buildings where tenants face a zero marginal cost for consumption because they have a full service lease.

We acknowledge that our findings are not based on a randomized experiment. In an ideal randomized trial, heterogeneous tenants would be randomly assigned to different buildings under randomized lease terms and then be exposed to randomized climate conditions. We would then study the electricity consumption of different commercial buildings as a function of the building's attributes, the tenants' attributes, the lease contract's terms and the outdoor climate conditions. In such a case OLS estimates of the electricity consumption would yield causal effects. In reality, there is a market for commercial real estate and a hedonic pricing gradient emerges as heterogeneous potential tenants choose their optimal location. In Section 2 of the paper, we explicitly discuss this assignment problem and the assumptions that must hold for our OLS estimates to not suffer from bias due to omitted variables and self-selection issues.

Our paper's focus on commercial buildings makes it considerably different from the growing literature on the environmental performance of the building stock, which is primarily focused on the residential sector. One hypothesis in the residential literature is that consumers underinvest in energy efficiency. This perceived market failure has been addressed through second-best responses such as standards and subsidies (Allcott et al., 2014). For example, Jacobsen and Kotchen (2013) document small but significant impacts of changes in building codes on the efficiency of residential dwellings in Florida, whereas Chong (2012) investigates changes in residential energy consumption in response to temperature shocks, finding that new buildings use more energy in hot weather. Allcott (2011) studies occupant behavior, documenting that residential customers reduce their electricity consumption when receiving peer comparisons that show how their consumption compares relative to their geographic neighbors.

The remainder of this paper is organized as follows: Section 2 describes the empirical framework and the econometric models. Section 3 discusses the data, which represent a unique combination of building-level electricity consumption with detailed information on the characteristics and occupants of those buildings. Sections 4 and 5 provide the main results, conclusions, and policy implications of the findings.

2. Empirical framework

The commercial real estate sector is a major consumer of electricity. This electricity consumption raises U.S. greenhouse gas emissions and exacerbates the risk of climate change. Thus, privately optimal choices for consumers impose social costs. We use our unique data to explore the major sources of this externality.

To begin to study this issue, we first document overall time trends. As Fig. 1A illustrates, the fraction of electricity consumed in residential and commercial (i.e., office, retail and industrial) buildings in the U.S. has increased from a total of about 52% in 1960 (29% residential and 23% commercial) to about 75% in 2010. For comparison, Fig. 1B shows that in California the fraction of electricity consumed in buildings has increased from about 65% to 81% during the same period. The commercial sector currently consumes about a third more than the residential sector in California.

At a point in time, a commercial building's electricity consumption depends on the building's physical attributes, the set of tenants who locate in the building, the incentives these tenants face for purchasing and operating energy intensive durables, and the outdoor climate conditions. The relevant physical attributes include the building's square footage, vintage and architecture. Once the building is in operation, its electricity consumption will be a function of core building energy

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[4] Recently, several working papers on commercial building energy consumption have emerged. Qiu (in press) analyzes the impact of energy efficiency technologies on steady state energy consumption, while Papineau (2013) investigates the capitalization of efficiency gains following the adoption of more stringent buildings codes, and the heterogeneity of the effects across leasing arrangements.

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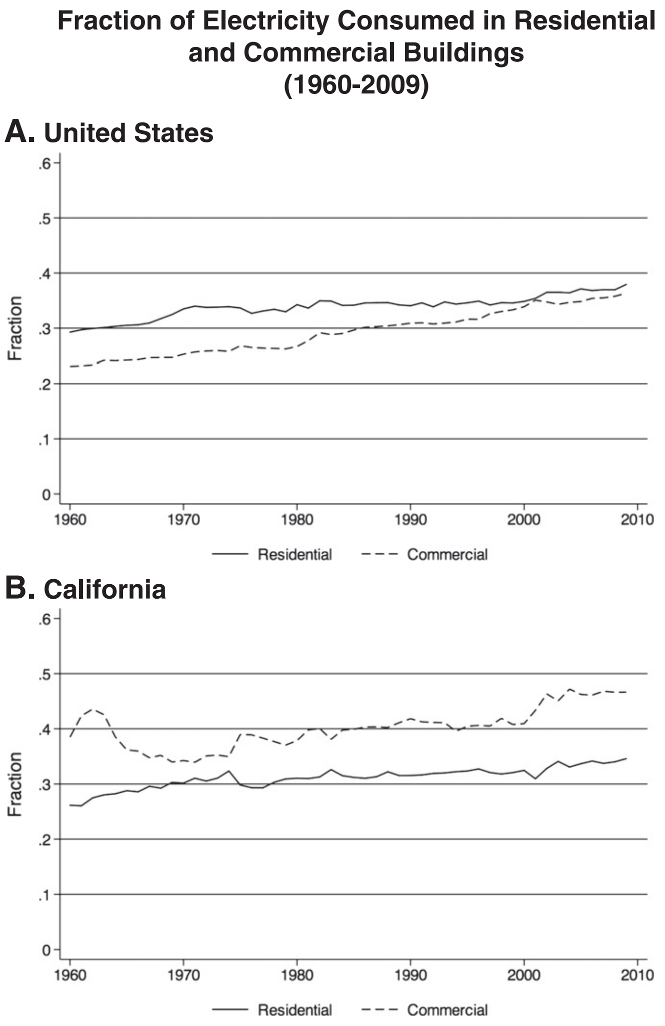

Fig. 1. Fraction of electricity consumed in residential and commercial buildings (1960–2009). Source: Energy Information Agency (EIA) Table 2.1a Energy Consumption Estimates by Sector, 1949-2011.http://www.eia.gov/totalenergy/data/annual/index.cfm.

consumption (from the requirements to heat, cool and ventilate the building) and consumption from (unobserved) appliances installed and used by the building occupants.

According to national benchmarks for building consumption (i.e., DOE's CBECS database), heating, cooling, lighting and office equipment account for most of the electricity consumption in commercial buildings, but these estimates are of course heavily dependent on climatic conditions. Fig. 2 shows that, on average, the heating, ventilation and air-conditioning (HVAC) systems alone account for about 65% of energy consumption in commercial buildings. Commercial buildings in our sample, located in a county in a Western utility district, show larger expenditures on lighting, about 30%, and smaller expenditures on HVAC (also about 30%) than the nation-wide averages (Kavalec and Gorin, 2009).

Commercial buildings are differentiated products. Energy efficiency is just one indicator of building quality. Other quality dimensions such as providing good lighting, elevator service, esthetic appeal and ambient comfort may require using more electricity. In the case of trends in automobile characteristics, Knittel (2012) documents that manufacturers have created a new generation of larger vehicles offering more safety and comfort. The vehicle fuel economy of this generation of cars would have been much higher had manufacturers not shifted the attributes bundled into new vehicles. In a similar spirit, we test whether newer vintages of buildings (that are subject to more stringent building codes) are more energy efficient than earlier vintages, or whether increased efficiency is bundled with energy consuming building attributes.[5]

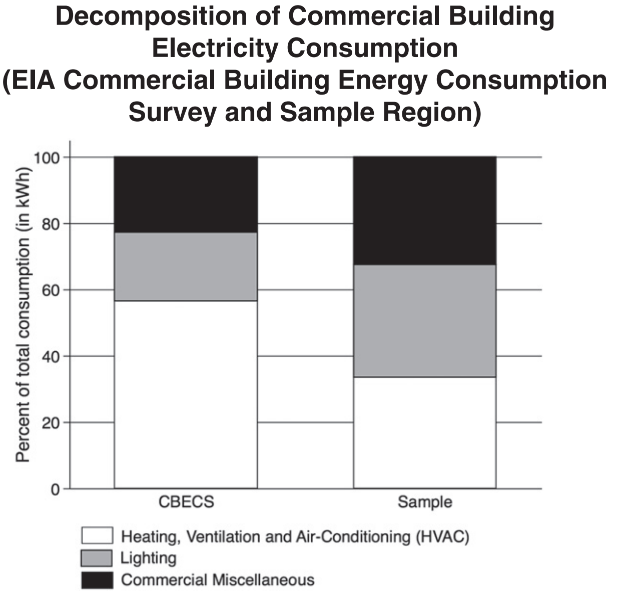

Fig. 2. Decomposition of commercial building electricity consumption (EIA Commercial building energy consumption survey and sample region). Source: Kavalec and Gorin (2009) and EIA Commercial Building Energy Consumption Survey (http://www.eia.gov/consumption/commercial/data/2003/).

