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A Measured Energy Use, Solar Production, and Building Air leakage Dataset for a Zero Energy Commercial Building

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Abstract
This paper provides an open dataset of measured energy use, solar energy production, and building air leakage data from a 328 m^2 (3,531 ft^2) all-electric, zero energy commercial building in Virginia, USA. Over two years of energy use data were collected at 1-hour intervals using circuit-level energy monitors. Over six years of solar energy production data were measured at 1-hour intervals by 56 microinverters. The building air leakage data was measured post-construction per ASTM-E779 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization and the United States Army Corps (USACE) Building Enclosure Testing procedure; both pressurization and depressurization results are provided. The architectural and engineering (AE) documents are provided to aid researchers and practitioners in reliable modelling of building performance. The paper describes the data collection methods, cleaning, and convergence with weather data. This dataset can be employed to predict, benchmark, and calibrate operational outcomes in zero energy commercial buildings.

Background & Summary
Significant data is generated in the built environment. Design and construction documents, performance simulations, commissioning results, and building performance data (BPD) are generated on all modern buildings. Today, system advancements in energy efficiency, integration, monitoring, and connectivity are expanding our design and facility management options throughout the built environment. Internet-enabled monitoring, ubiquitous user interfaces, machine learning, and artificial intelligence are facilitating analytical approaches not previously afforded to our industry. As buildings become more complex, the need to measure, analyze, and share BPD has become salient.

Open datasets are critical for advancing building performance and analytical methods. Open BPD can be leveraged to calibrate design simulations and inform future design, construction, and operational decisions. Open BPD can facilitate benchmarking performance across building types, vintage, and geographic distributions[1]. Conversely, open BPD can be used to benchmark machine learning techniques for the built environment[2]. Simply put, open BPD are a critical component in the systems approach necessary to improve outcomes in the built environment including, but not limited to reducing carbon emissions and operating costs and improving human experiences in the built environment.

The Architecture, Engineering, Construction, and Operation (AECO) industry rarely systematically collects or shares BPD. Researchers increasingly collect BPD, yet rarely share BPD in open-source data repositories[3]. In recent years, however, there has been a trend to develop and share open-source BPD[4–12]. For example, there are recent open BPD contributions focused on occupant behavior impacts on energy use and indoor environmental quality (IEQ). These contributions span human-building interactions with appliances[5], heat pumps[7], and natural ventilation systems[8]. Other recent contributions span energy use across building typologies (e.g., commercial and residential) [9–12]. This paper contributes to the recent trend toward open BPD datasets.

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There are two novel contributions of this work. First, the longitudinal energy use and energy production data can be employed in the pursuit of zero energy building design and performance. As we race toward zero energy buildings, open BPD become critical for reducing performance gaps between expected and realized performance. The volume and variety of small commercial buildings compounds the need to go beyond simple benchmarking exercises and requires higher resolutions of data to achieve performance targets. The second contribution of this work is the building air leakage dataset combined with longitudinal energy use and energy production data. While building air leakage is an important factor in predicting energy use, estimating heating and cooling loads, and designing for indoor environmental quality (IEQ), it is rarely available in open BPD. The balance of this paper characterizes the case study project, data collection methods, and resulting data records.

Methods

Case study context. This dataset was developed from a single, non-random case study project. The building serves as a leasing office and community building for a national non-profit housing provider (referred hereafter as the "owner"). The owner's mission whose is to create homes and communities that are healthy, sustainable, and affordable. The building was designed in 2013 and construction was completed in April 2014. The owner pursued EarthCraft Light Commercial (ECLC), a regional 3rd party green building program. The ECLC program was used to verify high performance design and construction targets were achieved. Table 1 provides an overview of the building specifications and the following section characterizes the data collection techniques for the energy use, energy production, and building air leakage data.

