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Net Zero Energy Housing: An Empirical Analysis from Measured Data

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Abstract
This study reports an empirical analysis of an all-electric, Net Zero Energy Housing (NZEH) development located in a mixed-humid climate zone (4A, Virginia, USA). Circuit-level energy monitors were used to measure energy consumption and energy production data (solar photovoltaic) at 1-hr intervals in six identical apartments over 24 months. The study employs a multi-step case study methodology to a) empirically evaluate energy consumption and production data, b) identify the temporal variability of energy consumption and production data at different time scales, c) understand the impact(s) of weather and human-building interaction on energy consumption and production, and d) synthesize the study's "lessons learned" toward data-driven recommendations for future NZEH researchers and practitioners. The study found that the development's net zero energy goal was achieved in three of six case units and that NZEH housing performance was more influenced by human-building interaction than weather variability. The analysis also found the solar photovoltaic (PV) performance to be reliable across the sampled units over the periods of measurement, suggesting that solar PV could be oversized as an approach to overcome verifiability in HBI and achieve NZEH performance goals.

Keywords: energy monitoring, net zero energy, human-building interaction, solar photovoltaics

1. Introduction

Concern in growing energy consumption in buildings and its environmental impacts, energy cost increase, and development of cheaper renewable energy generation technologies have led to increased interest in net zero energy buildings (NZEBs) over the past decade. According to the New Buildings Institute (NBI) [1], NZEBs in North America had a 11-fold increase in the past decade (2010-2021) with education, office, and multifamily building types being the most common. Part of the reason for such growing interest and investment in NZEBs is that various energy policy organizations and agencies are encouraging or demanding new construction to meet the net zero energy goals through legislation or incentives. For example, California's Title 24 legislation required that all new residential construction be net zero energy or 'equivalent to net zero energy' by 2020 and for all new commercial construction by 2030 [2]. In 2008, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) set the goal in their ASHRAE Vision 2020 [3] to provide necessary tools to design, construct, and operate net zero energy buildings by 2020, thus making NZEBs market-viable by 2030 [4]. The American Institute of Architects (AIA) set a goal in their 2030 Challenge to achieve a carbon-neutral target for all new buildings, developments, and major renovations by 2030 [5]. AIA initiated the 2030 commitment [6] to support the 2030 challenge and participating firms by prioritizing energy performance and transforming the practice of architecture in a way that is holistic, firm-wide, project based, and data-driven. The Energy Independence and Security Act of 2007 (EISA 2007) Title IV set a net zero energy target for all new commercial buildings built after 2025, followed by all existing and new U.S. commercial buildings by 2050 [7]. The International Energy Agency (IEA) provides a 'Net Zero by 2050 Roadmap' with the goal of decarbonizing the global economy in the coming three decades [8]. In EIA's pathways to reach net zero emissions by 2050, all new buildings by 2030 and 50% of existing buildings by 2040 should become zero-carbon ready (e.g., zero emissions). In addition to legislation and energy policies, some local government initiatives have proposed different incentives such as the California Solar Initiative and PV financing that aims to push marketable NZEBs [2].

Net Zero Energy Buildings or NZEBs emerged as a concept to offset the negative effects of buildings on the environment with energy-neutral development. The goal with NZEBs is to replace our dependence on fossil fuels with renewable energy through a decentralized approach to solve the current environmental crisis [9]. The strategy to achieving net zero performance is to reduce energy loads by maximizing energy efficiency of building enclosure systems, mechanical systems, lighting, and equipment, and then offset the remaining demand with on-site energy production by renewable energy sources so that annual net energy demand from the grid would be zero [15]. Several studies, however, have showed that net zero energy buildings in some cases failed to achieve their performance goal [10], [11], [15], [16].

Expectations to meet energy demand, generate energy, and interact with the grid while operating under energy efficiency restrictions with climatic, technological, social, and economic limitations make the design of NZEBs a complex, multivariate optimization problem [9]. Underestimating energy consumption and overestimating energy production in the design of NZEBs are the main reasons for failure to reach the zero-energy performance goal. The gap between estimated and actual measured energy consumption in buildings is a common problem caused by limitations in building energy simulation tools and inaccurate inputs for building systems, weather, and human-building interaction at the design phase [10]–[12]. Moreover, lack of quality assurance in the design and construction phases and changes in building services, facility management, occupancy density, surrounding vegetation and buildings as well as climate change and weather variations after construction can cause energy performance gaps in NZEBs [12]–[14]. There is a need for high-resolution, measured data in NZEBs to evaluate factors influencing energy performance toward a zero-energy target. However, studies that empirically evaluate energy performance of NZEBs with high-resolution, circuit-level measured data are limited. Furthermore, while several studies indicate weather and HBI as major influencing factors on building energy performance, the emergence of NZEBs necessitates further understanding of the influence of these factors on performance outcomes.

This study aims to empirically evaluate energy consumption and production outcomes for multi-family housing units. The authors conducted an in-depth case study methodology for 8 units, focusing on factors commonly known to influence NZEB performance. There were four research objectives for this work:

1. Empirically evaluate energy consumption and production data to characterize the performance of a net zero energy housing development with circuit-level hourly data;
2. Identify the temporal variability of energy consumption and production data on monthly and daily time scale(s);
3. Examine the impact of weather and human-building interaction on energy consumption and production variability;
4. Recommend data-driven solutions for practitioners to achieve performance goals.

The balance of the manuscript is structured as follows: section 2 synthesizes definitions, approaches, and performance indicators of zero energy buildings (ZEBs) from previous studies ; section 3 describes the case study methodology, data collection, and data analysis; before contextualizing the work in the discussion and conclusion. As a result of this work, researchers and practitioners can benchmark performance and anticipate variability in future net zero energy housing (NZEH) projects.

2. Background

2.1 Zero Energy Building Definitions and Terminology

Researchers have previously proposed several definitions and concepts for zero energy buildings, which vary by country, organization, and entity and depend on the climatic, economic, or political conditions [9]. Although definitions may differ in vision and framework, they all share a common goal: to reduce primary energy source (e.g., fossil fuels) consumption in buildings and, as a result, mitigate the environmental impact of buildings.

Zero energy buildings (ZEBs), net zero energy buildings (NZEBs), and zero net energy buildings (ZNEBs) are terms being used seemingly interchangeably with the same definition: a grid-connected building that produces at least as much energy on-site as it consumes annually (e.g., annual energy demand from the grid would be less than or equal to energy production). According to the U.S. Department of Energy's (DOE) definition, a ZEB balances between annual delivered energy and exported energy on a source energy basis [13]. However, it is still unclear for many researchers globally if site or source energy basis is meant when discussing ZEBs. Attia [9] introduced two terms for ZEBs that, depending upon the source (primary) energy or site energy, accounted for estimated energy use in the design of a ZEB: Zero Site Energy and Zero Source Energy.

Net zero source energy buildings (NZSEBs), consider the balance between imported and exported energy from/to the grid, including the primary energy required for generation and delivery of the energy to the site. To estimate source energy, appropriate site to source conversion factors are used depending upon the source of off-site energy [9]. A NZSEB offsets total CO_2 emissions at an off-site energy generation source (e.g., power plant) caused by energy use in the building. Hence, it is similar in definition to a Zero Carbon or Zero Emissions Building that are commonly referred to as a concept for a carbon-free or carbon-neutral built environment [17].

A net zero carbon building (NZCB) balances its annual energy demand only through off-site renewable energy sources (not a grid that utilizes fossil fuels for electricity generation) [18], which can be considered ambitious in many regions and countries in the world in the near future. However, NZCBs can lead to decarbonizing the entire building sector if it becomes achievable and infrastructurally feasible [19].

Life cycle zero energy buildings (LCZEBs) go one step beyond NZSEBs in mitigating CO_2 emissions. In addition to the source energy use, an LCZEB also includes the embodied energy of the building and its components to have a zero footprint on the environment. An LCZEB produces at least as much energy on-site by renewable energy systems as it consumes on a source basis and the energy embodied within its materials and systems (including energy generation system) over its lifetime [9], [17], [20].

Nearly zero energy building (nZEB) or nearly net zero energy building (nNZEB) along with ‘emerging ZEBs’ and ‘zero-energy ready’ are used to describe buildings that have the potential to become zero-energy. nZEBs and nNZEBs are energy efficient buildings built to minimize net energy consumption and include on-site renewable energy systems that do not produce enough energy to reach net-zero on an annual basis. According to Attia [9], an nZEB produces at least 30% of its energy demand on-site through renewable energy.

Off-grid zero energy buildings (OZEB) are highly energy efficient buildings that are not connected to an off-site energy utility facility (e.g., power plant) and produce required energy for building operation on-site by renewable energy systems. The balance between energy consumption and production in such buildings is on an hourly (or smaller intervals) basis. To do so, these buildings require extensive energy generation systems (5,000 to 15,000 ft^2 of space for residential buildings) and energy storage capability as backup power sources for times when energy production is limited throughout a day (night or cloudy sky) or months with shortened daylight. The estimated upfront cost for renewable energy systems in OZEBs is 10 times more than NZEBs [21].

In a net zero energy cost building (NZECB), the cost of purchased energy is balanced with the income from exported energy so that utility cost would be zero in a course of a year [9]. Therefore, the calculations for the required on-site energy production capacity not only depends on the energy demand, but also on the utility credits or net-metering rates ($/kWh for energy sold to grid) and utility rate costs for purchased energy from the grid which can vary by country, region, and local levels. Since the utility credits for the exported energy are lower than the cost for the purchased energy per kWh, the energy production in a NZECB is higher than building energy demand.

This research considers ZEB as a general term that includes any type of zero energy buildings (this was suggested in Sartori et al [14] as well) and the term NZEB for grid-connected ZEBs with site energy basis of design (as it generally refers to this type of building in literature, especially in the USA). In the residential building context, 'building' in all terms defined here for ZEBs can be replaced with 'housing' to specify the type of building (as opposed to commercial buildings). For example, the term 'net zero energy housing' is defined as a grid-connected residential building that balances its annual delivered energy with exported energy on a site energy basis.