We also explore the role that building occupants and contract details in their leases play in determining monthly electricity consumption. Building occupants have different use intensities, depending on their activities in the buildings, and the efficiency of their investments in durable equipment, such as appliances. A distinctive feature of our analysis is our ability to identify government tenants. We conjecture that relative to private sector firms, government tenants are more likely to face “soft budget constraints” and thus have weaker incentives to invest in energy efficiency, as they can pass on the costs taxpayers (Kornai et al., 2003). It is important to note that our sample of buildings does not include government-owned buildings. The media has widely reported that as of 2010 all new government buildings must be certified to be at a minimum standard of LEED Gold certification — a private sector measure for energy efficiency and sustainability.[6]

Lease contracts identify how the payments for operating expenses (including, but not limited to, energy consumption) are allocated between the landlord and the tenants. Lease contracts for commercial buildings commonly take one of three main formats: full service leases, net leases, and modified gross leases. Under a full service lease, the tenant makes one payment that covers both space rent and operating

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[5] As noted by one referee, there is considerable engineering science behind the issue of older versus newer buildings, with thermal mass, air leakage and overall R-value all influencing the energy performance of buildings (in addition to technical equipment). For example, new buildings often use more glazing, and often do not have windows that open, so all cooling and heating comes from the heating and cooling systems. Some of the older commercial buildings have windows that open, so they can delay using air-conditioning in the early part of summer and stop using air-conditioning earlier at the end of summer.

[6] See http://www.gsa.gov/portal/content/197325 for more information.

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expenses. The individual components are typically not identified. Modified gross leases and net leases share the feature that the tenant pays a share of the building's operating expenses, but on modified gross leases the tenant pays a prorated share of the building's total expenses, which are thus independent of the tenant's actual energy usage.[7] (See Jaffee et al., 2012, for a discussion.) We test whether the consumption of tenants that face a zero marginal cost of energy differs from tenants that face a marginal cost of consumption.[8]

Achieving efficient use of electricity requires certain human capital and expertise. Employing a building manager is expected to deliver significant electricity consumption reductions. Bloom et al. (2011) document using a survey of UK managers that manufacturing plants have a lower energy intensity (energy consumption per dollar of value added) at plants featuring more skilled managers. We conjecture that a similar effect plays out for commercial real estate, where the presence of an on-site building manager or engineer might have an effect on how efficiently a property is operated and maintained — especially in those buildings where tenants face a zero marginal cost of energy consumption.

To test these hypotheses related to building vintage, lease terms, tenant composition and human capital, we estimate a cross-sectional regression model reported in Eq. (1). In this equation, the dependent variable y_i is natural logarithm of average daily electricity consumption per square foot. X_i is a vector of the structural characteristics of building i, including building size, vintage, and quality. To control for the impact of occupants on building energy consumption, we also include T_i, a vector of variables measuring the percentage of the building that is occupied by each industry n, based on their SIC classification. ε_i is an error term, assumed i.i.d.

$$\ln y_i = \gamma \cdot \mathrm{X}_i + \sum_{n=1}^{k} \varphi_p \cdot T_i^n + \varepsilon_i \tag{1}$$

In estimating the cross-sectional regression reported in Eq. (1), we must acknowledge that the omitted variable bias is a valid concern about any non-experimental study. For example, tenants are not randomly assigned to buildings and building owners do not randomly assign lease contract terms to tenants.[9] For OLS estimates of Eq. (1) to yield consistent estimates, we must assume that the error term is uncorrelated with our explanatory variables. This assumption rules out the possibility of sorting on unobservables.

In addition to estimating cross-sectional regressions, we also estimate fixed effects regressions with a focus on understanding how buildings perform under different climatic conditions. People who work in commercial buildings will seek to be comfortable inside regardless of outdoor climatic conditions. For those buildings that have highly efficient air-conditioning systems, it is unclear how hot summer temperatures affect their electricity consumption. The “price” of summer temperature comfort is lower in buildings that are newer, as these tend to have more recent, efficient HVAC systems. Facing such an incentive, on hot days, tenants in new buildings may set their thermostat lower than tenants who know that their building has an energy inefficient HVAC system. This behavioral response is consistent with a “rebound effect,” such that more energy efficient technology is used more due to the substitution effect. The size of this behavioral response hinges on the disutility of working in a hot office building, the energy efficiency of the building's HVAC system and the pricing scheme for whether tenants pay for marginal increases in electricity consumption.[10] Finally, we address how the business cycle affects commercial electricity consumption dynamics. For example, as the unemployment rate increases fewer people may be employed for fewer hours in the building. In a retail building, fewer customers may shop.

To explain the longitudinal variation in commercial building energy consumption, we estimate the following model:

$$\ln y_{it} = \sum_{p=1}^{10} \beta_p \cdot D_{it}^p + \gamma \cdot \mathrm{Z}_{it} + \alpha_i + \theta_m + \lambda_y + \varepsilon_{it}. \tag{2a}$$

In Eq. (2a) we estimate a model in which the dependent variable is the logarithm of the average daily electricity consumption per square foot in month t (in kilowatt hours) for building i. D_{it} is a vector of p temperature dummies capturing the non-linear relation between outside temperature and building energy consumption,[11] Z_{it} is a vector that captures the occupancy rate and occupancy-rate squared in building i in month t, and the local unemployment rate (reflecting the business cycle). Macro conditions will also affect consumption, for example through economic conditions. During a recession, a commercial building's occupancy rate will decline and this will cause a reduction in electricity consumption. α_i is a variable capturing building-fixed effects, controlling for the time-invariant characteristics of each property i. λ_y are year-fixed effects and θ_m are month-fixed effects, both controlling for unobservable shocks to electricity consumption common to each building i. ε_{it} is an error term, assumed to be i.i.d.

We then estimate model (2b) to recover the heterogeneity in the building response to temperature shocks.

$$\ln y_{it} = \sum_{p=1}^{10} \sum_{j=1}^{8} \beta_p \cdot D_{it}^p \cdot \mathrm{X}_{it}^j + \gamma \cdot \mathrm{Z}_{it} + \alpha_i + \theta_m + \lambda_y + \varepsilon_{it} \tag{2b}$$

We consider four groups of variables (X_{it}) to be interacted with the vector of temperature dummies: 1) the occupancy rate, 2) building vintage (buildings constructed 10–30 years ago, and buildings constructed more than 30 years ago), 3) building quality (Class B and Class C), and 4) lease structure (net lease contracts, full service contracts, and modified gross lease contracts). α_i is a variable capturing building-fixed effects, controlling for the time-invariant characteristics of each property i. λ_y are year-fixed effects and θ_m are month-fixed effects, both controlling for unobservable shocks to electricity consumption common to each building i. ε_{it} is again the error term, assumed to be i.i.d.

