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Towards urban facilities energy performance evaluation using remote sensing

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Abstract

Urban facilities are major contributors to annual energy consumption and therefore, evaluating their energy efficiency and retrofit planning play a major role in achieving sustainability goals. For urban facilities, such as buildings, energy performance audits could be conducted by detailed evaluation at building level. However, at urban level, detailed evaluation is cost and time intensive. Therefore, in this study, we investigated the correlation between land surface temperature, obtained through satellite imagery, and energy consumption patterns at urban level to explore its feasibility for energy performance evaluations. New York City was used as the main case study for conducting the analysis. We have investigated the correlation between energy consumption intensity and temperature at city block level for selected points. The outcome demonstrates a strong correlation between energy consumption intensity and land surface temperature. The observed correlation could potentially be leveraged for developing an approach for energy performance auditing.

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Keywords: Urban facilities, Energy management, Remote sensing, Thermal imagery ;

1. Introduction

Energy consumption in buildings specifically for air conditioning and lighting systems significantly contribute in energy expenditure and emission foot print of the buildings. Accordingly, performance evaluation of the building assets plays a critical role in infrastructure operational analytics. Building energy evaluations could be carried out for different aspects including the building material, building systems and appliances[1, 2], and occupant behavior [3].

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Nomenclature

L	spectral radiance
DN	digital number of satellite image
K_1	calibration constant
K_2	calibration constant
LST	land surface temperature

Building envelope retrofit is at the forefront of the practical techniques for improving the energy performance of buildings. Energy audits are commonly carried out to identify the extent and location for retrofitting the envelope. Upon identification of the locations, different techniques could be used for improvement. These methods seek to prevent the waste of energy in buildings by improving physical characteristics of the envelope such as R value of the walls.

Energy audits for buildings are commonly carried out by visual inspection as well as thermographic imagery using manual Infrared (IR) thermal imaging cameras. Upon these inspections, the retrofit plans are suggested based on the material characteristics. Although these methods are being practically used for building level evaluations, expanding their applications for energy performance assessment at urban/neighborhood level would be prohibitively expensive due to scale increase. The facility-level performance assessments and retrofit planning are justified by evaluating the trade-off between cost and thermal comfort gain. However, at urban level, building asset energy performance evaluations could contribute to implementing federal or local policies for energy conservation and emission control or participating in improving the urban heat island phenomena (higher temperatures in urban areas compared to corresponding rural environment [4]). By having this information, city authorities can identify inefficient facilities, notify their owners and provide incentives for mitigating strategies. Although a few studies have explored the relationship between energy management in facilities and phenomena such as UHI and climate change [5], the anthropogenic effect of facilities' energy management on these phenomena are yet to be systematically explored.

Remote sensing technologies were also used for land surface temperature sensing. Thermal infrared satellite images have been used in climatic condition studies such as distribution of air temperature. In general, remote sensing infrared images could be captured using either space-borne sensors (satellite imaging) or air-borne sensors (sensors that are commonly carried by airplanes). In urban studies, several research efforts have used remote sensing technologies for study of the UHI phenomenon and remedial methods [6, 7]. Examples applications include identifying the solar reflectivity [8-10], solar absorbance [11], surface albedo calculation [12], as well as solar energy potential evaluation. However, in majority of the studies, air-borne sensing techniques were used to ensure that images with higher resolution could be captured. Since air-borne sensing solutions could provide customized data acquisition specifications, their application is cost intensive compared to satellite imagery.

In this study, we have explored the feasibility of space-borne remote sensing technologies for evaluation of urban infrastructure energy performance. The highest resolution of thermal images, acquired by using space-borne IR sensors is 90-100 meters in its raw format (LANDSAT 8 satellite can provide up to 30-meter resolution through resampling and interpolation). Such resolution cannot provide enough information for building level evaluations considering the common dimensions of buildings in urban areas. However, surface temperature information at this resolution could be used as a potential source of information for regional/neighborhood level evaluations. These evaluations provide the urban infrastructure managers with information resources to identify susceptible areas for detail explorations by using either air-borne or building level infrared imaging techniques. In order to achieve this objective, we have explored the correlation between energy use in building/neighborhood levels with surface temperature obtained from satellite images. As our case study, we have selected New York city considering its multiscale urban levels including neighborhoods and building blocks.

Our methodology section (Section 2) describes the data sources and techniques that we used for processing the data. The results of the exploration are presented in Section 3, followed by discussion on future applications of the technology as well as conclusion.