2.2 Design Principles and Approaches of ZEBs

Designers need to consider the best fit for the building based on its occupancy, intended use (e.g., residential, commercial), and climatic context. According to Attia [9], there are four basic design principles for ZEBs.:

1) *Reduce energy demand and internal loads by means of energy efficiency measures and passive energy systems*;
2) *Improve energy efficiency in indoor environmental quality (IEQ) control;*
3) *Produce energy from renewable sources on-site* (the amount of required energy production through on-site renewable energy is estimated based on the type of ZEB);
4) *Reduce primary energy consumption and the carbon emissions related to delivered energy* (the extent of incorporating this step into the design relates to targeting a type of ZEB).

Different design approaches can be applied to maximize energy efficiency, IEQ, and solar energy production. Employing building energy simulation tools to inform the performance for the building enclosure based on the climatic parameters can be vital to minimize heating and cooling loads of the building. For example, thicker wall insulation in an office building with high lighting power densities in a hot climate increased cooling energy demand to the point that it had almost zero impact in reducing the annual load for heating and cooling [22]. Other measures to reduce internal

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loads include efficient HVAC systems and appliances, occupancy-based control systems for heating, cooling, and lighting, high efficiency LED lighting, and heat recovery ventilation systems [23]–[26]. Minimizing plug-loads could be complicated as it depends on occupant consumption behaviors, but it plays a critical role in meeting zero energy performance goals [2]. The optimal balance between increasing energy efficiency or energy production has always been a cost-effectiveness challenge and is dependent on many factors including building type (e.g., residential versus commercial), building technologies, and climatic context [9], [15].

2.3 Previous NZEH Empirical Studies

Previous researchers have aimed to understand the performance of NZEH. Previous studies vary in vintage, sample size, climate context and data resolution. The studies in Table 1 do not provide an exhaustive summary, but rather represents three seminal empirical studies of NZEHs. Two themes emerge from these three representative studies. First, each study reported some sampled units achieving their NZEH goal, while others failed to achieve the goal. Second, the authors report variations in weather and human-building interaction as contributing factors of unit performance failures.

Table 1. Summary of studies that investigated the energy performance of NZEBs.

Study	Building Type/ Sample size	Climate Context	Method	Data Resolution	Findings
[15]	Residential / n=19	Cool and Humid	• Measured 12 months of energy consumption and production data • Developed custom models to predict consumption and production • Compared measured performance to	• Monthly • Whole building	• 6 out of 10 buildings achieved net-zero energy or better • Measured energy consumption averaged 14% below predictions by models • Generated energy was within ±10% of predicted for 17 out of 18 on-site PV systems

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			modeled predictions		
[10]	Residential / n=8	Cool and Humid	• Monthly measurement of electricity consumption and production for the whole unit and with sub-meters for heating, cooling, and hot water in all 8 buildings	• Monthly • Circuit-level	• 6 out of 8 homes failed zero energy goal while all 8 units being identical in location, building specifications, and energy production potential. • Building energy performance ultimately comes down to household size and energy consumption behavior
[16]	Residential n=2 / Commercial (office, education, mixed use) n=32	Hot and Humid	• Collected and analyzed annual energy data for 25 buildings • Analyzed energy performance of 3 buildings on an annual, monthly, and daily basis	• Annual, monthly, and daily • Whole building	• 8 out of 25 buildings with available energy data failed to achieve zero energy target. • Buildings with excellent energy efficiency performance failed the zero-energy target due to limited on-site energy sources (inaccurate sizing or overestimation of production).

2.4 Influence of Weather and Human-building Interaction on Performance

Now that we have defined ZEB terminology and described common design approaches to ZEB performance, the next step is to examine common variables for analyzing performance outcomes. The building performance literature often cites variations in weather and human-building interaction (HBI) as major uncertainties in building performance [36]. As we race toward ZEBs, do the impacts of weather and HBI compound performance uncertainties in ZEBs?

Several studies have empirically evaluated performance outcomes and found weather to have a significant influence on ZEB performance in both residential and commercial contexts [27], [28], [29]. Simulation-based studies [27], [12], [28], [29] evaluated ZEB performance with weather variables including Solar Radiation Intensity (SRI), Outdoor dry bulb temperature (ODB), and Heating Degree Days (HDD). While some reported ZEB performance being jeopardized by measured variations in SRI [11] from “standard weather years,” other research has used comparisons in measured weather to a standard weather year to validate ZEB predictive models [29]. Since ZEBs are often promoted as a climate change mitigation approach, increasingly the role of future weather is often considered [27].

Conversely, human-building interaction (HBI) is an emergent building performance research area. HBI, often referred to as "occupant behavior" in the literature, becomes more important to understand as energy end-uses shift from the building enclosures to human-centered end-uses (e.g., domestic water heating, lighting, and MELs). As stricter building codes require more efficient buildings, HBI has a more significant impact on performance outcomes [28], [15]. Brandemuehl and Field [28] developed a sensitivity analysis of a theoretical ZEB across four U.S. climate zones and found that ZEB performance was more dependent on variations in HBI than weather. However, the significance of HBI on ZEB performance varies based on the building context [12] and occupancy profile(s) used to simulate HBI [30], [31].

Increasingly researchers are measuring the impact of HBI on ZEB performance [10], [15], [32], a major goal of this work.

3. Methodology

This study employed a multi-step, case study. The relationship between the study's research steps, objectives, and methodology are illustrated in Figure 1. The research team utilized a single database (referred to hereafter as "Project Database") to organize and analyze the data, thus enhancing the work's reliability.

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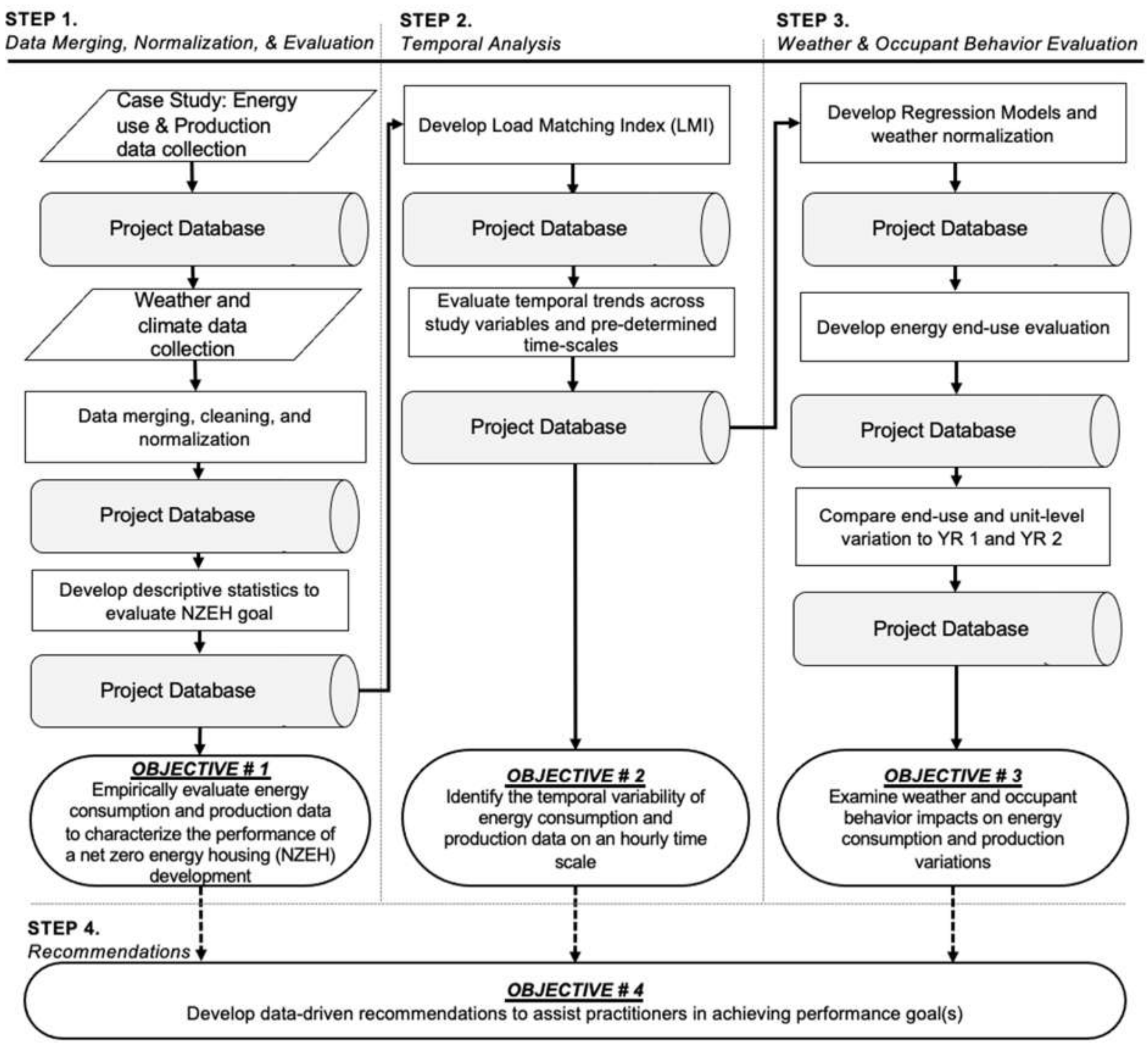

Fig. 1. Flowchart of the research steps, objectives, and methods.

3.1 Case Study Description

A case study was employed to develop an empirical evaluation of a NZEH. The sample is a convenient, non-random sample of four NZEH duplexes (8 housing units, with 2 units/building) in Virginia, USA (Climate zone: 4A, mixed-humid). The rental property was designed, developed, and is managed by a non-profit housing organization, who routinely is certified to a high-efficiency standard. Each 2-bedroom affordable unit houses one to two seniors (+65). Building 1 (two units)

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was later excluded from the analysis due to incomplete collected data. The development team engaged architecture, construction, building science, and renewable energy consultants with the explicit goal of achieving zero energy performance goals. To minimize the size of the renewable energy systems, the buildings were designed to be approximately 50% more efficient than the 2015 International Energy Efficiency Code (IECC) requirements for this climate zone. Table 2 characterizes the development's context and system performance.

Table 2. Development, building systems, and enclosure characteristics of sample residential units.