While this paper investigates electricity consumption, we do not attempt to estimate a demand curve for commercial electricity. Our

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[7] Under a net lease (often referred to as a “triple net” lease), the tenant pays separately for space rent and the tenant's actual or allocated share of the specified operating expenses. Under a modified gross lease, contracts specify a payment for the space rent and require an actual amount to be paid for operating expenses in the first year. For later years, the landlord provides an audit of building expenses, and the tenants pay a prorated share of the realized percentage increase in the building expenses.

[8] Data access has limited research on examining how contractual form affects economic performance, and there is a dearth of systematic evidence on contracting in commercial and residential buildings. Eric D. Gould et al. (2005) use a unique dataset of mall tenant contracts and show that rental contracts are written to: efficiently price the net externality of each store, and align the incentives to induce optimal effort by the developer and each mall store according to the externality of each store's effort. Levinson and Niemann (2004) document for a sample of residential homes that market rents for full service, utility-included apartments are higher than for otherwise similar metered apartments. This difference is smaller than the cost of the energy used, which indicates that landlords value the contractual arrangement more than the potential additional energy consumption.

[9] This issue would for example arise if there are energy-intensive firms who intentionally choose to locate in a building because they know that their total electricity consumption will be lower relative to if they are located in other buildings. Consider a case with perfect information about building energy efficiency such that more energy efficient buildings command a price premium. In this case, the most energy intensive tenants in an industry will be likely to self-select and choose to locate in the most energy efficient buildings or in buildings for which electricity bills are bundled into the rent.

[10] In this sense, our study builds on the “rebound effect” literature that has examined the performance of products including commercial buildings (Greening et al., 2000), vehicles (Small and Van Dender, 2007), and clothes washers (Davis, 2008).

[11] In the spirit of Anin Aroonruengsawat and Maximilian Auffhammer (2011), we split the temperature distribution into deciles to capture the non-linear effect of climate on building energy consumption.

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data comes from an electric utility whose pricing tiers feature little variation or increase from off-peak to peak. To control for average price variation over the course of the year, we include month-fixed effects.[12]

3. Data

Through a research partnership with an electric utility in the Western U.S., we access monthly electricity consumption for more than 50,000 commercial accounts within the service area. We focus on the subset of buildings that we can match to the buildings identified in the archives maintained by the CoStar Group. The CoStar service and the data files maintained by CoStar are advertised as "the most complete source of commercial real estate information in the U.S.,"[13] and have been used extensively in academic studies on the commercial property sector (see for example Eichholtz et al., 2010). Spanning the years 2000 to 2010, our match yielded 38,906 accounts in 3521 buildings for which information on occupants, lease contracts and building characteristics could be identified in CoStar. Our sample represents the population of transacted buildings (in either a lease or a sale) over the years 2000 to 2010.[14] CoStar monitors each building over time and continuously updates time-varying information, such as the occupancy rate and average weighted rents. The building types in the sample include "Office," "Flex," "Industrial," and "Retail" properties.[15]

We observe monthly electricity consumption and expenditure, including information on the start date and length of each billing cycle. To account for variation in billing cycles, we transform electricity consumption and expenditures into daily data, by dividing the billing cycle totals by the number of days in the cycle. If data are available for multiple accounts within a single building (there are about three accounts per building, on average), we aggregate the daily energy consumption at the building level.

We standardize the daily energy consumption by building size, omitting all observations where energy consumption is zero. To account for outliers in the data, we censor the energy consumption per square foot at the 99th percentile. The distribution of the dependent variable is right-skewed and we use the natural logarithm of electricity consumption per square foot.

Data on local daily weather conditions is collected from the National Oceanic and Atmospheric Administration's (NOAA) Climatic Data Center. We calculate the average maximum daily temperature during the billing cycle for each building, averaging across accounts if there are multiple accounts within a single building.[16]

Information on building occupants is gathered from the CoStar Tenant module. For each building in the sample, we collect data on the floor space occupied and the identity of the tenants in 2009. The industry of each tenant is classified by a four-digit SIC code, and we aggregate the fraction of floor space occupied into thirteen groups.[17] We include the percentage of space occupied by each industry in model (1).

Table 1 presents a description of the four types of commercial buildings in our sample (for 2009).[18] Average energy usage varies from about 11,000 kWh per month for industrial buildings to three times that for office buildings. The Building Owners and Managers Association (BOMA) groups commercial properties into three classes: Class A, Class B, or Class C. These classes represent a subjective quality rating of buildings which indicates the competitive ability of each building to attract similar types of tenants. Factors determining the building quality include: rent, building finishes, system standards and efficiency, building amenities, location/accessibility and market perception.[19] Presumably, some of these factors might affect energy consumption (e.g., larger HVAC capacity, more and faster elevators).

Our sample includes some centrally located, high-rise, and high quality ("Class A") properties, but on average the distance to the city center is some 12 km; the majority of properties are low-rise (about two stories) and fall into quality categories "B" and "C." The average age of buildings in our sample is 27 years, where age is calculated as a "running variable" that changes depending on the month/year for the dependent variable. About 8% of the buildings have been renovated at some point during the economic life.

Our data merge allows us to provide some facts about tenant "sorting on observables". Appendix Table A1 provides some descriptive statistics on the average percentage of each of the fourteen industries in our sample of commercial buildings. Although the industry averages mask the underlying heterogeneity in the energy intensity of individual tenants, these simple statistics give some insight into the sorting of tenant types based on observable characteristics. Panel A shows that government tenants are present in some 4% of the commercial office buildings in our sample. Government tenants, as well as financial services, are clustered into higher quality, Class A buildings. Panel B provides more insight into the sorting of tenants based on vintage and lease contract type of commercial office buildings. Tenants in the retail industry are more prevalent in older building, whereas government tenants and the professional service sector seem to sort into more recent vintages of buildings. Tenants from these industries are also more likely to be present in buildings with full-service lease contracts.

4. Results

4.1. Cross-sectional variation in commercial building electricity consumption

In this section, we report the estimates of Eq. (1). These cross-sectional regressions are informative about the association between building attributes, contract incentives, and management human capital.

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[12] Ito (2014) documents that residential electricity consumers are more responsive to average prices than to marginal prices, estimating a price elasticity of roughly -0.05.

[13] The CoStar Group maintains an extensive micro database of approximately 2.4 million U.S. commercial properties, their locations, and hedonic characteristics, as well as the current tenancy and rental terms for the buildings. Of these 2.4 million commercial buildings, approximately 17% are offices, 22% are industrial properties, 34% is retail, 11% is land, and 12% is multifamily. A separate file is maintained of the recent sales of commercial buildings.

[14] One reader noted that this might lead to selection bias, as the thermal quality of owner-occupied properties may differ from "investment" properties. But the direction of the bias is not obvious: owner-occupiers may have a longer holding period, allowing for investments in building retrofits and more energy-efficient equipment, without the requirement of short "payback periods," which is often quoted as a barrier to energy-efficiency upgrades. However, one could also argue that professional property investors are more rational agents when it comes to trading off large upfront investments with savings realized over a longer time period. And well-capitalized institutional property investors may suffer less from liquidity constraints as compared to smaller, private real estate investors and owner-occupiers.

[15] Buildings designated as "Flex" buildings are designed to be versatile, and may be used in combination with office (corporate headquarters), research and development, quasi-retail sales, and including but not limited to industrial, warehouse, and distribution uses. At least half of the rentable area of the building must be used as office space. Buildings designated as "Industrial" are buildings adapted for a combination of uses such as warehousing, distribution, maintenance facilities, or self-storage. Additional uses include assemblage, processing, and/or manufacturing products from raw materials or fabricated parts. See http://www.costar.com/about/glossary.aspx?hl=A.