Category	Parameters	Building Characteristics
General	Climate zone	Mixed-humid, US 4A
	Building type	Office
	Area	328 m^2 (3,531 ft^2)
Enclosure	Enclosure surface area	1,155 m^2 (12,437 ft^2)
	Window U-value SHGC (g-value)	0.30 BTUh/ft^2/°F (1.70/W/m^2K) 0.22
	Visible light transmittance	0.41
	Wall U-value	0.04 BTUh/ft^2/°F (0.13 W/m^2K)
	Roof/Attic U-value	0.02 BTUh/ft^2/°F (0.11 W/m^2K)
	Air tightness	1.02 L/s-m^2 at 75 Pa (0.20 cfm_{75}/ft^2)
Systems	Heating system	Air-source heat pump, 9 HSPF (n=3)
	Cooling system	Air-source heat pump, 15.5 SEER (n=3)
	Distribution	3 ducted air systems, within thermal boundary
	Temperature control	Programmable thermostat (n=3)
	Water heating	30-gallon, electric storage (0.93 EF)
	Ventilation	Energy recovery ventilator
	Int. Lighting Power Density	7.62 W/m^2 (designed)
	Ext. Lighting Power Density	1.21 W/m^2 (designed)
	Solar PV-system	75.2 m^2, 12.3 kWp, panels & microinverters (n=56), Azimuth: 135°

Table 1. Building specifications.

Energy use. Energy use data were measured using a SiteSage energy monitoring system. 150A current transformers (CTs) were installed on the building electrical mains, while 20A or 50A CTs were installed on the balance of the building's circuits depending on the circuit load (e.g., water heating, lights, heat pump). Thirty discrete circuits are measured and reported in the dataset. Each CT transmitted energy use in one-hour intervals to an internet-enabled

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gateway located in the electrical panel. Data were accessed via an online user interface and downloaded as a .csv file for the purposes of this data descriptor. It is important to note that for safety reasons related to accessing a live electrical panel, a licensed electrician installed the CTs in the presence of the corresponding author.

Energy production. Energy production data were measured from the building's roof mounted, 12.3 kWp solar photovoltaic (PV) system. The solar PV system was equipped with 56 microinverters that reported production data via power line communications to an Enphase internet-enabled gateway. The microinverter production data is aggregated and reported in one-hour intervals. Data were accessed through an online user interface and downloaded as a .csv files for the purposes of this data descriptor. The energy production monitoring system was installed by a licensed solar contractor. Access to the user interface and data was provided to the authors by the owner.

Building air leakage. The case study's building enclosure was tested at the end of the project's construction phase in April 2014. Building air leakage data were measured per the U.S. Army Corps of Engineers (USACE) Air Leakage Protocol for Building Envelopes[13] and ASTM E779 - Standard Test Method for Determining Air Leakage Rate by Fan Pressurization[14]. Building air leakage rates were measured with two calibrated blower door fans, and two calibrated digital micromanometer gauges. Category 5 (CAT5) cable was used to connect the gauges to TECLOG3, a data logging software developed by the fan and gauge manufacturer. The software was also used to provide results in compliance with ASTM E779 (described in the Data Records section of this descriptor).

The USACE protocol requires two tests: a multi-point depressurization test and a multi-point pressurization test. During the test, all intentional enclosure penetrations (e.g., outdoor air, make-up air, and exhaust air penetrations) are sealed with masking. Following a pre-test baseline, ten points were collected ±20 Pa (0.08 inH_2O) to ±75 Pa (0.3 inH_2O) at 5 Pa (0.02 inH_2O) intervals. Following each test, a post-test baseline was measured. Each point was averaged over 10 seconds. Figure 1 provides a representation of the building air leakage tests per the USACE protocol.