Sample Units		
Development Context	**Enclosure** (unit-level)	**Systems & Loads** (unit-level)
▪ # of Units: 6 ▪ # of unit types: 2 ▪ # of buildings: 3 ▪ Fuel source(s): Electric, net-metered solar PV ▪ 10-year average heating degree days (HDDs) (18ºC base): 2,665 ▪ 10-year average cooling degree days (CDDs) (18ºC base): 553	▪ Condition floor area/apt: [a] 966 ft² (89.7 m²) [b] 929 ft² (86.3 m²) ▪ Window to wall ratio: 0.141 ▪ Window u-value: 0.25 BTUh/ft²/°F ▪ Window SHGC: 0.27 ▪ Slab u-value: 0.05 BTU/hr/ft²/°F ▪ Wall u-value: 0.04 BTUh/ft²/°F ▪ Ceiling u-value: 0.02 BTUh/ft²/°F ▪ Avg. enclosure tightness: 2.0 ACH_{50}	▪ Space heating: 9K Btu/h, 18 SEER ▪ Space cooling: 9K Btu/h, 10 HSPF ▪ Ducted air system tightness: 1% ▪ Water heating: 2.75 EF, 50 gal. electric hybrid ▪ Ventilation: 1 CFM/Watt exhaust fan with passive inlets ▪ Lighting: 100% LED ▪ Dishwasher, clothes washer, dryer: Energy Star rated

Notes: Average monthly HDDs and CDDs data over 2011 to 2020 were obtained from www.degreedays.net.
[a] Units: B, C, D, F
[b] Units: A, E

To offset the development's annual site energy consumption, a local solar PV firm designed and installed the net-metered solar PV system on the roof of three of four buildings (Fig. 2). One of the buildings is significantly shaded by trees, so that building's panels were installed on the nearest building to maximize solar radiation potential. The solar PV systems are southeast facing with a total mean power capacity of 3.8 kWp. Each unit's PV array was sized 1) based on projected weather conditions from 20-year historical data and 2) to offset the estimated energy consumption of each apartment unit. Key performance characteristics of unit-level solar PV systems are summarized in Table 3.

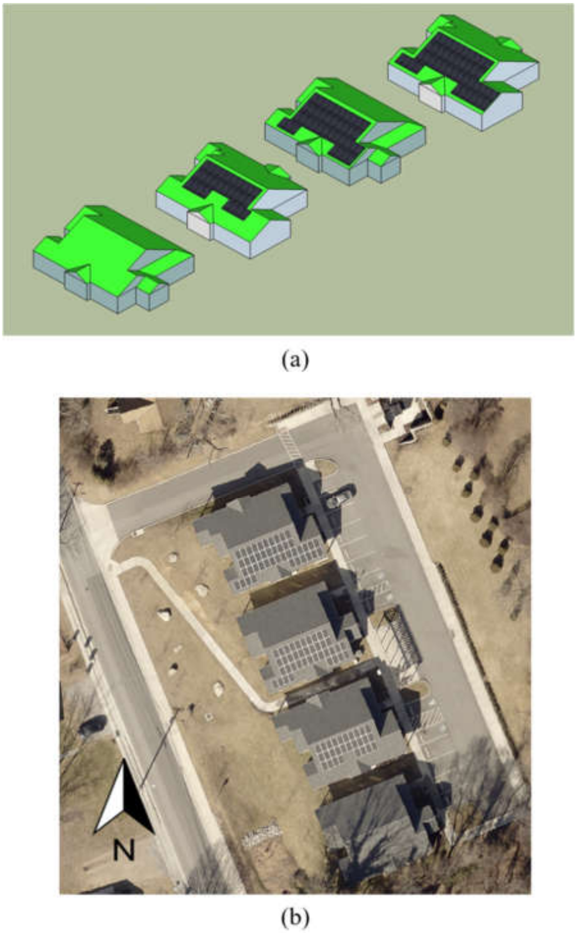

Fig. 2. a) designed and b) as-built solar PV systems for the case study project.

Table 3. Solar PV system characteristics.

Parameters	Values
Rated power	3.78 kWp (for Units C, D, E, F) 3.51 kWp (for Units A and B)
Number of modules	14 (for Units C, D, E, F) 13 (for Units C, D, E, F)
Module dimension	1.67 × 1.0 m
Module weight	21.18 kg
Module efficiency	16.1%
Solar cell type	Mono-crystalline
Frame material	Clear anodized aluminum
Inverter efficiency	96.5%

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System Azimuth	170
System Tilt	27

3.2 Data Collection

Energy consumption and production data was measured in the six apartment units at 1-hour intervals from March 5, 2015 to December 31, 2016. Energy consumption was measured at both unit-level for total energy use and at circuit-level for heat pump, water heater, range, and dryer in order to have higher resolution insights about performance. Energy data (kWh) were measured, recorded, and accessed by the installation of eGauge, wifi-enabled energy monitoring systems. Fig. 3 provides the monitoring system architecture.

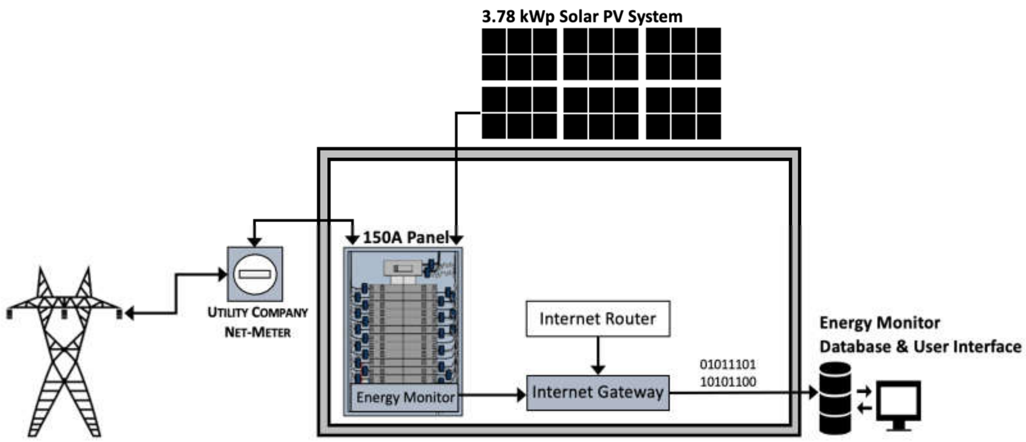

Fig. 3. Energy monitoring system architecture.

Data was accessed using eGauage's online user interface [33]. Data was downloaded for each unit in a .CSV file and imported into Microsoft Excel for data quality checks, formatting, and analysis. Table 4. characterizes the energy monitoring system hardware, variables measured, and manufacturer-rated accuracy of the measurement channels.

Table 4. Unit-level energy monitoring system overview.

Hardware	Quantity	Measurement	Accuracy
eGauge Core (EG4115)	1	15-channel meter	ANSI C12.2 - 0.5% Compliant
100A Split-core Current Transmitter	3	▪ Mains ▪ Solar PV system	1% from 10% to 100% of rated amperage
50A Split-core Current Transmitter	6	▪ Heat Pump ▪ Water Heater ▪ Range ▪ Dryer ▪ Living Room plugs ▪ Bedroom plugs	1% from 1% to 100% of rated amperage

3.2.1 Variables

To understand unit-level performance as well as commonly studied variables for HBI, the research team organized the study's variables (Table 5) including description, value, and previous studies that have employed the same variables for analysis.

Table 5. Summary of variables for data analysis.

Variable	Description	*Value*, unit of analysis	Literature
EU_{meas}	Measured total energy use (unit-level resolution)	*Continuous*, kWh/hr	[10],[33], [34]
HP_{meas}	Measured heat pump energy use (circuit-level resolution)	*Continuous*, kWh/hr	[32], [35]
DWH_{meas}	Measured water heater energy use (circuit-level resolution)	*Continuous*, kWh/hr	[32], [35]
DRY_{meas}	Measured dryer energy use (circuit-level resolution)	*Continuous*, kWh/hr	[35]
$RANG_{meas}$	Measured range energy use (circuit-level resolution)	*Continuous*, kWh/hr	[32], [35]
EP_{meas}	Measured energy production (unit-level resolution)	*Continuous*, kWh/hr	[15]
$HDD_{18\ (65F)}$	Heating degree day base 18ºC (65ºF)	*Continuous*, # of degree days	[34], [36]
$CDD_{18\ (65F)}$	Cooling degree day base 18ºC (65ºF)	*Continuous*, # of degree days	[34], [36]
OTEMP	Outdoor air temperature	*Continuous*, ºC	[37]
GHI	Global horizontal irradiance (GHI)	*Continuous*, kW/m^2	[38]

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3.3 Data Analysis

3.3.1 Data Cleaning and Organization

Energy consumption for the unit, heat pump, water heater, range, and dryer machine as well as solar PV energy production were analyzed for each unit at hourly, daily, monthly, and annual resolutions. Two 1-year periods (March 5, 2015 to March 4, 2016 and January 1, 2016 to December 31, 2016) were considered for energy analysis to compare energy consumption and production variations through different periods of time. This longitudinal approach enables investigating external conditions such as weather influencing energy consumption and production throughout a year, where YR1 and YR2 were warmer years compared to standard weather. The timeline of the two adopted periods is different due to the availability of measured data. The two periods of March 5, 2015 to March 4, 2016 and January 1, 2016 to December 31, 2016 are respectively called YR1 and YR2 hereinafter. During the data cleaning process, the team identified 13 hours of missing data in the whole measurement period (on January 13, 2016), 16,009 hours of data for energy consumption and production were measured for each unit with an exception for energy production in Unit D. Energy production measurement in Unit D was inaccurately recorded in the server for several months in 2015. Therefore, because of high uncertainty in data in 2015, YR1 for this unit was removed from the dataset. Hence, Unit D only has data for energy production in the YR2. Year 2016 was a leap year, so excluding 13 hours of missing data, 8,760 hours of measured data were retained for each 1-year period.