[16] Presumably, commercial properties are occupied mostly throughout the day, so it is the maximum daily temperature that matters for energy consumption, not the average daily temperature. A robustness check using the average daily temperature does not yield significantly different results (results are available from the authors upon request).

[17] The thirteen groups are defined in line with the U.S. Department of Labor SIC guide, and include: Agriculture & Mining; Construction; Manufacturing; Transportation; Communication; Utilities; Distribution; Retail; Financial; Services; Non-Profits; Professional Services; and Government.

[18] See the Online Appendix for a correlation matrix of all covariates, and for some plots between selected variables.

[19] See also http://www.boma.org/research/Pages/building-class-definitions.aspx.

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Table 1
Commercial building energy consumption (office, flex, industrial and retail properties, 2009).

	Office		Flex		Industrial		Retail	
	(n = 1478)		(n = 322)		(n = 1120)		(n = 601)	
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Energy & climate#								
Daily expenditures ($)	130.32	(281.76)	68.36	(150.79)	46.63	(99.16)	96.82	(350.99)
Daily consumption (kWh)	1,147.67	(2,705.28)	588.83	(1556.10)	386.03	(888.55)	843.05	(2,990.36)
Daily consumption/square foot (kWh)	0.035	(0.032)	0.024	(0.034)	0.014	(0.023)	0.062	(0.069)
monthly temperature (F, maximum)	24.31	(8.02)	24.29	(8.03)	24.31	(8.02)	24.31	(7.99)
Building characteristics								
Building size (in thousands of sq ft)	27.96	(49.05)	21.65	(19.11)	32.62	(60.23)	16.79	(48.13)
Class A (percent)	6.44	(24.55)	–	–	3.36	(18.03)	–	–
Class B (percent)	39.41	(48.87)	45.17	(49.77)	38.42	(48.64)	–	–
Class C (percent)	54.14	(49.83)	41.96	(49.36)	58.13	(49.34)	–	–
Vintage (years)	27.41	(20.41)	22.96	(11.89)	24.46	(15.22)	35.79	(25.96)
Renovated (percent)	7.89	(26.96)	2.80	(16.50)	1.45	(11.94)	5.98	(23.71)
Number of stories	1.90	(2.23)	1.07	(0.26)	1.01	(0.12)	1.16	(0.47)
Distance to CBD (in km)	12.73	(10.02)	12.92	(7.35)	12.77	(7.34)	7.52	(4.68)
Occupancy								
Occupancy rate (fraction)	0.81	(0.29)	0.73	(0.34)	0.78	(0.34)	0.88	(0.26)
Government tenants (1 = yes)	7.84	(26.87)	4.71	(21.18)	1.17	(10.77)	0.33	(5.70)
Space occupied by government (percent)	3.90	(16.88)	3.13	(16.30)	0.68	(7.13)	0.10	(1.78)
Rents & contract type								
Total asking rent ($ per sq ft)	20.15	(5.83)	10.41	(3.77)	6.29	(2.63)	19.31	(7.42)
Total gross rent ($ per sq ft)	21.10	(5.83)			12.00	(0.00)	22.70	(0.91)
Triple net (percent)	7.12	(25.72)	37.11	(48.32)	29.80	(45.74)	27.18	(44.49)
Modified gross (percent)	10.32	(30.42)	16.75	(37.35)	18.21	(38.59)	3.56	(18.54)
Full service (percent)	34.36	(47.49)	3.20	(17.61)	1.05	(10.21)	1.59	(12.52)
Number of accounts per building	3.11	(5.02)	6.11	(8.58)	4.17	(6.10)	5.03	(23.16)

Notes:
#Daily energy consumption is aggregated at the building level if data are available for multiple accounts within a single building (there are about three accounts per building, on average).
"Flex" buildings are designed to be versatile, and may be used in combination with office (corporate headquarters), research and development, quasi-retail sales, and including but not limited to industrial, warehouse, and distribution uses. At least half of the rentable area of the building must be used as office space.
"Industrial" buildings are adapted for a combination of uses such as warehousing, distribution, maintenance facilities, or self-storage. Additional uses include assemblage, processing, and/or manufacturing products from raw materials or fabricated parts.

In Table 2, we provide the results from estimating Eq. (1) using monthly data from calendar year 2009 to explain commercial buildings' electricity consumption. We include month-fixed effects to capture seasonal variations in temperature and to account for the peak and off-peak pricing schedules at the utility. We first address how the structural attributes of commercial properties correlate with electricity consumption. Large buildings consume less electricity per square foot. The coefficient on building size indicates that there are economies of scale in heating and cooling buildings, although the squared-term shows that very large buildings behave differently than their smaller counterparts — at the point of means, a one standard deviation increase in the log of building size increases energy consumption by 1.7%. Presumably, heating and cooling of large structures requires additional equipment to bridge large vertical distances, offsetting otherwise beneficial economies of scale. This is confirmed by the significantly positive consumption effect for buildings taller than four stories.

Importantly, we document that newer buildings consume more electricity than older vintages. Buildings constructed before 1960 are slightly less efficient than those constructed during the 1960–1970 period, but buildings that are 30 years or younger consume consistently more electricity than old buildings.[20] These findings contrast with results examining vintage effects for residential housing in the same county, documenting increased energy efficiency for the most recent vintages (Costa and Kahn, 2011).

We also note that the electricity consumption of commercial buildings constructed recently (with a vintage less than ten years) is slightly lower as compared to those properties constructed more than ten years ago. Some have asserted that the recent improvement in energy use intensity is a result of strict legislation (an example is California's Title 24 building energy efficiency program), but there is no systematic evidence to support this notion.

Like vintage, renovation and building quality have a distinct effect on commercial building energy consumption. Column (2) shows that renovated buildings feature 19% higher electricity consumption than similarly sized buildings. "Class A" real estate consumes some 20% more electricity than "Class C" real estate.

The findings on building vintage and building quality are consistent with the hypothesis that electricity consumption and building quality are complements, not substitutes. Technological progress may reduce the energy demand from heating, cooling and ventilating the base building, but the increase in quality attributes (e.g., a nicer lobby, more elevators, the ability of tenants to independently adapt comfort temperature) may actually increase energy consumption. This finding is consistent with recent work on automobiles, which has documented that technological progress in fuel economy has been partially offset by the increase in vehicle weight and engine power (Knittel, 2012). The general point here is that consumers of both automobiles and commercial buildings value quality, and energy efficiency is just one indicator of quality. In both cases, the producer of these differentiated products can raise the overall quality of the product by increasing its energy used to operate the product.

In columns (3) and (4), we exploit the rich set of observables in the CoStar database to explore in more detail the role that building

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[20] We recognize that at any point in time year built and building age are collinear. We have exploited the panel nature of our 2000 to 2010 data to test for aging effects. In results available upon request, we have estimated versions of Eq. (2a) in which we include building fixed effects and an age of building variable. The age coefficient is 0.027 and is statistically insignificant with a *t*-statistic of 0.53. This finding raises our confidence that the year built coefficients we report represent vintage effects rather than a convolution of vintage and aging effects.

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Table 2
Determinants of commercial building energy consumption (dependent variable: natural logarithm of kWh per square foot, 2009).