2. Data Sources and Processing

2.1. Remotely Sensed Infrared Imagery

There are two main data sources for space-borne thermal infrared images from ASTER and LANSDAT 8 satellites, that are described as follows:

- ASTER
  The Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) is an advanced multispectral imager that takes images with 14 bands from the visible to the thermal infrared. Bands 10-14 are associated with TIRS (Thermal Infrared Sensor). Approximate scene size is 120 by 150 kilometers. The spatial resolution for the thermal infrared (TIR) images is 90 m. ASTER was launched in December 1999, and the data is available since 2000.

- LANDSAT 8
  LANDSAT 8 satellite has thermal infrared sensor with the spatial resolution of 100 m. The data is available since April 2013. It has 11 bands, and bands 10 and 11 are thermal infrared (TIR). Approximate scene size is 170 km north-south by 183 km east-west. Band 10 has wavelength of 10.6-11.19 micrometers and band 11 has 11.50-12.51 micrometers. Although TIRS bands are acquired at 100-meter resolution, they are resampled to 30 meter in delivered data product.

  In this study, we have used LANDSAT 8 images. In the following section, the process of converting images to surface temperature maps are presented.

2.2. Thermal Infrared Image Processing

The first step for processing the satellite images is to correct images radiometrically to be able to compare them with in situ infrared thermometer measurements. The process converts digital number (DN) in the LANDSAT images to radiance:

$$L = L_{min} + (L_{max} - L_{min}) * \frac{DN}{255}$$

where L is spectral radiance, L_{min} is spectral radiance of DN value 1, L_{min} is spectral radiance of DN value 255. For DN we are using B_{10}, which is the thermal infra-red information in satellite images. The radiance is converted to land surface temperature (LST) as follows:

$$LST = \frac{K_2}{\ln\left(\frac{K_1}{L}\right) + 1}$$

in which, K_1 and K_2 are calibration constants equal to 774.89 and 1321.08, respectively. The resulted land surface temperature is in Kelvin and a conversion to Celsius ($LST_C = LST_K - 273.15$) is carried out.

2.3. Energy Consumption Data

Energy data in an urban area could be found in different granularities including building unit level, building level, block level, and neighborhood level. Considering the resolution of the thermal images, we need to use an energy data source that helps us compare the energy consumption with land surface temperature. Therefore, scale compatibility is an important factor in our analysis. Furthermore, the energy consumption should reflect the operation of air conditioning systems (for space heating and cooling), which includes electricity and fuel use, in addition to other applications including appliances, water heating, etc. Moreover, in order to account for building scale effect, the energy consumption per floor area should be considered. To account for these factors, we adopted the data set developed by Howard et al. [13].

Howard et al. developed a model that estimates buildings energy intensity for different end-use applications. Their model represents energy intensity in terms of kwh/m^2 (m^2 of buildings' floor area) for space heating, domestic hot water, electricity for space cooling, and electricity for non-space cooling, and therefore, it accounts for air conditioning. The total energy consumption reflects annual electricity and natural gas, steam, or fuel oil consumption. PLUTO, the geo-rectified NYC building stock database, obtained from NYC Department of City Planning, was used for extracting the building floor area. The spatial resolution of this database is at the tax lot level and therefore, this is the resolution that was used in total annual energy consumption calculation. Their data set and thus their model reflects the energy consumption for 2009. For the year 2009, annual heating and cooling degree days were close to the 30-year average suggesting that minimal bias is introduced by selecting this specific year. Fig. 1. shows the electricity distribution map in different boroughs.