3.3.2. Energy Performance Evaluation

Zero-energy balances in the NZEH case study were analyzed to empirically evaluate whether the zero-energy goal was achieved in the case study development. Annual mean energy consumption and energy production in each unit and sample mean were calculated by averaging annual data in

YR1 and YR2. Then, annual energy consumption and production were compared in each unit and sample mean (Eq. 1). Further, monthly, daily, and hourly measured data were analyzed using Eq. 1 to reveal how many intervals were net zero site energy in the whole measurement period, YR1, YR2, and annual mean (average of YR1 and YR2). To further characterize the development's performance, the Load Matching Index (LMI) was calculated for each unit and sample mean in yearly, monthly, daily, and hourly intervals (Eq. 2). The LMI represents the overall performance of a ZEB in a course of year in terms of achieving zero-energy goal [39]. LMIs vary between 0 to 1 and the lower the LMI for a building, the worse the performance. An LMI of 1 means that the building is 100% zero energy compliant in the considered intervals.

$$P_i - C_i \geq 0 \qquad (1)$$

$$\mathrm{LMI}_i = \frac{1}{n} \times \sum_{year} \min[1, \frac{P_i}{C_i}] \qquad (2)$$

Where *P* stands for energy production, *C* for energy consumption, *i* for time interval number (yearly, monthly, daily, hourly), and *n* for the number of data samples in a year.

Descriptive statistics were developed to understand the distribution of energy consumption and production data. Annual energy consumption and production in all units and sample means in each 1-year period with the associated median, 25^{th} percentile, and 75^{th} percentile are presented to illustrate variations of energy consumption and production in different periods of time and among different units. Energy Use Intensity (EUI: kWh/m^2-yr) for each unit and sample mean are provided to evaluate energy efficiency of the NZEH case study compared to available benchmarks.

3.3.3 Regression Analysis

This study also investigates the influences of weather conditions on energy consumption and production variations using regression modeling. These models were applied for daily and monthly energy consumption and energy production data compared to three weather parameter variables (shown in Table 5). Total energy consumption (EU_{meas}) is correlated to 1) the sum of HDDs and CCDs and 2) average outdoor air temperature while energy production is correlated to global horizontal irradiance. Daily HDDs and CCDs and hourly average outdoor air temperature for National Oceanic and Atmospheric Administration's (NOAA) Virginia Tech Airport weather station (80.41W, 37.21N) data were accessed from the bizEE Degree Days website [40]. The weather station is approximately 2.2 kilometers from the case study site. Hourly GHI for Blacksburg, VA was purchased from the Solcast website [41] for the measurement period. Daily data for HDDs and CCDs and hourly data for OTEMP and GHI were aggregated to daily, monthly, and annual data using a spreadsheet application. HP_{meas}, DWH_{meas}, and energy consumption for miscellaneous electric loads (MELs) were corelated with monthly OTEMP as the regression results for EU_{meas} showed strong correlation between energy consumption and OTEMP. MELs were calculated by subtracting energy consumption for heat pumps and water heaters from total energy consumption for each unit.

3.3.4 Data Normalization

The researchers also employed three weather normalization methods in order to compare variations in energy consumption and production in the two measurement periods with different weather conditions, and more importantly to evaluate long-term energy performance of NZEH units under study. First, valid conclusions for energy performance evaluations require normalizing energy consumption and production based on variability in weather conditions when comparing multiple years of data. Researchers commonly employ climate data (average HDDs/CDDs or outdoor air temperature over 20-40 years) to normalize actual weather during periods of record [27], [36]. Annual and monthly HP_{meas} in each unit and in sample mean were normalized in each 1-year period with sum of HDDs and CDDs and average outdoor air temperature separately.

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Normalized energy consumptions for heat pumps were added to actual energy consumption for other end-uses (HP_{meas} subtracted from EU_{meas}) to represent the normalized total energy consumption. HDDs/CDDs were chosen as these parameters are commonly applied to estimate building loads and design HVAC systems. The outdoor air temperature was also adopted for data normalization as the regression analysis results showed strong correlation with total energy consumption. Annual and monthly energy production was normalized with GHI in each unit and sample mean in each 1-year period. A simple ratio-based normalization was used to normalize energy data based on three weather parameters (Eq. 3-4). For normalization with monthly data, the sum of normalized monthly energy consumption/production represents normalized annual energy consumption/production.

$$\mathrm{NEU}_i = \sum_{i=1}^{n}\left(\left(\frac{\mathrm{HPmeas}_i}{AW_i}\right) \times SW_i \; + \; (\mathrm{EUmeas}_i - \mathrm{HPmeas}_i)\right) \quad (3)$$

$$\mathrm{NEP}_i = \sum_{i=1}^{n}\left(\left(\frac{\mathrm{EPmeas}_i}{AW_i}\right) \times SW_i \right) \quad (4)$$

Where NEU stands for normalized energy use, NEP for normalized energy production, *i* for time interval (annual or monthly), *n* for the total number of intervals (1 for annual and 12 for monthly), *AW* for actual weather, and *SW* for standard weather.

The researchers obtained the respective EnergyPlus weather file (EPW-TMY3) from the EnergyPlus website [42] and employed it as the 'Typical Meteorological Year (TMY), representing a long-term average as the baseline for normalization. Fig. 4 shows HDDs, CDDs, and GHI in the measurement period versus EPW-TMY3. HDDs in YR1 and YR2 are 5.6% and 4.3% lower than the TMY respectively. Conversely, CDDs in YR1 and YR2 are 18.2% and 31.1% higher than TMY respectively. This means the measurement period had warmer weather compared to the long-term average weather represented in TMY3 data for Blacksburg, VA. For the sum of HDDs and CDDs, YR1 is 2.1% lower and YR2 is 1.3% higher than the TMY. GHI in both periods is higher than TMY (9.0% in YR1 and 11.5% in YR2), indicating higher solar radiation in the measurement period than listed in the standard weather file.

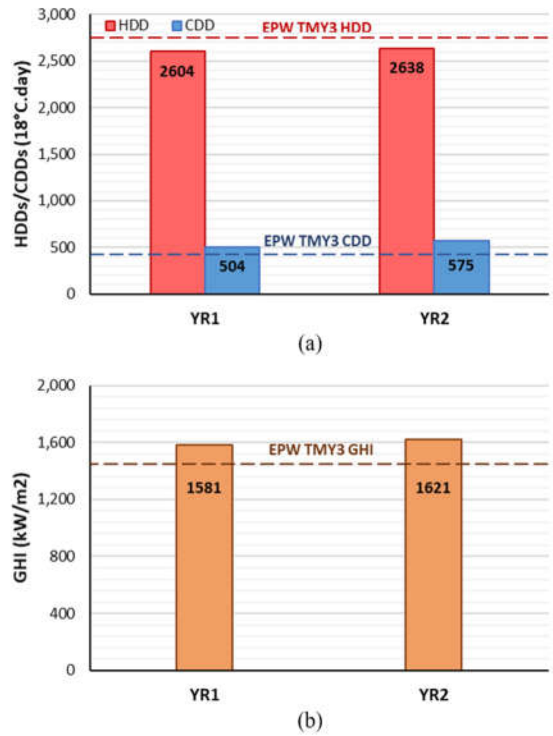

Fig. 4. (a) HDDs & CDDs and (b) GHI for the two 1-year periods and EPW TMY3.

4. Results

4.1 Comparison of Energy Consumption and Production (Objective 1)

NZEHs are designed to produce as much energy on-site as they consume in a year. In the sample of six units under study, however, annual energy consumption on average over both periods and all units (5,127 kWh) is 3% higher than annual mean energy production (4,973 kWh). Fig. 5 shows the annual mean energy consumption and production (over the two 1-year periods) for each unit separately and for sample mean. Mean EUI over YR1 and YR2 vary between 52.6 to 65.0 kWh/m^2-

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yr in different units (sample mean of 57.9 kWh/m^2-yr), indicating that all six units are highly energy efficient (Table A.1 in Appendix A). However, only three units (D, E, and F) met the development owner's net-zero energy goal. The unit-level solar PV systems failed to meet energy demand in units A, B, and C by at least 360 – 840 kWh in a year. Variation in energy consumption between different units is higher than energy production. The standard deviation (STD) of energy consumption across the sample is 415 kWh, compared to 159 kWh for production. The largest difference in energy consumption is 27% between units E and C. This value decreases to 23% when considering EUIs since units A and E are 4% (3.4 m^2) smaller in floor area than the other units.

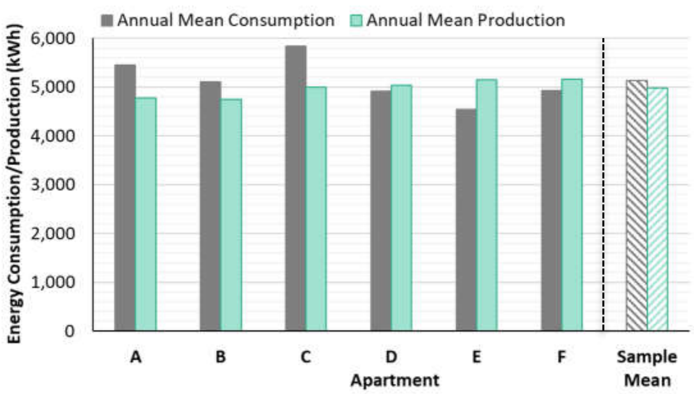

Fig.5. Comparison of annual mean energy consumption and production in six units and sample mean.

4.1.1 Temporal Trends (Objective 2)

NZEHs rely on the grid to meet the building energy demand for some months of a year depending upon the climate zone. In a cold climate for example, energy use exceeds on-site energy production in colder months of the year because of higher energy demand for heating and lower solar radiation due to shorter days. Fig. 6 shows variations of monthly mean energy consumption and production averaged over an approximately 2-year measurement period for the sample mean, reflecting the influences of both HBI with building systems and weather conditions. Standard deviations in

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energy consumption and production (Fig. 6) represent unit-level measured values in measurement period across the sample.

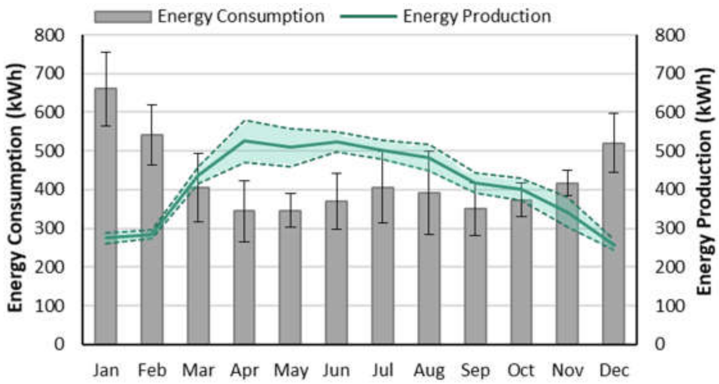

Fig.6. Monthly mean energy consumption and energy production.