	(1)	(2)	(3)	(4)
Occupancy rate (fraction)	2.506***	2.480***	2.703***	2.719***
	[0.103]	[0.103]	[0.106]	[0.106]
Occupancy rate^2 (fraction)	−1.275***	−1.238***	−1.523***	−1.566***
	[0.082]	[0.082]	[0.087]	[0.087]
Building size (natural logarithm)	−0.505***	−0.369***	−0.364***	−0.365***
	[0.075]	[0.079]	[0.078]	[0.078]
Building size^2 (natural logarithm)	0.026***	0.017***	0.018***	0.017***
	[0.004]	[0.004]	[0.004]	[0.004]
Vintage (omitted: age > 50 years)				
Age <10 years (1 = yes)	0.098***	0.048**	0.066***	0.067***
	[0.022]	[0.023]	[0.023]	[0.023]
Age 10–20 years (1 = yes)	0.157***	0.136***	0.142***	0.144***
	[0.024]	[0.024]	[0.024]	[0.024]
Age 20–30 years (1 = yes)	0.105***	0.112***	0.131***	0.133***
	[0.020]	[0.020]	[0.020]	[0.020]
Age 30–40 years (1 = yes)	−0.006	0.010	0.024	0.021
	[0.022]	[0.022]	[0.022]	[0.022]
Age 40–50 years (1 = yes)	−0.089***	−0.081***	−0.099***	−0.094***
	[0.031]	[0.031]	[0.031]	[0.031]
Renovated (1 = yes)	0.204***	0.190***	0.208***	0.194***
	[0.023]	[0.024]	[0.023]	[0.023]
Stories (omitted: single story)				
2–4 (1 = yes)		0.027	0.001	0.008
		[0.016]	[0.016]	[0.016]
>4 (1 = yes)		0.241***	0.230***	0.281***
		[0.048]	[0.047]	[0.048]
Building quality (omitted: Class C)				
Class A (1 = yes)		0.195***	0.165***	0.171***
		[0.032]	[0.032]	[0.033]
Class B (1 = yes)		0.118***	0.111***	0.115***
		[0.015]	[0.014]	[0.014]
Rental contract				
Triple net (1 = yes)			−0.284***	−0.274***
			[0.019]	[0.019]
Modified gross (1 = yes)			−0.346***	−0.324***
			[0.021]	[0.021]
Full service (1 = yes)			0.027	0.031
			[0.020]	[0.020]
Fraction occupied by government (percent)				0.360***
				[0.044]
On-site management (1 = yes)				−0.084***
				[0.027]
Constant	−2.679***	−3.296***	−2.751***	−3.165***
	[0.368]	[0.383]	[0.382]	[0.380]
Observations	21,053	21,053	21,053	20,969
R-squared	0.399	0.402	0.411	0.415
Adj R^2	0.397	0.401	0.410	0.414

Notes:
Panel includes all buildings during the 12 months of 2009. Specifications include: tenant composition (by SIC), property type fixed effects, and month-fixed effects.
Standard errors are in brackets.
*** $p < 0.01$.

occupants, lease structures and human capital play in determining electricity consumption. In column (3), we add a vector of lease contract attributes to the model. The results show that contracting matters for energy consumption: the variable indicating the presence of a triple net lease has a negative coefficient of about 20%.[21] This finding is consistent with our hypothesis that tenants facing marginal costs for energy consumption have an incentive to conserve. For occupants with full service rental contracts, energy consumption is higher as compared to occupants for which the rental contract is unknown, but the results are insignificantly different from zero.

To control for the heterogeneity of energy-use intensity across industries, we include the tenant composition in each building in all models. Our interest is primarily in the behavior of government tenants and the efficiency of the buildings of this specific tenant group. As shown in column (4) of Table 2, the variable measuring the fraction of a building occupied by a government tenant dummy is positive. If a building experiences an occupancy increase by a government tenant of 10%, the energy consumption in that building is about 3.6% higher, *ceteris paribus*. This result is obtained when controlled for building quality, but of course, building maintenance and the quality of equipment and appliances cannot be observed in our dataset.

In column (4), we also include a variable measuring the presence of on-site building management. Presumably, human capital is important in building energy efficiency optimization, and having an engineer on-site should be negatively related to commercial building energy consumption. Especially for buildings with a full-service

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[21] Again, our findings are based on the assumption that lease contract terms are exogenous. If energy-intensive tenants sort into buildings where they face zero marginal cost for electricity consumption, our results reflect a combination of selection and treatment effects, rather than treatment effects alone.

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Table 3
Dynamics in commercial building energy consumption (dependent variable: natural logarithm of kWh per square foot, 2000–2010).

	(1)	(2)	(3)	(4)	(5)
	All buildings	Office	Flex	Industrial	Retail
Occupancy rate (fraction)	2.189***	2.306***	1.855***	1.759***	2.481***
	[0.132]	[0.178]	[0.475]	[0.249]	[0.397]
Occupancy rate^2 (fraction)	−1.059***	−1.095***	−0.703**	−0.710***	−1.494***
	[0.094]	[0.128]	[0.339]	[0.184]	[0.265]
Unemployment rate (percent)	−0.016***	−0.012***	−0.013	−0.024***	−0.010
	[0.003]	[0.004]	[0.009]	[0.007]	[0.007]
Transaction dummy (1 = yes)	0.042***	0.045***	0.030	0.015	0.056**
	[0.011]	[0.015]	[0.044]	[0.026]	[0.025]
Constant	−4.860***	−4.653***	−5.130***	−5.538***	−4.380***
	[0.046]	[0.062]	[0.157]	[0.088]	[0.146]
Temperature-fixed effects$^{\#}$	Y	Y	Y	Y	Y
Month-fixed effects	Y	Y	Y	Y	Y
Year-fixed effects	Y	Y	Y	Y	Y
Building-fixed effects	Y	Y	Y	Y	Y
Observations	299,726	143,704	21,889	75,007	59,126
R-squared (within)	0.140	0.179	0.217	0.137	0.078
Number of buildings	2976	1430	208	742	596

Notes:
Coefficients based on model (2a). Building-fixed effects, year and month-fixed effects are included but not reported.
$^{\#}$Temperature decile 4 (40–50th percentile) omitted.
Standard errors are clustered at the building level and reported in brackets.
*** $p < 0.01$.
** $p < 0.05$.

lease structure, owners should be aware of the adverse incentive effects and they should have a greater incentive to invest in costly building management to increase energy efficiency. On-site management is present for some 17% of full-service buildings, whereas on-site management is present for just 2% of triple-net buildings.[22] The coefficient for "On-Site Management" shows that building management has a positive effect on commercial building energy efficiency, reducing energy consumption by some 7–8% — this finding is in line with the impact of management quality at corporations on the energy intensity of manufacturing plants, as documented by Bloom et al. (2011).

4.2. Electricity consumption dynamics

In this section, we exploit our building panel dataset from 2000 to 2010 to study the role of dynamic factors in determining a building's electricity consumption, i.e., how a building's electricity consumption varies as a function of climatic conditions (the average daily maximum outdoor temperature during the billing cycle) and the business cycle (the occupancy rate and the unemployment rate). We are especially interested in the interaction between climatic conditions and building observable attributes such as building vintage, building quality, and lease structure.

Using the panel, we also address the energy consumption dynamics as they relate to overall economic activity. Recent macroeconomic research by Henderson et al. (2011) documents a strong correlation between "night lights" and the overall economic performance of an economy. During a recession, a commercial building's occupancy rate will decline and this will cause a reduction in electricity consumption. Given that our data set covers the years during the recent great recession, we investigate what types of buildings are most responsive to spikes in the unemployment rate, and how carbon emissions are thus affected by changes in economic activity.