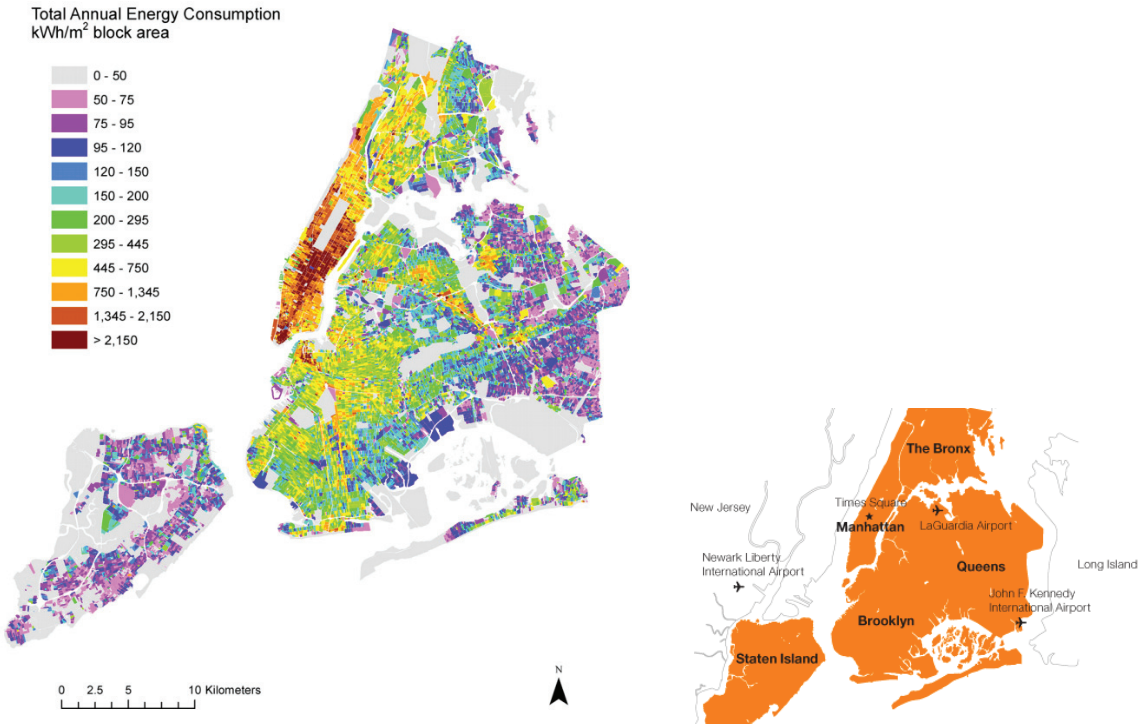


Fig. 1. Total annual energy consumption in New York City per block (left) [13] and New York City Neighborhoods (right) (from nycgo.com)

3. Data Analysis and Discussion

3.1. Correlation Analysis

Using the aforementioned processes, we processed the LANDSAT 8 satellite image for NYC to obtain the LST values. We selected the data from March 2015 for our analysis. For selecting the images for processing we had two main criteria: a) the image should reflect surface temperature for a cold season so that the effect of the indoor heating on the buildings' envelope could be investigated; b) the image should have maximum clarity, which practically means minimum occlusions from clouds. Fig. 2. illustrates the distribution of land surface temperature for NYC. The minimum values are at the ocean and therefore, we have removed those areas from the image. The maximum LST reaches 12 °C.