In the case study's climate (climate zone 4A, mixed-humid), during the four heating season months (November to February), energy demand exceeds energy production even with considering the highest measured energy production and the lowest measured energy use across all units. However, solar PV systems in this climate can still provide 50% of energy demand in December, January, and February per the sample mean. From March to October, sample mean energy consumption is lower than mean energy production per month (below 400 kWh per month). However, April, May, and June are the only months when adequate energy is produced on site regardless of variations due to HBI and weather conditions (e.g., maximum energy use is lower than minimum energy production). The largest variations in monthly energy consumption across the sample are observed in August, January, and July when the energy demand for HVAC systems is high. The greatest variations in energy production occur in April and May likely due to varying weather conditions commonly observed during shoulder months.

Daily and hourly data analysis show that 57% of days (207 days) and 29% of hours (2,542 hours) in a year are net zero site energy for sample mean considering annual mean data. Table A.2 in Appendix A shows the calculated zero-energy balance (Eq. 1) separately in YR1, YR2, annual mean, and the whole measurement period for each unit and sample mean. Based on the calculated LMI for annual, monthly, daily, and hourly intervals for the typical year (mean of YR1 and YR2), unit E has the best net-zero energy performance followed by units D and F, and unit C has the worst performance among all units (Table 6). LMI of 1 for units D, E, and F show that these units achieved the zero-energy target and are 100% "zero energy" in a year. Monthly, daily, and hourly LMIs for units D, E, and F show that at least 85% of monthly energy demand, 81% of daily energy demand, and 39% of hourly energy demand in a year is met in a NZEH with produced on-site energy.

Table 6. Load matching index for a typical year.

Time Interval	A	B	C	D	E	F	Sample Mean	STD
Annual	0.88	0.93	0.86	1.00	1.00	1.00	0.97	0.06
Monthly	0.83	0.85	0.83	0.89	0.89	0.85	0.86	0.03
Daily	0.79	0.81	0.78	0.81	0.86	0.83	0.82	0.03
Hourly	0.37	0.37	0.37	0.39	0.39	0.39	0.38	0.01

4.2 Influence of Weather on Performance

The influences of weather conditions on energy consumption and production variations were analyzed (Fig. 7). Energy consumption (kWh) was compared to HDDs and CDDs (18ºC.day) while energy production (kWh) was compared to GHI (kW/m^2). Similar trends between energy consumption and HDDs & CDDs as well as between energy production and GHI suggest that these parameters highly influence energy consumption and production in these residential units. However, variations in energy consumption between different units illustrate human-building interaction impact on energy consumption. Energy production, in contrast, is almost consistent across the sample, confirming that energy production is primarily influenced by weather. The researchers also conducted a regression analysis to investigate the correlation between energy consumption/production and weather condition parameters.

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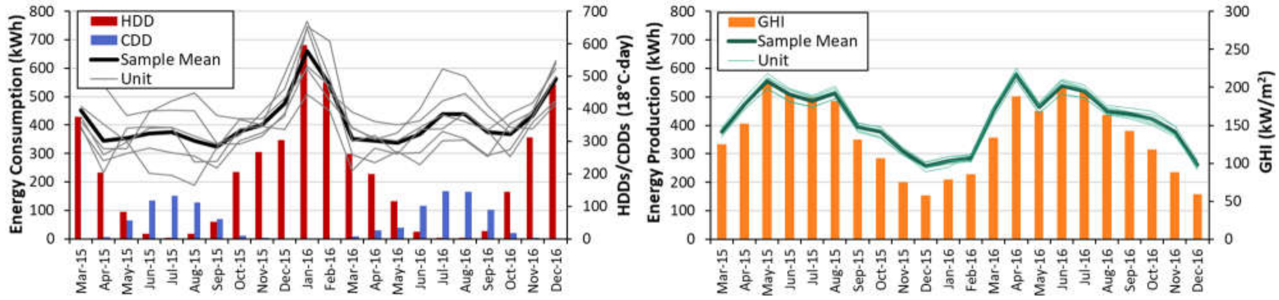

(a) (b)

Fig.7. Influences of weather conditions on monthly a) energy consumption and b) energy production.

4.2.1 Regression Analysis

Results of the regression analysis show that monthly energy consumption and energy production in the sample mean strongly correlate with outdoor air temperature and GHI respectively (Fig. 8). Monthly energy consumption in the sample mean has a moderate linear correlation with the sum of HDDs and CDDs (R^2= 0.78) while indicating a stronger correlation with outdoor air temperature (R^2= 0.90). For daily energy consumption data, the correlation is moderate for both sums of HDDs and CDDs and outdoor air temperature. Energy production strongly correlates with GHI for both monthly (R^2 = 0.93) and daily data (R^2 = 0.88). The range of energy consumption in the daily and monthly graphs in Fig.8 suggest that aggregating energy consumption data cancels out variations in human-building interaction on a daily basis. This finding also suggests that human-building interaction variations in a residential unit are less significant when monthly energy consumption is considered. Similarly, aggregating energy production data cancels out daily variations due to parameters other than GHI, such as the cloudiness of sky, precipitation, and dust level. Thus, energy consumption and production by weather conditions are more predictable using monthly data.

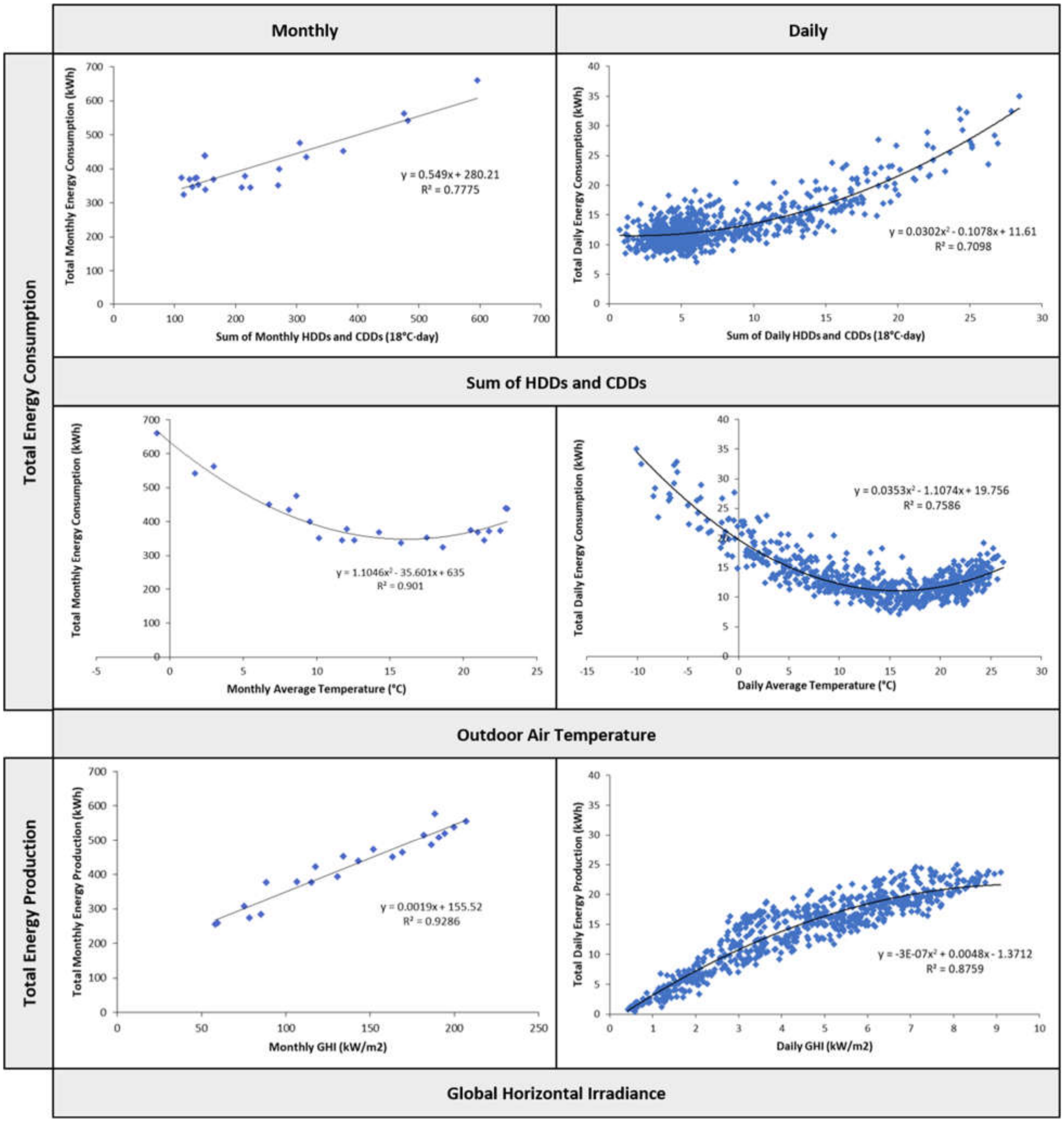

Fig.8 Regression results for monthly and daily measured energy data and weather data.

Three end-uses for energy consumption were analyzed to understand their predictability based on outdoor air temperature. Regression analysis results indicate a strong correlation between monthly energy consumption for heat pumps and outdoor air temperature ($R^2 = 0.97$) (Fig. A.1 in Appendix A). Energy consumption by the water heaters has a weak correlation with outdoor air temperature ($R^2 = 0.48$), supporting the common assumption of hot water heaters' independence from weather conditions. Having said that, results show higher hot water consumption when outdoor temperatures are colder; likely due to colder ground water temperatures leading to greater hot water deltas. March and April have the highest variations in energy consumption for water heater across different units and periods (Fig. A.2 in Appendix A). Regression modeling for MELs suggests no correlation between energy consumption and outdoor air temperature ($R^2 = 0.10$), indicating that variations in energy consumption for MELs is solely dependent on human-building interaction (Fig. A.3 in Appendix A).