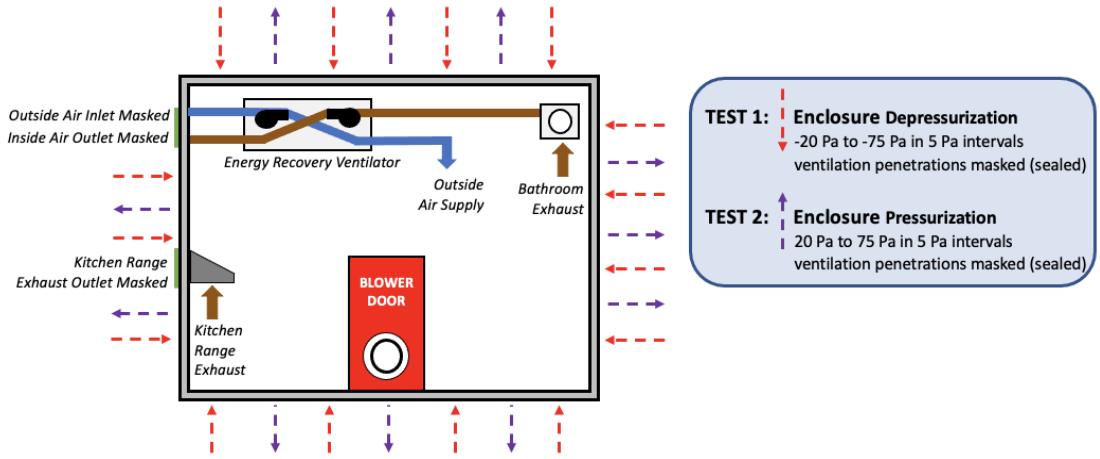

Fig. 1 USACE Building Enclosure Testing procedure.

Data Records

The primary and secondary data that accompany this data descriptor are provided at the Open Science Framework (OSF) respiratory[15]. The dataset is organized in five categories: 1) measured energy use, 2) measured energy production, 3) measured building air leakage, 4) weather, and 5) architectural and engineering (AE) documents. All data are provided in .xlsx,

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with the exception of the EnergyPlus weather files and AE documents. Table 2 characterizes the study's primary data records.

Category	Data Description	Unit	Data Resolution	Data Output
Energy Use	Circuit-level energy consumption	kWh	☐ Hourly ☐ Daily ☐ Monthly	☐ HVAC.xlsx ☐ Lighting.xlsx ☐ Plug & Process Loads.xlsx ☐ Whole Building.xlsx
Energy Production	Solar energy production	kWh	☐ Hourly ☐ Daily ☐ Monthly	☐ Energy Production.xlsx
Building Air Leakage	Mean building pressure	Pa	Discrete test (n=2)	☐ Building Air Tightness.xlsx
	Mean building air flow	CFM_{75}		
	Mean building pressure	(-)Pa		
	Mean building air flow	CFM_{-75}		

Table 2. Primary data output overview.

To assist users of this dataset, the authors provide AE documents, publicly available weather data, and the EnergyPlus weather file (.EPW) for the case study building's site. These data are considered as secondary data since they were not directly measured by authors. Table 3 provides an overview of the secondary data for the period of data measurements.

Category	Data Description	Unit	Data Resolution	Data Output
Weather	Temperature	°C (°F)	Daily Monthly	☐ Weather_Daily_IP.xlsx ☐ Weather_Monthly_IP.xlsx ☐ Weather_Monthly_SI.xlsx
	Dew point	°C (°F)	Daily Monthly	
	Humidity	%	Daily Monthly	
	Wind speed	m/s (mph)	Daily Monthly	
	Pressure	kPa (Hg)	Daily Monthly	
	Precipitation	cm (inch)	Daily Monthly	
	Heating degree days	# of days	Monthly	
	Cooling degree days	# of days	Monthly	
	Solar radiation	W/m^2	Hourly Daily Monthly	☐ Solar Radiation_Daily.xlsx ☐ Solar Radiation_Hourly.xlsx ☐ Solar Radiation_Monthly.xlsx
	EPW, DDY, and STAT	N/A	N/A	☐ AP.724016_TMY3.zip
AE Documents	Architectural, mechanical, electrical, plumping plans	N/A	N/A	☐ AE Documents.pdf

Table 3. Secondary data overview.

Energy consumption. Circuit-level energy consumption data were measured from June 18, 2014 to December 13, 2016. Data are organized into four datasets presenting energy use for the whole building and three end-use categories: lighting, plug & process loads (PPLs), HVAC & hot water energy use. Each dataset has circuit-level hourly data and aggregated data for total consumption for the whole building at hourly, daily, and monthly resolutions presented at separate tabs. In addition to the total energy use for the whole building and the three end-uses, energy use for first floor vs. second floor, interior vs. exterior lights, and HVAC

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vs. hot water are provided in the end-uses datasets in the tabs for hourly, daily, and monthly aggregated data.