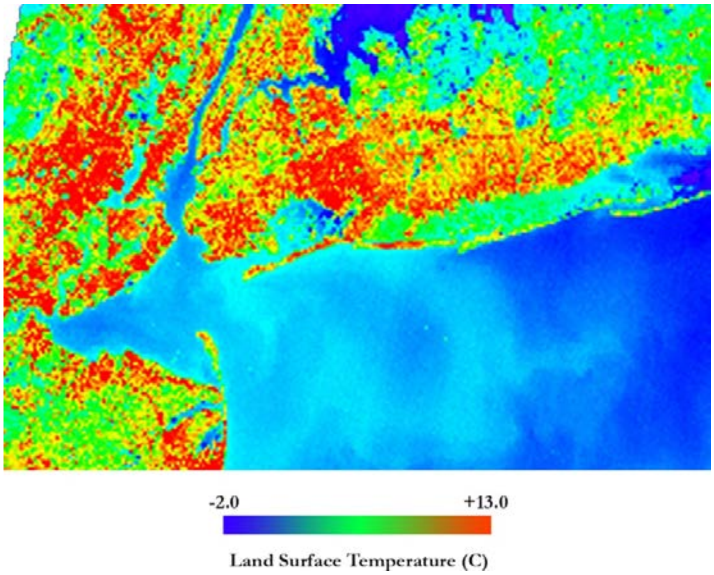


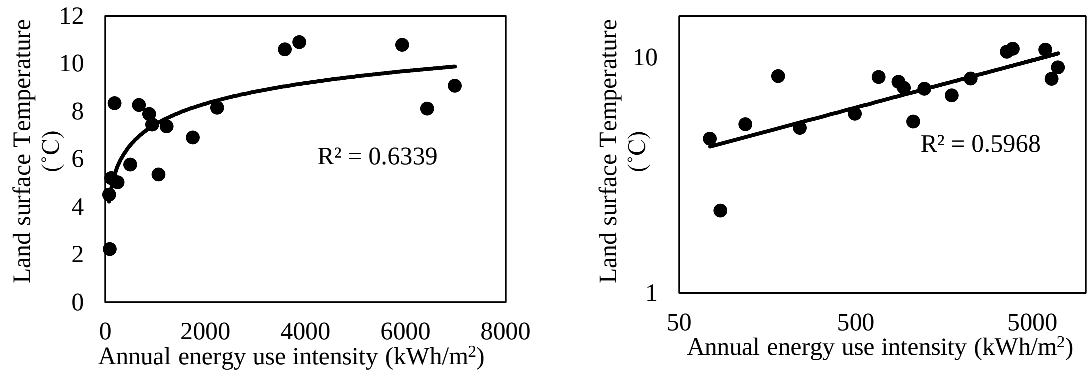
Fig. 2. Land surface temperature (LST) of NYC in March 2015 converted from LANDSAT 8 satellite images

In order to investigate the potential correlation between the land surface temperature and total annual energy consumption in the buildings, 20 points of data were selected from different boroughs (neighborhood) to account for variation and a relatively full range of LST values. In order to account for extreme cases, the points were chosen from different urban areas (ranging from parks and shores to dense neighborhoods). Table 1 shows the data pairs, extracted from energy and temperature data sets and matched between two data sources. In this table, two points were selected in green areas and therefore, no Block ID was assigned to them.

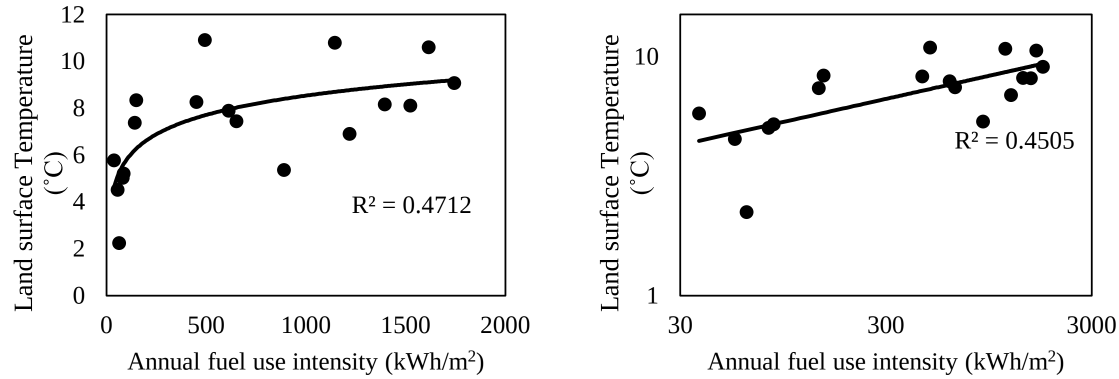
Table 1. Selected sample pairs from different neighborhoods based on full range of temperature variations

Block ID	22	559	8231	Green Area	Green Area	6943	1918	1004	1500	6792
Electricity (kWh/m^2)	4906.7	170.4	19.5	0	0	160.4	3386.1	5243.4	1973.7	1080.5
Fuel (kWh/m^2)	1523.7	889.2	55.3	0	0	80.8	492.5	1743.1	1616.3	141.7
Total Energy (kWh/ m^2)	6430.4	1059.6	74.8	0	0	241.1	3878.6	6986.5	3589.9	1222.3
LST (°C)	8.12	5.36	4.52	1.2	0.76	5.03	10.91	9.08	10.6	7.38
Block ID	8329	8606	8907	147	2174	1503	1730	1669	3226	8689
Energy (kWh/m^2)	32.4	22.7	33.5	4789.1	284.4	530.7	262.1	842.2	222.6	456.9
Fuel (kWh/m^2)	149.3	63.1	85.4	1144.2	651.9	1218.2	611.9	1395.4	451.4	37.0
Total Energy (kWh/ m^2)	181.7	85.8	118.9	5933.3	936.3	1748.9	873.9	2237.6	673.9	494
LST (°C)	8.35	2.24	5.21	10.8	7.45	6.91	7.89	8.16	8.27	5.78