Results demonstrate that estimating energy consumption and energy production based on weather parameters can yield relatively accurate predictions. However, ranges of energy consumption in six units versus energy production in Fig. 7 show the impact of human-building interaction that can increase uncertainties in energy consumption predictions and challenge ZEBs performance targets. Therefore, this analysis suggests that predictions for solar energy production are more reliable than energy consumption in net zero energy housing due to occupant variability. The challenge for energy consumption prediction is to accurately estimate the baseload (mean) and its variation throughout a year.

4.3 Weather-normalization

Energy performance evaluation of a building in different periods with various weather conditions could lead to inaccurate results and interpretations. Furthermore, zero-energy balance analysis for a short period of time in a building's lifetime could be biased by weather conditions in the measurement period, thus yielding invalid conclusions. Hence, both energy consumption and energy production in YR1 and YR2 were weather-normalized: energy consumption was normalized with outdoor air temperature and sum of HDDs and CDDs while energy production was normalized with GHI.

Results of data normalization indicate that the zero energy target is only achieved in unit E in the long-term. Fig. 9 shows the results of data normalization with annual and monthly data for both energy consumption and production. The measurement period was warmer than standard weather data predict and also had more solar radiation. Hence, normalized energy production would be almost 10% lower than actual measured data in both YR1 and YR2. Normalization with annual and monthly data yielded similar results for energy production; however, variation in energy production between the two 1-year periods is lower when monthly data was considered for normalization (0.9% for sample mean compared to 1.7%). Variations in energy production in different units occur because of differences in PV system design for each unit and energy loss in transmission between buildings. Units in the same building have the same energy production. This shows that solar energy production is basically the same in identical buildings with the same PV system design and is very consistent with weather conditions. Thus, energy production estimations are accurate over the lifetime of a building (over 20 years) although predictions can be overestimated by 10% in a short-term scenario.

For energy consumption normalization, energy used for the heat pumps was normalized as the only end-use correlating with weather conditions. Since the energy consumption for HVAC is one third of the total energy consumption in these NZEH units and the difference between actual weather in the measurement period and standard weather is relatively low, the normalized energy consumption is very close to the actual measured data for both YR1 and YR2. Because YR1 and YR2 were warmer years compared to standard weather, it is expected that normalized data will be higher than actual measured data considering the climate zone 4A (dominant heating demand). Thus, results for normalization with monthly data for average outdoor air temperature are deemed to be more reasonable than annual data, results considered as unreliable. Normalization with the sum of HDDs and CDDs yielded very close results to the actual measured energy consumption for both annual and monthly data. Considering -2.1% in YR1 and +1.3% in YR2 annual differences in actual HDDs and CDDs with standard weather, normalized energy consumption is slightly higher than actual data in YR1 and is marginally lower in YR2 (almost the same). Normalized energy consumption in the sample mean compared to actual data is 0.1% higher in annual data and 0.9% lower in monthly data for the average of YR1 and YR2. Normalized energy consumption with monthly data in both methods show 0.3% - 9.4% variations between YR1 and YR2 across different units (2.6% in sample mean). This finding shows that annual energy consumption in a housing unit can vary as large as 9.4% regardless of weather conditions. The highest variation in energy consumption between different units remains between units E and C as 26%. Data normalization results reveal the impact of human-building interaction on variations in energy consumption between different apartment units and periods.

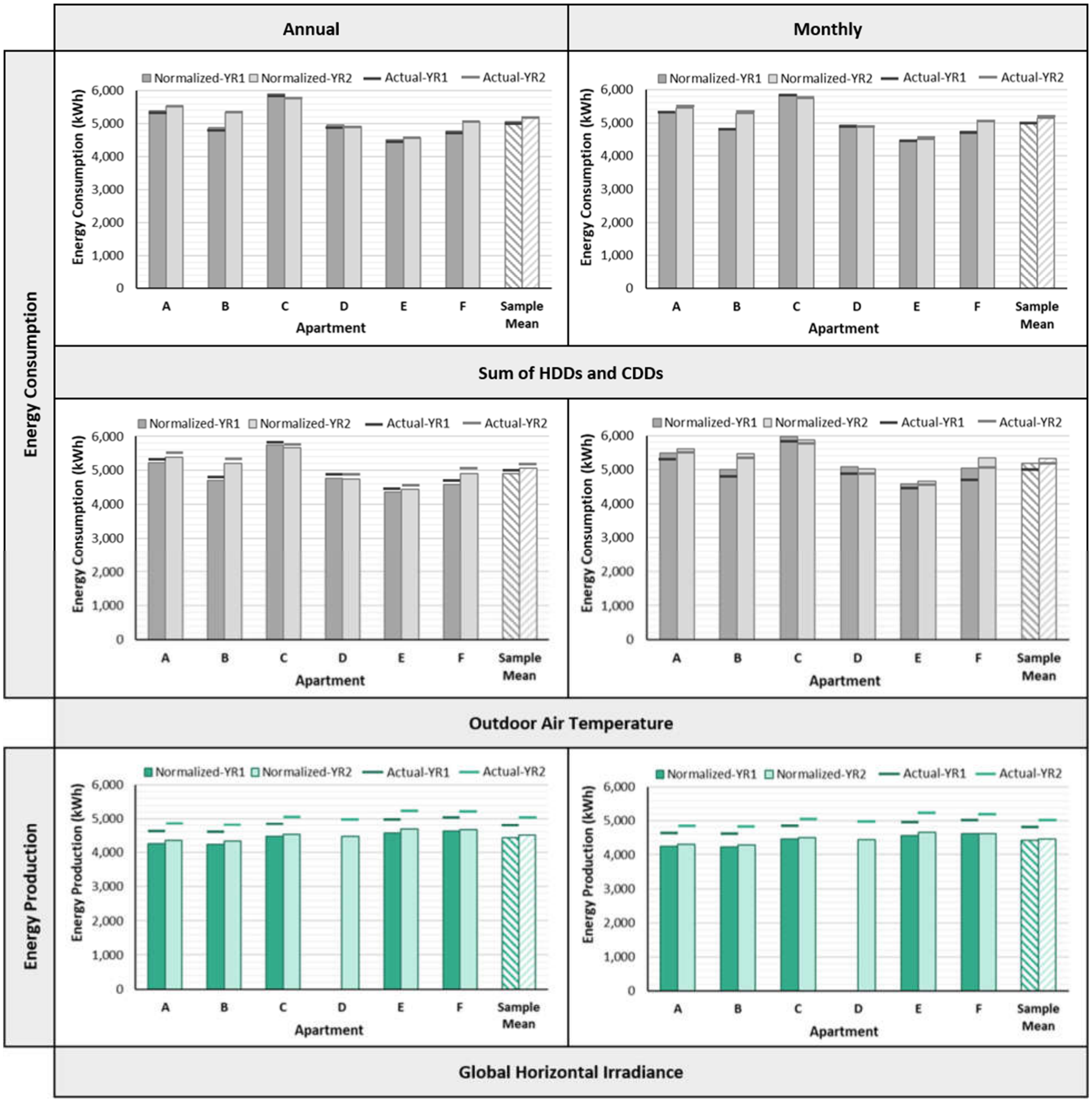

Fig.9. Total actual and weather-normalized energy consumption and energy production in six units in two periods.

Depending upon the availability of weather data, normalization with annual and monthly data for GHI and HDD/CDDs can yield acceptable and reasonable results. For OTEMP, only monthly data deemed acceptable to be applied for the normalization of energy consumption. Data normalization results demonstrate that underestimation of energy consumption is the reason for not achieving zero-energy targets across the sample under study. Inaccurate inputs for baseload (end-uses non-related to weather) and temperature setpoints for heating and cooling systems are the probable reasons for underestimation of energy consumption. To better explore and understand reasons for energy use underestimation and zero-energy target failure, investigating end-uses energy consumption through circuit-level measured data is essential.

4.4 Human-building Interaction and Energy End-uses

Circuit-level energy consumption results and regression analysis for end-uses show that 65% of building total annual energy use relates primarily to human-building interaction. Heat pumps, water heaters, and miscellaneous electric loads (range, lighting, equipment, etc.) represent 35%, 12%, and 53% of the buildings total annual energy consumption respectively. The regression results indicate a strong correlation between HVAC energy consumption and weather factors, 35% of total energy consumption is predictable with HDD/CDD. Fig. 10 shows the end-use monthly energy consumption in the sample for the measurement period. Except for January and February 2016 with high energy consumption for the heat pumps, energy consumption for MELs and the water heaters surpassed the heat pump throughout the measurement period. The highest variation occurs in energy consumption for the heat pump due to variations in weather conditions throughout the year (coefficient of variation (CV) of 55%), which confirms previous findings. In the sample mean, monthly energy consumptions for the water heater and MELs vary 19% and 12% throughout the measurement period respectively regardless of weather conditions. To find out which end-use yields the highest uncertainty in energy consumption estimations, it is necessary to analyze energy consumption across different units and periods of time.

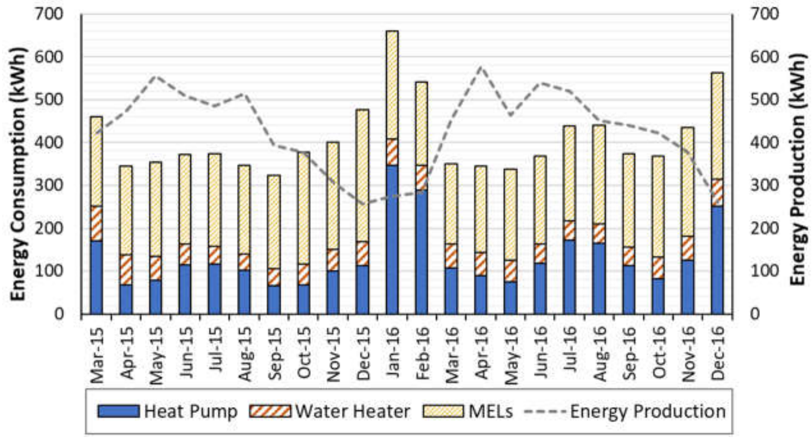

Fig.10. Energy production and end-use energy consumption in sample mean in the measurement period.

4.4.1 Variations Between Different Units and Periods

Miscellaneous electric loads (MELs) represent 1) the largest portion of total energy consumption 2) the highest variability across the sample. Water heater energy consumption has the lowest variability between units and periods under study and could be predicted with a relatively high accuracy. Fig. 11 illustrates the distribution of annual and monthly energy consumption for heat pump, water heater, MELs in six units and sample mean.