In Table 3, we report the estimates of Eq. (2a). We document a concave relationship between a building's occupancy rate and its electricity consumption — buildings that are partially occupied need to be heated or cooled as well, and there seems to be limited flexibility in "switching on or off" parts of a building. (In an ideal "smart building," the cooling and lighting is such that areas that are not occupied are not receiving such services. In such a building, electricity consumption will be very low when occupancy rates are low.) Beyond affecting occupancy rates, increases in local unemployment are associated with a reduction in commercial electricity consumption. A 1% increase in the unemployment rate decreases commercial building electricity consumption by about 2%. This may reflect the lower use-intensity of space (for instance, corporations having reduced presence of employees in the space they occupy).[23]

Columns (2) to (5) present the results stratified by building type. The regression coefficients indicate that industrial real estate seems to be the most responsive to building occupancy — at the point of means, a one standard deviation increase in the occupancy rate of industrial buildings increases electricity consumption by 9.1%. Office buildings are least responsive — a one standard deviation increase in the occupancy rate of office buildings increases electricity consumption by just 2.6%. Presumably, energy consumption in office buildings is for the largest part determined by whole building heating, cooling and ventilation.

In Table 3, we also report the coefficient for a dummy variable that is equal to one if the building has recently been sold (the dummy has a value of one for a period of 12 months after each transaction). For the full sample, electricity consumption increases by 4% in the year after buildings have transacted. We believe that this variable embodies two offsetting factors. A new owner is likely to make investments to raise

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[22] A *t*-test shows that the difference between these means is statistically significant from zero at the 1% level.

[23] The Federal Highway Administration has documented that total miles driven decreased as the 2008 recession took place (http://research.stlouisfed.org/fred2/series/M12MTVUSM227NFWA?rid=254). Our results complement this work and highlight the aggregate energy consumption consequences of business cycles.

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Table 4

Variation in the temperature response gradient by building attributes (dependent variable: natural logarithm of kWh per square foot, 2000–2010).

Temperature bin#	Temperature	Occupancy	Vintage (10–30)	Vintage (>30)	Class B	Class C	Triple net	Modified gross	Full service
1st	-0.035	-0.045^{**}	0.072^{***}	0.036^{**}	0.047^{***}	0.072^{***}	0.003	0.021	-0.035^{**}
	[0.026]	[0.021]	[0.015]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.015]
2nd	0.059^{**}	-0.157^{***}	0.072^{***}	0.062^{***}	0.051^{***}	0.056^{***}	-0.045^{***}	-0.025	-0.050^{***}
	[0.026]	[0.021]	[0.016]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.015]
3rd	-0.030	-0.042^{**}	0.040^{***}	0.039^{**}	0.014	0.023^{*}	0.012	0.034^{*}	-0.017
	[0.025]	[0.021]	[0.016]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.015]
5th	0.088^{***}	-0.080^{***}	-0.010	0.019	-0.028^{**}	-0.035^{***}	-0.052^{***}	-0.069^{***}	0.024
	[0.025]	[0.021]	[0.016]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.015]
6th	0.040	0.025	-0.013	0.010	-0.039^{***}	-0.037^{***}	-0.029^{*}	-0.044^{**}	0.029^{**}
	[0.025]	[0.021]	[0.015]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.014]
7th	0.037	0.040^{*}	0.026^{*}	0.066^{***}	-0.041^{***}	-0.033^{***}	-0.013	-0.030	0.034^{**}
	[0.025]	[0.021]	[0.015]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.015]
8th	0.094^{***}	0.062^{***}	0.004	0.052^{***}	-0.011	0.010	-0.026	-0.050^{**}	0.042^{***}
	[0.027]	[0.022]	[0.016]	[0.016]	[0.013]	[0.012]	[0.018]	[0.020]	[0.015]
9th	0.044	0.096^{***}	0.045^{***}	0.093^{***}	-0.012	0.021^{*}	-0.028	0.005	0.041^{***}
	[0.027]	[0.021]	[0.016]	[0.017]	[0.013]	[0.012]	[0.018]	[0.021]	[0.015]
10th	0.102^{***}	0.110^{***}	0.027^{*}	0.063^{***}	-0.029^{**}	0.008	-0.026	0.003	0.041^{***}
	[0.026]	[0.021]	[0.015]	[0.016]	[0.013]	[0.012]	[0.017]	[0.020]	[0.014]
F test	6.25	29.47	8.03	6.12	12.08	19.53	2.77	5.30	10.38
(p-Value)	0.000	0.000	0.002	0.000	0.000	0.000	0.003	0.000	0.000
Observations	299,726								
R-squared (within)	0.134								
Number of Buildings	2976								

Notes:

Coefficients from on a single regression based on model (2b). Each column (except for "Temperature") reports coefficients on the interaction between temperature and the corresponding variable. Building-fixed effects, year and month-fixed effects, and covariates on age and occupancy are included but not reported.

#Temperature decile 4 (40–50th percentile) omitted.

Standard errors are clustered at the building level and reported in brackets.

*** $p < 0.01$.

** $p < 0.05$.

* $p < 0.00$.

the quality of the building. Such investments, including a more efficient HVAC system and more efficient lighting, could make the building more energy efficient. Conversely, improvements in quality that result in better HVAC and lighting systems may induce greater use.

The final set of hypotheses we seek to test is how different types of commercial buildings perform under different temperature conditions. To study the temperature-elasticity, we estimate model (2b) for all buildings in one large pooled regression model, interacting the temperature bins with a large set of covariates (and building fixed effects). The results are reported in Table 4. The omitted category is a new building (age smaller than ten years) that is Class A real estate, whose lease term is "unknown." To flexibly model the temperature gradient, we include ten temperature bins, where the omitted category is the fourth decile. In this regression, the age of buildings and the occupancy rate vary within buildings over time. To illustrate the temperature-elasticity of electricity consumption, we calculate the predicted coefficients for buildings younger than ten years, buildings that are 10–30 years old, and buildings that are older than 30 years, at the mean occupancy (80.92%). We make analogous calculations for buildings with different lease structures.[24] We plot the predicted coefficients in Fig. 3.

Table 4 shows that, not surprisingly, the electricity consumption in buildings is higher during those months when it is very hot, and the differentials are quite large: for fully-occupied buildings, constructed less than ten years ago, monthly consumption is 21.2% higher when the temperature is 93 F, on average (the tenth decile), relative to when the temperature is 66 F (the fourth decile). We find little evidence of a large temperature gradient across Class B and C quality buildings, relative to new, Class A buildings (the omitted category). In colder months, lower quality buildings consume more energy than high quality buildings — this may be related to the increased thermal quality (windows, insulation, etc.) of more recently constructed buildings, following stricter building codes.

Fig. 3A shows that a high outdoor temperature is associated with a smaller increase in electricity consumption for newer buildings than for older buildings. At 90 F, the difference is about 10%. This finding stands in contrast with recent evidence on changes in electricity consumption of residential dwellings in response to temperature shocks. Chong (2012) finds for a large sample of homes in Southern California that more recently constructed homes exhibit significantly higher energy consumption during periods of peak temperatures. The findings also contrast our results for the absolute consumption of buildings as it relates to vintage: the lower temperature-elasticity of new buildings implies that peak electricity demand may decrease with the rejuvenation of the commercial building stock.

Fig. 3B shows the heterogeneity of the temperature-elasticity of electricity consumption across lease types. In buildings with triple-net leases, tenants are directly responsible for energy costs, whereas in buildings with full service lease contracts, tenants pay a lump sum for total housing costs, including energy and other service costs. We find that for buildings where tenants face a zero marginal cost for energy consumption, the response to increases in outside temperature starts at lower temperatures and increases more rapidly. This finding highlights the important role that occupant behavior plays in determining a building's electricity consumption dynamics. On hotter days, there will be greater demand for air conditioning and this demand will be even higher in buildings where tenants face a zero marginal cost for

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[24] For buildings younger than ten years, the predicted coefficient is simply [temperature + occupancy $*$ 0.809]. For buildings that are 10–30 years old, the coefficient is calculated as [temperature + occupancy $*$ 0.809 + age 10–30], whereas for buildings older than 30 years, the coefficient is [temperature + occupancy $*$ 0.809 + age 30]. Calculations are analogous for buildings with different lease types.