Monthly energy use for the whole building varies from 985 kWh to 2,482 kWh over the measurement period (with the monthly average of 1,499 kWh). Average daily energy use over the whole measurement period is 49.4 kWh per day. Higher energy use for HVAC, hot water, and interior lighting is observed in colder months with longer night hours. Seasonal variations for HVAC energy use are over 1,000 kWh while for interior lighting is about 100 kWh. No major seasonal or monthly variations were observed for exterior lightings. However, there is an increase in energy use for exterior lighting from December 2014 due to a change in the control system that resulted in some of the lights being on consistently during the day. Monthly energy use for PPLs were below 300 kWh per month with a fluctuation of 100 kWh between different months from July 2014 to October 2015. No major outliers were found in the datasets. A few outliers in PPLs were observed likely due to occupant behaviors. Data for energy recovery ventilation (ERV) systems are included in the dataset, but it should be noted that the ERV was unplugged by the owner of the within the first month of operation due to concerns related to indoor humidity.

Energy production. Energy production data are provided in a single .xlsx file. Both daily and monthly resolutions for data for the period of April 23, 2014 to December 31, 2020. Monthly means over the 7-year period are also provided. Years 2015, 2016, and 2017 have missing data for two to eight months in the year due to accidental system shutoffs. Overall, 66 months have complete data for all days in the month.

More than 1,000 kWh energy is produced in a month from March through October. More energy production, however, was observed in April to August with July having the highest energy production on average over 7 years of data measurement. Highest energy production in a month was recorded as 2,213 kWh in May 2015 in a 7-year period. Daily energy production data finds that in summer months with the highest energy production, the window of energy production is between 7 am to 7 pm. However, 10 am to 3 pm is when solar panels produce the highest energy throughout the day (Fig. 2).

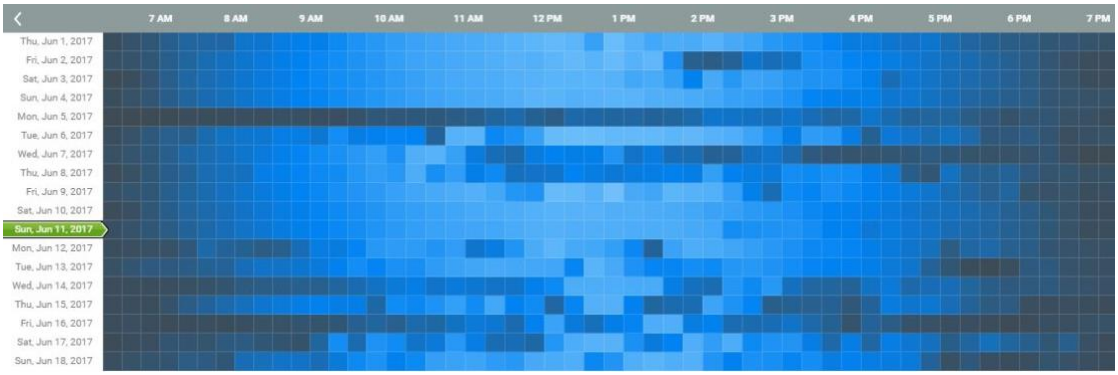

Fig 2. Hourly energy production data. Lighter colors show higher energy production.

Building air leakage. Building air leakage data is provided in a single .xlsx file. The USACE protocol and ASTM E779 standard require the reporting of both depressurization and pressurization tests. Results are separated by tab in the file. Each test (e.g., tab) reports three columns of data: 1) test point, 2) mean induced enclosure pressure (+/- 75 Pa), and 3) total corrected fan flow (CFM).