Regarding heat pump energy consumption, while the researchers acknowledge that there could be slight performance variances in the identical heat pumps, the 12% variation in total energy consumption could be attributed to changing thermal comfort preferences (see figure 11). Under the same weather conditions in identical buildings, differences in thermal comfort among occupants and desirable temperature setpoint can cause up to 12% differences in total energy consumption in a NZEH. Unit F has the highest and unit C has the lowest energy consumption for the heat pump with 35% and 30% differences between units in YR1 and YR2 respectively. Variations in energy consumption for heat pumps in YR1 and YR2 are similar across all units and sample mean. Energy consumptions in YR2 are 10% – 22% higher than YR1 (17% for sample mean) partly due to differences in weather conditions between the two periods. Normalized energy consumptions for heat pumps, however, shows that energy consumption in all units is 7% - 18% higher in YR2 regardless of differences in weather conditions (13% for sample mean). The reason for such an increase in all units is unknown, but it shows the possible variability in energy consumption for HVAC that is not predictable by weather conditions. Monthly energy consumptions show the impact of weather and seasonal variations. All units follow a similar trend with a wider range in cooling and heating seasons, illustrating differences in thermal comfort among occupants. Unit A has the highest consumption in cooling seasons and lowest in heating seasons; vice versa, unit F has the highest consumption in heating seasons and lowest after unit D in cooling seasons. This shows differences in desired indoor temperature among building occupants. Considering thermal preferences is essential for NZEH design because it impacts the baseload and accuracy of predictions. Especially in cold climates that accurate energy consumption estimation in the heating season is critical for meeting the net-zero energy goal.

Energy consumption for the water heater can vary as much as 75% between identical apartment units. No similar patterns for energy consumption changes over different periods were observed in this study sample. Units in the same building share one water heater. Thus, measured energy consumption for the water heater for each building was divided by two to represent the energy consumption for each unit. Units C and D have the highest energy consumption for water heating, which is 75% and 59% more than units A and B in YR1 and YR2 respectively. Energy consumption for the water heater in units A and B is 4% and in units E and F 9% higher in YR2 compared to YR1. Conversely, units C and D consumed 14% less energy for hot water in YR2. Results show that with energy consumption variations for the water heater, total energy consumption in identical NZEHs can vary up to 9% among different units and 2% in different years. Monthly energy consumption shows an almost constant trend throughout the measurement period in all units except March and April in units C and D. This shows that with accurate assumptions for the baseload for hot water usage, variations in annual energy consumption for the water heater can be negligible and insignificant when annual total energy consumption is estimated.

Energy consumption for MELs indicates the highest uncertainty for total energy consumption estimations. Across the sample, the annual energy consumption for MELs varies as large as 54% between units, which is a 29% difference in total energy consumption. Energy consumption between YR1 and YR2 changes between 2% - 13% (3% in sample mean). The monthly energy consumption for MELs demonstrates the wide range of energy consumption between units. Unit D has the largest monthly variations throughout the measurement period (41 – 374 kWh/month). The magnitude and variations of energy consumption for MELs highly depends on human-building interaction. DRY_{meas} and $RANG_{meas}$ show 138% and 141% differences between units and up to 21% and 54% differences between the two periods respectively (Fig. A.4 in Appendix A). Variations in energy consumption for dryer and range (cooking) illustrates the wide range of human-building interactions in MELs.

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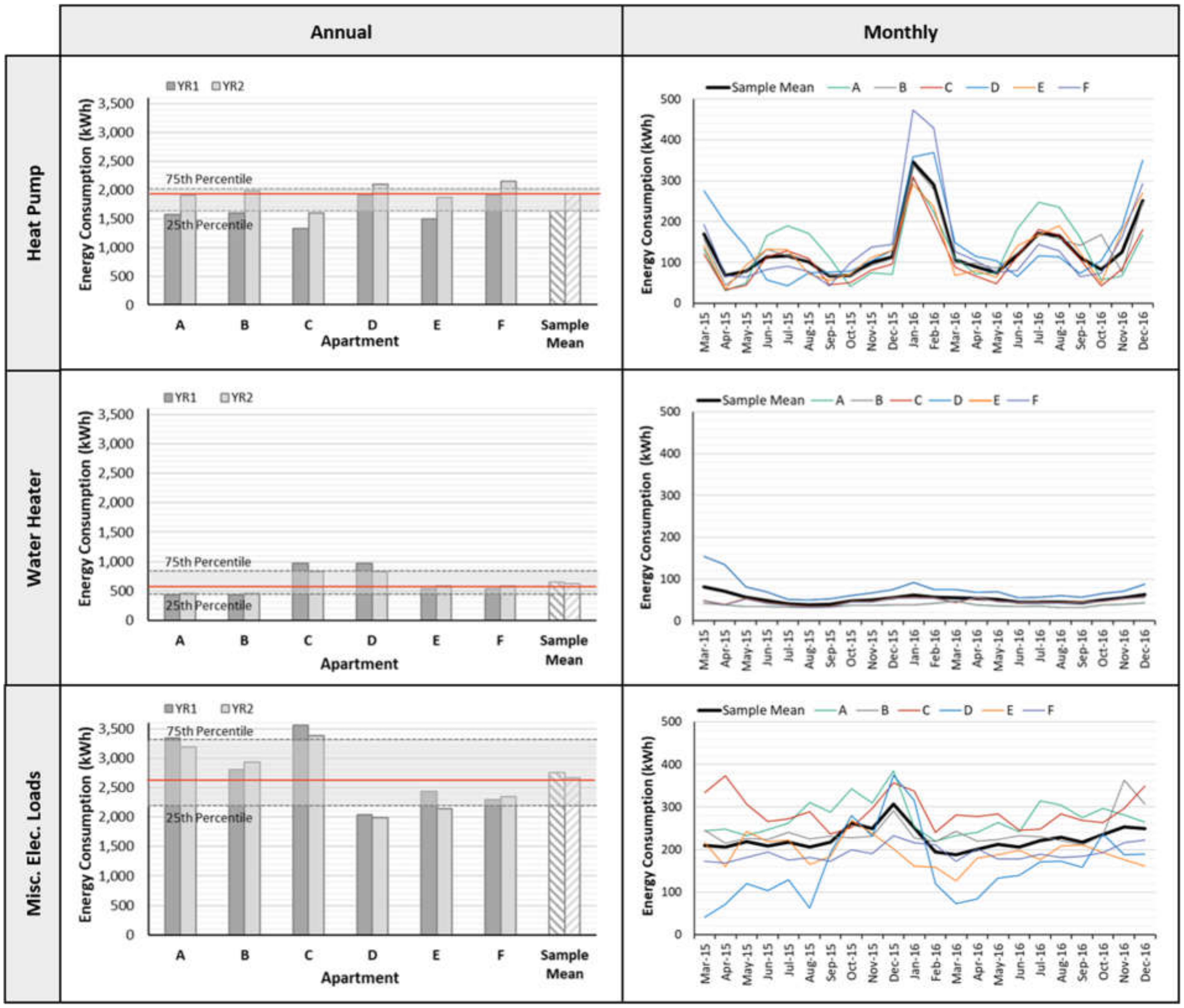

Fig.11. Annual and monthly energy consumption for heat pump, water heater, and MELs in six units and sample mean.

Energy consumption for MELs has the highest impact on total energy estimations with the largest portion of total energy and highest variations across sample. Units D, E, and F are not among low energy users for heat pump and water heater, but they met the zero-energy goal with having the lowest energy consumption for MELs compared to the other units. Unit C with the worst energy performance among all units, has the lowest energy consumption for HVAC systems and highest for MELs. Thus, results illustrate the importance of energy conservation for MELs in order to achieve zero-energy targets.

5. Discussion

5.1 Key results and Comparison with Previous Research

Although all apartment units are identical in location, weather conditions, HVAC systems, building characteristics, and occupant characteristics (age, income, household type), only half of units achieved the net-zero energy goal in the period under study. Energy production is impacted by climatic parameters such as solar radiation, precipitation, cloud cover, and wind. Energy consumption is not only impacted by external conditions such as weather, but also is influenced by human-building interaction, which is intrinsically hard to predict. One study shows that identical residential buildings could have as large as 300% differences in energy consumption mainly due to human-building interaction variations [43]. Our research found similar occupant-centered loads (e.g., domestic water heating, MELs) accounting for the majority of measured energy use [10], [15] during the sample period.

The Energy Information Administration (EIA) projected 94% growth for plug loads from 2005 to 2030 [2]. Results in this study showed that 40% - 62% of total energy demand across all samples was consumed by MELs. With more advanced energy efficient HVAC systems and growth in new technologies for appliances and electronics, the largest portion of energy consumption in buildings has shifted from HVAC system loads to MELs. Uncertainties in energy consumption for MELs, which primarily depend on occupant consumption patterns and preferences, can cause ZEHs to fail their target. Thomas and Duffy [15] investigated 8 NZEHs and reasons why they failed the net-zero energy targets. They found that some houses exceeded the predicted energy consumption because of having multiple appliances and electronics that were not considered in simulations such as a computer server room and an air-conditioned wine cellar. Incorporating occupant types that share specific characterizations (age, income, work schedule, household type) into simulations can

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potentially improve the accuracy of predictions. This requires inputs for end-use load profiles for a specific group of occupants that is currently not available for all occupant types. Having said that, results of this study demonstrated the possibility of having 29% difference in total energy consumption because of variations in energy use for MELs in identical buildings with the same occupant type. Hence, because of the wide range of energy use for appliances and plug loads among different occupants, MELs energy demand is very difficult to accurately predict if not impossible. Therefore, collecting data from occupants for their personal habits and preferences is essential for the success of a ZEH design.

ZEH designs would not be successful without incorporating the human element into design. Pre-occupancy and post-occupancy surveys and interviews with occupants, depending upon if the buildings' occupants are known, at the design phase needs to become a critical step for energy consumption estimations in ZEHs. If occupants are unknown at the design phase, post-occupancy surveys can help revise the design to meet energy demand if necessary. Solar PV systems can be designed to be flexible with the potential for adding more panels if required. This would impact building structure and construction cost. Another solution to meet the demand post-occupancy is to increase building's energy efficiency instead of increasing energy production capacity. Designing NZEHs with the potential to increase building energy efficiency or on-site energy production post-occupancy is a critical challenge and requires a thorough cost-benefit analysis, which remains for future studies about NZEH design under uncertainties due to human-building interaction. Performance-based design approaches and clear performance thresholds can help making the decision and designing robust NZEH [44].