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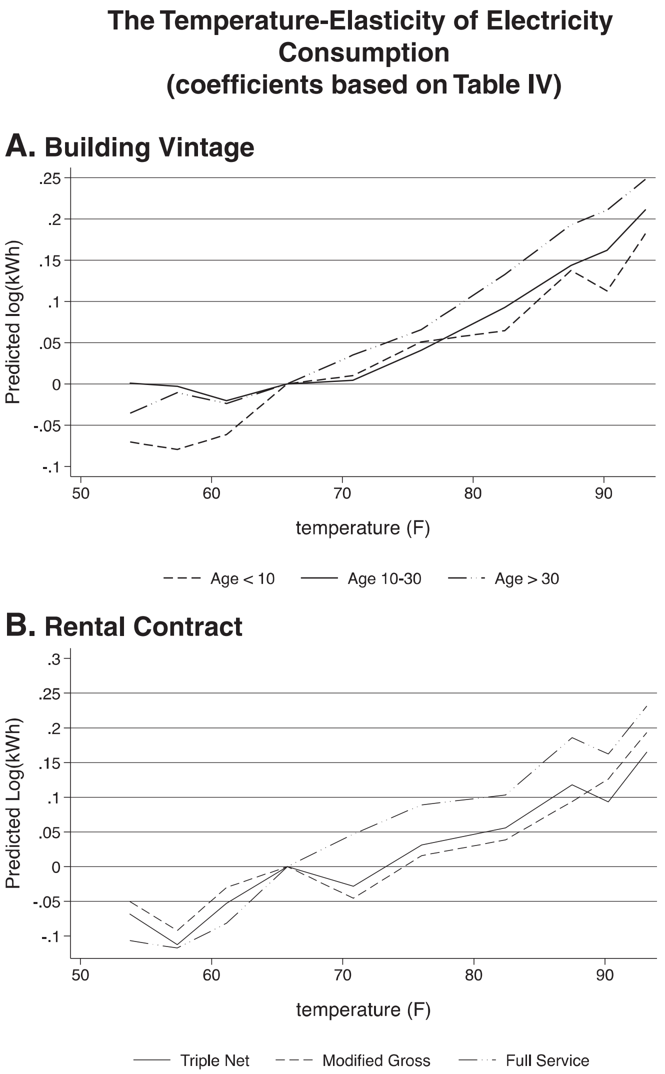

Fig. 3. The temperature-elasticity of electricity consumption (coefficients based on Table 4). Panel A represents predicted daily energy consumption, based on model (2b), for buildings younger than 10 years, buildings that are 10–30 years old, and buildings that are older than 30 years, at the mean occupancy rate (80.92%). Panel B presents analogous predictions for buildings with triple net rental contracts, modified gross rental contracts, and full service rental contracts. Values on horizontal axis represent average temperature of the corresponding decile. Temperature decile 4 (40–50th percentile) omitted.

consumption because they have a full service lease. One explanation for this finding may be that the indoor thermostat is set at a lower, more comfortable temperature when tenants do not face a marginal cost for energy consumption.

5. Conclusion

The Energy Information Agency predicts that between the years 2013 and 2040, residential electricity consumption will increase by 13%, industrial consumption will increase by 17%, and commercial electricity consumption will increase by 19%.[25] Such increased consumption will have significant greenhouse gas externality consequences. The EPA reports that in 2009, the nation's electric utilities produced on average 1,216 lb of carbon dioxide per MWH of electricity generated. Based on this emissions factor and a social cost of $35 per ton of carbon dioxide, this means that the U.S. commercial building stock currently imposes an annual social cost of $28 billion.[26]

An ongoing policy agenda seeks to identify cost-effective climate change mitigation strategies (Konrad and Thun, 2012; Stern, 2008). Our work highlights the importance of focusing on the commercial building stock. Given that commercial buildings are often operated by for-profit managers, this sector is likely to be more responsive to economic incentives for energy conservation relative to the residential sector, where households have been found to exhibit behavioral biases that sometimes discourage making cost effective energy efficiency investments (Allcott et al., 2014).

There is a well-developed literature on residential energy efficiency policies, programs, and interventions, but it is surprising how little we know about commercial building electricity consumption. To fill this void, we partnered with a major electric utility and merged information on electricity consumption at the building level with detailed physical attributes of the building. Although the commercial building stock has been subject to building codes, we document that, since 1970, there is an inverse relation between building age and electricity consumption. This finding stands in contrast with evidence on energy consumption trends for residential structures. Our finding of a negative correlation between commercial building age and electricity consumption means that the commercial's share of total electricity consumption could rise over time. We also address the tenant–landlord problem, a well-known market failure, and its relation to energy efficiency. We document that in buildings where the tenant does not face a marginal cost of energy consumption, energy consumption is higher, and is more responsive to increases in outdoor temperature.

Our findings have implications for public policies related to energy consumption and resulting environmental externalities. The commercial building stock has to date faced limited regulation to reduce externalities from carbon emissions. While newer vintages are subject to building energy efficiency codes, electricity consumers in the commercial real estate sector have not faced a carbon tax. It is notable that during the 1960–2010 period, for tenants in commercial buildings, average real electricity prices decreased by 14%.[27] Our work highlights the large differences in electricity consumption across commercial buildings, and based on our findings regarding lease contracts we find evidence that tenants do respond to the marginal cost of electricity consumption.

Future research should investigate whether the operation of real assets by institutional real estate owners actually helps to mitigate the carbon externality associated with the commercial real estate sector. Such owners may have access to the financing and the human capital needed to achieve a more efficient energy performance than smaller landlords per square foot of real estate. A substantial capital investment in new commercial buildings is currently taking place and, given the durability of the capital stock, the choices made today (in the absence of a carbon tax) will have consequences for decades.

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[25] See the Energy Information Administration's *Annual Energy Outlook 2014 Early Release Overview*. http://www.eia.gov/forecasts/aeo/er/excel/aeotab_2.xlsx.

[26] Calculation based on total electricity consumption of the commercial real estate sector (source: U.S. Energy Information Administration — January 2014 Monthly Energy Review) and eGRID 2009 emission factor (source: http://www.epa.gov/cleanenergy/energy-resources/refs.html).

[27] Energy Information Agency. Annual Energy Review 2010. See http://205.254.135.24/totalenergy/data/annual/pdf/aer.pdf.

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Appendix A

Appendix Table A1
Tenants in commercial buildings (building type, vintage and lease structure, 2009).