Weather data. An EnergyPlus weather file (.EPW) for Charlottesville, VA is provided for building energy simulation applications[16]. Measured weather data for Charlottesville, VA provided by Weather Underground website[17] from June 2014 to December 2016 is also available in the OSF respiratory. Daily and monthly resolutions of weather data are provided

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into two separate subfolders in the respiratory. Weather data includes temperature, dew point, humidity, wind speed, pressure, and precipitation. Daily weather data in the .xlsx file is provided in separate tabs for each month of the energy use measurement period. The average for the month is presented at the last row in the tab for that month. Monthly weather data includes heating degree days (HDDs) and cooling degree days (CDDs) and is provided in both SI and IP unit systems. The base temperature was 18 °C (65 °F) for both HDDs and CDDs[18]. To facilitate investigating of the correlation between solar radiation and solar energy production, solar radiation data is provided from the National Oceanic and Atmospheric Administration (NOAA) website[19] for Charlottesville, VA for the energy production measurement period (2014 to 2020) in hourly, daily, and monthly resolutions.

AE documents. Design documents are provided with permission from the design team in a single .pdf. The architectural floor plans, elevations, sections, and details provide massing context and enclosure thermal performance context. Schedules and notes accompany the scaled mechanical, electrical, and plumbing plans. The corresponding author verified the field conditions against the plans during the project's original commissioning process.

Technical Validation

The authors recognize the importance of providing reliable measurements when reporting BPD. Measurement reliability is particularly important when data is sourced from a single, non-random case study since there are no other use cases to identify outliers. Table 4 summarizes the measurement instrumentation, associated standard(s), and accuracy of the study's measurements.

Category	Instrument	Standard	Accuracy
Energy Use	□ SiteSage IOT Gateway □ 150A CT (n=2) □ 50A CT (n=20) □ 20A CT (n=8)	□ UL 61010-1 □ IEC 61869-2	+/- 1%
Energy Production	□ Enphase Envoy Gateway Microinverter (n=56)	□ ANSI C12.20	+/- 0.5%
Building Air Leakage	□ DG-700 Pressure and Flow Gauge (n=2) □ Model 3 Blower Door Fan (n=2) □ TECLOG3 data logging software	□ ASTM E779 □ ASTM E1258-88	□ DG-700: +/- 1% □ Fan: +/- 3%

Table 4. Data instrument, standard, and accuracy overview.

The data presented in this descriptor required multiple instruments and represented multiple domains of BPD. A discrete experiment could not validate all data provided in this descriptor. The following section summarizes steps taken to ensure data reliability.

Energy use. The longitudinal collection of energy use data is an important feature of this dataset. The thirty months of energy use data provided in this descriptor can be used to identify monthly and yearly outliers. The authors also benchmarked the whole building site energy use intensity (EUI) with energy standard performance. For example, the case building site EUI is 56.3 kWh/m^2-yr, and the ASHRAE 90.1-2016 benchmark for small office buildings is 82.0 kWh/m^2-yr[20]. Finally, the authors validated monthly heating and cooling consumption with monthly HDDs and CDDs data as energy demand for heating and cooling correlates with HDDs and CDDs for the building location. Fig. 3 demonstrates the influence of monthly HDD/CDD on monthly heating and cooling energy use.