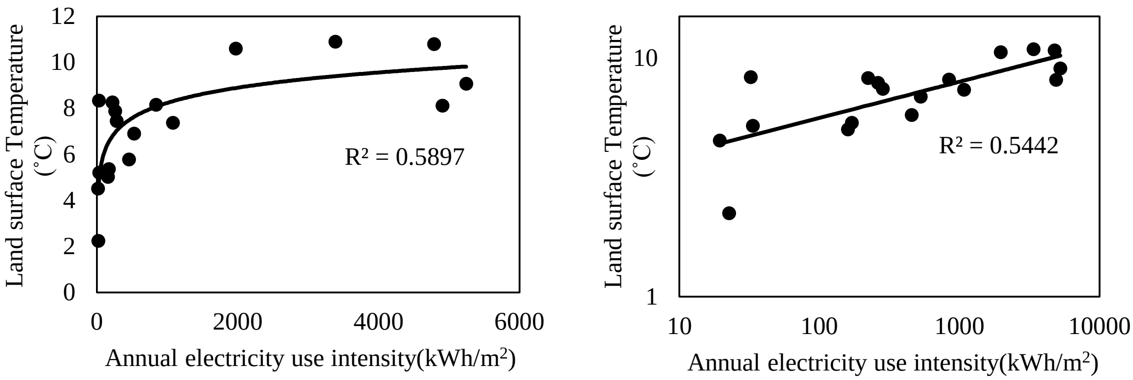
In order to explore correlation between these two sources of data a regression analysis was used. Fig. 3. illustrates the results of the regression analysis in both arithmetic and logarithmic scale. As the plots in this figure illustrate, the total annual energy consumption per floor area in different blocks is highly correlated (R^2=0.63) with land surface temperature obtained from the satellite analysis. Highly correlated energy-LST data shows the potential for leveraging the satellite imagery-based thermal evaluation for energy efficiency at urban level.



Total annual energy concumption (electricty and fuel) - Spearman Corr. Coef.=0.73



Annual fuel consumption - Spearman Corr. Coef.=0.64



Annual electricty consumption - Spearman Corr. Coef.=0.71

Fig. 3. Regression analysis and correlation between annual energy consumption and land surface temperature in different blocks of NYC in arithmetic (left) and logarithmic (right) scales

Fig. 3. also shows the scatter plot for electricity and fuel consumption intensity. Fuel includes natural gas, heating oil, and steam. The results for Spearman correlation coefficients were also presented in Fig. 3. As the results show, although the fuel consumption intensity is the least correlated parameter with land surface temperature, combination of electricity and fuel consumption intensities shows a higher correlation compared to electricity consumption intensity alone.

3.2. Correlation and Causality Discussion

As noted, the total annual energy consumption and land surface temperature in a cold season of the year are highly correlated. The total energy includes the end use energy consumption including space heating and air conditioning. In a cold season, the indoor air conditioning is conducted through heating. The indoor temperature is higher than the outdoor temperature and therefore, it is rational to have a heat flux from indoor to outdoor environment. However, in an efficient building envelope, the heat flux from inside to outside should be avoided as it is commonly measured in energy audits using thermal cameras at building levels for calculating R values.

Now, the question is whether we can conclude that the areas with higher LST values are susceptible areas and should be prioritized for retrofit planning? Answering this question calls for causality analysis in addition to observed correlations. Since energy data, used in this study, is the energy intensity values (i.e., energy consumption per floor area of buildings), normalization of building scale effect has been taken into account. Therefore, high correlation between the energy intensity and LST shows that the satellite thermal imagery has potential to be used for energy efficiency assessment. However, conclusive causality inference calls for further investigations at smaller scales to evaluate the building scale effect, as well as building envelope material characteristics.

4. Conclusion

New York city was used as a case study to investigate the correlation between energy consumption intensity and land surface temperature. The data from thermal infrared sensor on LANDSAT satellite (in march 2015) was used for calculation of the land surface temperature. The energy information was used from Howard et al. [13] to account for total energy consumption for air conditioning at block level. This data set includes the energy consumption information in both electricity and fuel consumption forms. Regression and correlation analyses were conducted for data points, collected from different locations in NYC to cover a wide range of energy consumption and variability. A strong correlation between total energy consumption intensity (energy consumption per floor area including electricity and fuel consumption) and land surface temperature was observed. This correlation shows that there is a potential to use satellite infrared imagery for building assets energy performance evaluation at urban level. However, further studies are required in order to draw significant conclusions regarding the causality and effectiveness of the satellite images for retrofit planning.

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