Panel A. Commercial building type

		Building class				Property type		
Industry of tenant	Overall	Class A	Class B	Class C	Office	Retail	Flex	Industrial
Agri/mining/utilities	5.18	2.55	6.02	7.14	2.59	0.00	9.22	11.31
Communications	0.94	3.79	1.17	0.90	1.14	0.00	1.70	1.00
Data processing	1.55	3.22	2.64	1.18	2.26	0.00	4.46	0.53
Distribution	8.85	5.34	9.26	12.70	3.00	0.04	10.47	23.23
Financial services	10.17	17.89	11.34	10.59	19.16	5.84	3.39	1.55
Government	4.30	15.28	6.11	3.52	7.72	0.48	5.29	1.28
Manufacturing	5.93	6.57	6.75	7.68	1.49	0.14	13.03	14.31
Medical services	6.85	4.57	9.22	8.25	14.27	0.38	5.01	0.40
Non-profits	0.12	0.00	0.14	0.09	0.17	0.20	0.10	0.00
Professional services	9.50	14.62	12.09	10.74	16.71	0.25	9.00	4.80
Retail	7.79	0.00	0.64	0.24	0.12	39.34	0.37	0.79
Services	17.04	13.43	16.91	19.69	18.08	11.86	20.12	17.91
Transportation	1.44	0.84	1.50	2.14	0.66	0.00	0.54	3.90
Personal services	13.98	12.75	15.82	18.64	17.82	0.21	17.62	16.13
Other	20.34	11.90	16.22	15.12	12.63	41.47	17.32	18.97

Panel B. Vintage and lease structure

	<10 years		>50 years		Full service		Triple net	
Industry of tenant	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Agri/mining/utilities	4.61	(19.2)	4.02	(19.28)	2.55	(12.60)	2.08	(12.70)
Communications	0.45	(6.35)	0.74	(7.7)	0.68	(4.82)	0.18	(1.25)
Data processing	0.97	(7.44)	0.13	(2.52)	2.61	(11.60)	0.90	(6.43)
Distribution	7.16	(23.06)	4.06	(17.26)	2.23	(8.54)	6.12	(21.37)
Financial services	13.72	(30.8)	7.83	(24.15)	23.86	(32.53)	23.36	(38.50)
Government	2.53	(13.81)	1.85	(12.19)	10.24	(25.91)	0.41	(4.16)
Manufacturing	4.45	(18.3)	1.58	(11.37)	1.65	(8.74)	2.15	(13.85)
Medical services	7.3	(24.33)	6.83	(24.24)	9.62	(24.49)	10.37	(27.39)
Non-profits	0.14	(2.16)	0.34	(3.96)	0.11	(1.37)	0.77	(5.57)
Professional services	8.08	(22.27)	4.64	(18.96)	19.51	(28.40)	9.28	(23.70)
Retail	9.75	(26.87)	18.95	(36.36)	0.08	(1.49)	0.13	(1.88)
Services	3.3	(16.32)	5.37	(20.62)	0.21	(2.09)	0.15	(2.21)
Transportation	2.27	(13.97)	0.55	(7.3)	0.50	(3.83)	0.09	(1.22)
Personal services	10.69	(28.16)	9.62	(27.21)	14.64	(26.74)	15.33	(32.36)
Other	24.57	(39.02)	33.51	(44.5)	11.53	(23.46)	28.68	(39.13)

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jpubeco.2014.03.003.

References

Allcott, Hunt, 2011. Social norms and energy conservation. J. Public Econ. 95 (5), 1082–1095.

Allcott, Hunt, Mullainathan, Sendhil, Taubinsky, Dmitry, April 2014. Energy policy with externalities and internalities. J. Public Econ. 112, 72–88.

Aroonruengsawat, Anin, Auffhammer, Maximillian, 2011. Simulating California's Future Residential Electricity Consumption Under Different Scenarios of Climate Change. Climatic Change 111 (2), 411–424.

Bloom, Nicholas, Genakos, Christos, Martin, Ralf, Sadun, Raffaella, 2011. Modern management: good for the environment, or just hot air? Econ. J. 120, 551–572.

Chong, Howard, 2012. Building vintage and electricity use: old homes use less electricity in hot weather. Eur. Econ. Rev. 56 (5), 906–930.

Costa, Dora L., Kahn, Matthew E., 2011. Electricity consumption and durable housing: understanding cohort effects. Am. Econ. Rev. 101 (3), 88–92.

Davis, Lucas W., 2008. Durable goods and residential demand for energy and water: evidence from a field trial. RAND J. Econ. 39 (2), 530–546.

Davis, Lucas W., 2010. Evaluating the slow adoption of energy efficient investments: are renters less likely to have energy efficient appliances? In: Fullerton, D., Wolfram, C. (Eds.), The Design and Implementation of US Climate Policy. The University of Chicago Press, Chicago.

Dêschenes, Olivier, Greenstone, Michael, 2011. Climate change, mortality, and adaptation: evidence from annual fluctuations in weather in the US. Am. Econ. J. Appl. Econ. 3, 152–185.

Eichholtz, Piet M.A., Kok, Nils, Quigley, John M., 2010. Doing well by doing good: green office buildings. Am. Econ. Rev. 100 (5), 2494–2511.

Glaeser, Edward L., Kahn, Matthew E., 2010. The greenness of cities: carbon dioxide emissions and urban development. J. Urban Econ. 67 (3), 404–418.

Greening, Lorna, Greene, David L., Difiglio, Carmen, 2000. Energy efficiency and consumption—the rebound effect—a survey. Energy Policy 6, 389–401.

Gould, Eric D., Pashigian, B. Peter, Prendergast, Canice J., 2005. Contracts, externalities, and incentives in shopping malls. Rev. Econ. Stat. 87 (3), 411–422.

Ham, John C., Mountain, Dean C., Luke Chan, M.W., 1997. Time-of-use prices and electricity demand: allowing for selection bias in experimental data. RAND J. Econ. 28, 113–141.

Henderson, Vernon, Storeygard, Adam, Weil, David N., 2011. A bright idea for measuring economic growth. Am. Econ. Rev. 101 (3), 194–199.

Hirst, Eric, Jackson, Jerry, 1977. Historical patterns of residential and commercial energy uses. Energy 2 (2), 131–140.

Horowitz, Marvin J., 2004. Electricity intensity in the commercial sector: market and public program effects. Energy J. 25 (2), 115–137.

Ito, Koichiro, 2014. Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing. Am. Econ. Rev. 140 (2), 537–563.

Jacobsen, Grant D., Kotchen, Matthew J., 2013. Do building energy codes matter? Evidence from Florida. Rev. Econ.Stat. 95 (1), 34–49.

Jaffee, Dwight, Stanton, Richard, Wallace, Nancy, 2012. Energy factors, leasing structure and the market price of office buildings in the U.S. AREUEA Annual Meeting. Chicago.

Kavalec, Chris, Gorin, Tom, 2009. California Energy Demand 2010–2020, Adopted Forecast. California Energy Commission.

Knittel, Christopher R., 2012. Automobiles on steroids: product attribute trade-offs and technological progress in the automobile sector. Am. Econ. Rev. 101 (7), 3368–3399.

Konrad, Kai A., Thun, Marcel, 2012. The Role of Economic Policy in Climate Change Adaptation. Max Planck Institute for Tax Law and Public Finance.

Kornai, Janus, Maskin, Eric, Roland, Gerard, 2003. Understanding the soft budget constraint. J. Econ. Lit. 41 (4), 1095–1136.

Kotchen, Matthew J., Mansur, Erin T., 2014. How stringent is the EPA's proposed carbon pollution standard for new power plants? Rev. Environ. Econ. Policy (in press).

Levinson, Arik, Niemann, Scott, 2004. Energy use by apartment tenants when landlords pay for utilities. Resour. Energy Econ. 26 (1), 51–75.

Author's personal copy

Papineau, Maya, 2013. Energy codes and the landlord–tenant problem. CUDARE Working Papers. UC Berkeley.

Qiu, Lucy Yueming, 2014. Energy efficiency and rebound effects: an econometric analysis of energy demand in the commercial building sector. Environ. Resour. Econ. (in press).

Sappington, David E.M., 1991. Incentives in principal–agent relationships. J. Econ. Perspect. 5 (2), 45–66.

Small, Kenneth A., Van Dender, Kurt, 2007. Fuel efficiency and motor vehicle travel: the declining rebound effect. Energy J. 28, 25–51.

Stern, Nicholas, 2008. The economics of climate change. Am. Econ. Rev. 98 (2), 1–37.