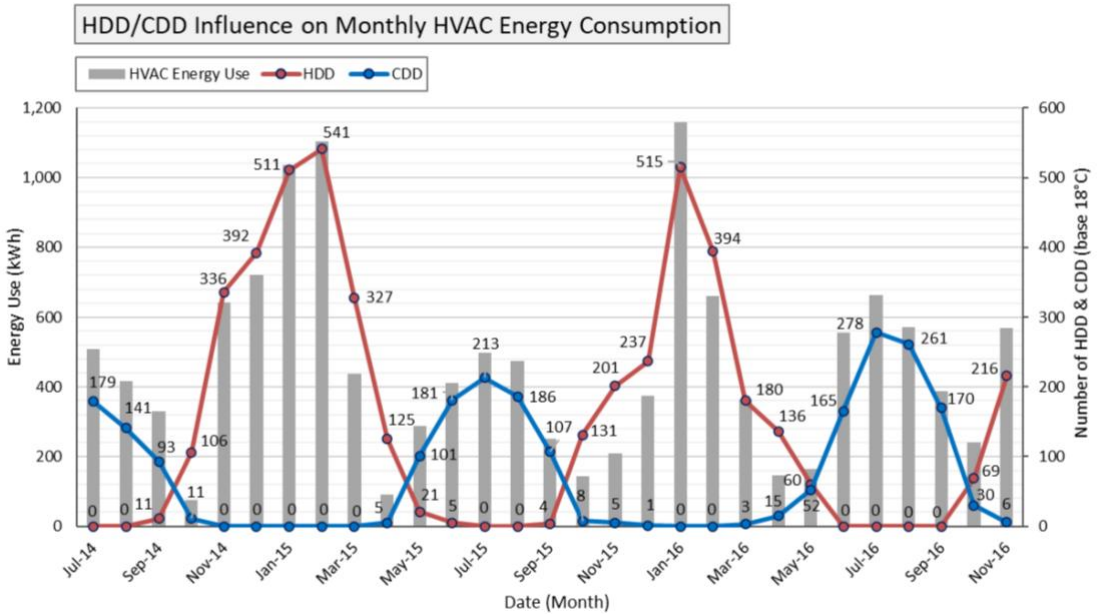


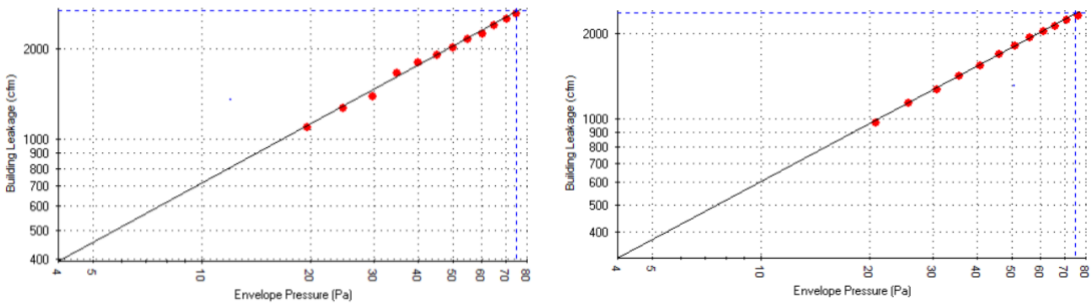
Fig. 3 HDD/CDD (base 18°C) influence on monthly HVAC consumption.

Energy production. The longitudinal collection of energy production data is an important feature of this dataset. The sixty-six months of energy production data provided in this descriptor can be used to identify monthly and yearly outliers. The provided weather data and solar radiation data can also be employed to correlate weather conditions with energy production outcomes.

Building air leakage. Beyond the fan and gauge calibration requirements, the building air leakage test must follow, and results must meet several reliability steps. Specifically, the test requires flow rates to be sampled at a minimum of 10 test pressure points (between 20 - 75 Pa). Flows are averaged for at least 10 seconds per test point. Per the USACE test protocol and ASTM E779, test results must achieve a squared correlation coefficient (r^2) ≥0.98. Both depressurization and pressurization tests resulted in a $r^2 = 0.99$, thus passing the standard. Finally, during the test, TECLOG3 (e.g., building air leakage software) records the multi-point test results and generates curve fit to the Power Law Equation (1) in compliance with ASTM E779.

$$\boldsymbol{Q = C\Delta P^n} \qquad (1)$$

where Q is the infiltration/exfiltration rate, C is the air flow coefficient, ΔP is the pressure differences across the building enclosure, and n is the pressure exponent. The curve predicts infiltration rates from 0 Pa (0.0 inH_2O) to 75 Pa (0.3 inH_2O). See Fig. 4a for the pressurization curve and Fig. 4b for the depressurization curve.



a) b)

Fig. 4 Building air tightness test results a) pressurization and b) depressurization.

Code Availability

No code is required to access or analyze this dataset.

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Author contributions

Philip Agee installed the energy monitoring equipment, performed the building air leakage testing, led the manuscript and dataset development, coordination, obtained the informed consent from the owner, and performed the final review. Leila Nikdel organized, cleaned, and converged the dataset. She also wrote the dataset description and reviewed the final manuscript. Sydney Roberts oversaw the energy use and building air leakage data collection and reviewed the final manuscript. https://guides.lib.vt.edu/oasf/request

Competing interests

The authors declare no competing interests.

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