Although multiple energy efficient measures and technologies are employed in ZEBs, studies show that not all ZEBs are energy efficient buildings. Feng et. al [16] reviewed the energy performance of 25 NZEBs and showed that at least 5 of those buildings had high EUIs while meeting the zero-energy performance goal. A ZEB should have a low EUI and CO_2 emissions by design, rather than meet high energy demand with more onsite renewable energy generation [11], [44]. Although the optimal balance between energy efficiency measures and onsite renewable energy production for ZEBs remains a challenge, performance indicators and thresholds can provide a common standard for ZEBs and ease evaluating the performance of ZEBs. This is essential for the construction community across the world for developing marketable solutions in a coherent framework for ZEBs. Proposed energy efficiency thresholds vary worldwide mainly due to the climatic, social, technological, and economic variations between countries and differences in ZEBs definition and terminology. For example, several European countries adopted incentives to meet the Passive House (PH) standard that calls for a heating and cooling demand energy below 15 kWh/m^2 per year [44]. The European Energy Performance Building Directive (EPBD) requires 3 kgCO_2/m^2 or lower per year associated with building energy demand from grid as the carbon emissions threshold to achieve the 2050 goal of becoming the first climate neutral continent [45]. Some studies employed the EUI of 56.8 kWh/m^2 (18 kbtu/ft^2) as the energy performance threshold, which is the median EUI in 482 zero energy projects in North America listed and verified by the NBI [11], [46]. NBI's verified projects include different types of buildings in various sizes and climate zones. A proper performance threshold needs to be defined primarily based on the building type (ex. multi-family residential, office, education, etc.) and climate zone. The energy demand for HVAC depends on climate, occupant density, activity type, and building size. In residential buildings, occupants' type (households vs. students), age (a family with young kids vs. a senior couple), income level, and many other factors can influence energy needs [47]. Therefore, the energy performance threshold for NZEBs should be a dynamic criterion calculated and defined based on the building type and its occupants' density and characteristics at local levels considering typology, location, region, and climate. Having clear performance goals and thresholds would help designers in their decisions for reducing building energy load or increasing on-site energy production to address human-building interaction variations.

Educating occupants for energy conservation is another solution to tackle human-building interaction impacts on the performance of ZEHs. People living in more efficient buildings tend to use more energy (rebound effect)[48]. In addition to the rebound effect, zero energy housing gives the impression to occupants that they can use more energy that is not harmful to the environment. The increased energy consumption over the predicted value in the design phase causes the failure of zero-energy goals. Hence, intervention and education seem necessary for occupants living in ZEHs. Hand-in notes, emails, or flyers with tips for energy savings when occupants move into the building can be useful to educate occupants for energy conservation [32]. Similar to tags on energy efficient appliances, ZEBs should come with tags (information for how to use). Education should become part of the design steps for ZEBs. Overall, interacting with building occupants before and after design and using post-occupancy evaluations is very important to get constructive feedback and empower occupants, thus creating a balance between energy performance targets and designing healthy buildings (thermal comfort and desired IEQ) [44].

Sharing energy production between units would cancel out human-building interaction variations and help units with high energy demand to meet the zero-energy goal. Purchasing energy from neighbors would be more beneficial than grid because of no energy delivery charges and less wasted energy. Connected communities could facilitate the pathway to zero carbon buildings by providing decentralized renewable energy sources. Eventually, zero energy neighborhoods lead to zero energy cities [13].

6. Conclusion

NZEHs are designed to produce at least as much energy on-site as it is consumed in a year. Not all designed NZEHs fulfil their zero-energy goal, however. Human-building interaction and weather condition variations are factors commonly known to a NZEH failing to achieve its performance goal(s). This study empirically evaluated energy consumption and production in a multi-unit housing case study to investigate which factors have more significant impacts on the performance of NZEHs. Energy consumption and energy production longitudinal data were measured hourly in six units from IoT enabled circuit-level monitors. Regression, weather-normalization, and descriptive statistics were conducted for data analysis. Results demonstrated that half of units achieved the net-zero energy goal in the 22-month measurement period. Weather-normalized data, however, showed that only one unit is likely NZEH in the long-term. Energy consumption was underestimated in housing development case study due to uncertainties in energy use for MELs.

6.1 Data-driven Recommendations

Recommendations to improve ZEHs performance based on the researcher’s lessons learned:

- Establish and integrate clear performance goals, system requirements, and measurement tools to facilitate team understanding of performance;
- Incorporate context-driven, human-building interactions into simulations (or augment existing simulations and empirical evaluation approaches) to reduce the risk of not achieving ZEH performance goals;
- Integrate occupants in the design process (if possible) to anchor the design in their needs and maximize the efficiency of building technologies;
- Systematically integrate post-occupancy evaluations (POE) into the design, construction, and operation workflow of buildings to provide critical feedback for incremental project improvement;
- Integrate post-occupancy education interventions to empower occupants with the knowledge needed to operate the building;

- Design and construct ZEHs for future adaptability (e.g., increase on-site energy production by adding additional solar PV panels to overcome variability in HBI);

With this study, researchers and practitioners can benchmark performance and better anticipate potential variability in future ZEH projects. Furthermore, practice recommendations provided here can help future ZEH designs to achieve their performance goal(s) and reduce the risk for under-performing ZEH projects.

6.2 Limitations

The authors recognize that there are limitations to this study. The use of the case study method with a non-random sample reduces the generalizability of the study's findings. The authors mitigated the case study generalizability challenge through three approaches that add depth and richness to the work. First, the authors developed and presented a clear procedure to enhance the repeatability of the methodology. Second, the study employed a multi-step empirical analysis, relying on commonly used variables in the literature. Finally, the authors shared lessons learned that can assist other researchers and practitioners.

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Appendix A

1.1 A.1 Energy use intensities

Table A.1. EUIs in six units and sample mean in different periods.

	EUI (kWh/m^2-yr)						
Period	**A**	**B**	**C**	**D**	**E**	**F**	**Sample Mean**
YR1	62.01	53.95	65.33	54.73	51.93	52.88	56.81
YR2	64.29	59.95	64.68	54.89	53.25	56.79	58.97
Annual Mean	63.15	56.95	65.01	54.81	52.59	54.83	57.89

1.2 A.2 Zero-energy balance

Table A.2. Zero-energy balance in six units and sample mean (P-C ≥ 0).

Time Interval	**Period**	**Total # of Intervals**	Unit						**Sample Mean**	**STD**
			A	**B**	**C**	**D**	**E**	**F**		
Monthly	**Measurement Period**	22	9	14	13	-	16	16	15	2.6
		% to total #	41%	64%	59%	-	73%	73%	68%	
	YR1	12	4	7	6	-	8	8	7	2.8
		% to total #	33%	58%	50%	-	67%	67%	58%	
	YR2	12	5	7	7	8	8	8	8	1.0
		% to total #	42%	58%	58%	67%	67%	67%	67%	
	Annual Mean	12	4.5	7	6.5	8	8	8	7.5	1.26
		% to total #	38%	58%	54%	67%	67%	67%	63%	
Daily	**Measurement Period**	667	313	383	325	-	436	446	406	54.8
		% to total #	47%	57%	49%	-	65%	67%	61%	
	YR1	365	164	200	156	-	220	221	203	27.5
		% to total #	45%	55%	43%	-	60%	61%	56%	
	YR2	365	156	187	177	218	233	230	210	28.7
		% to total #	43%	51%	48%	62%**	64%	63%	58%	
	Annual Mean	365	160	193.5	166.5	218	226.5	225.5	206.5	27.2
		% to total #	44%	53%	45%	62%	62%	62%	57%	
Hourly	**Measurement Period**	16,009	4,609	4,760	4,733	-	5,138	5,206	4,820	237.4
		% to total #	29%	30%	30%	-	32%	33%	30%	
	YR1	8,761	2,420	2,502	2,489	-	2,656	2,702	2,507	107.0
		% to total #	28%	29%	28%	-	30%	31%	29%	
	YR2	8,761	2,486	2,529	2,510	2,865	2,753	2,765	2,576	147.9
		% to total #	28%	29%	29%	34%	31%	32%	29%	
	Annual Mean	8,761	2,453	2,516	2,500	2,865	2,705	2,734	2,542	148.9
		% to total #	28%	29%	29%	34%	31%	31%	29%	

Notes: Year 2016 was a leap year, but we had 23 hours of missing data.

1.3 A.3 Monthly End-use Energy Consumption Analysis

1.3.1 A.3.1 Heat Pump

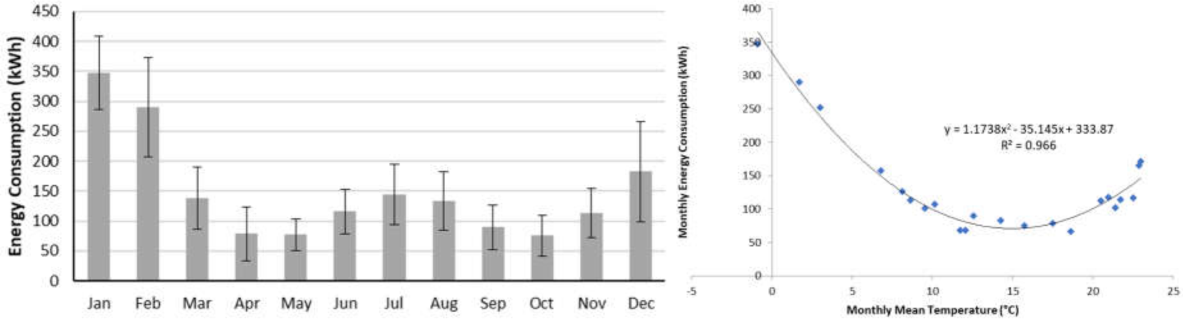


Fig. A.1.
a) Monthly energy consumption for heat pump in sample mean in a typical year (average of both 1-year periods)
b) Regression result for monthly energy consumption for heat pump and average outdoor air temperature.

1.3.2 A.3.2 Water Heater

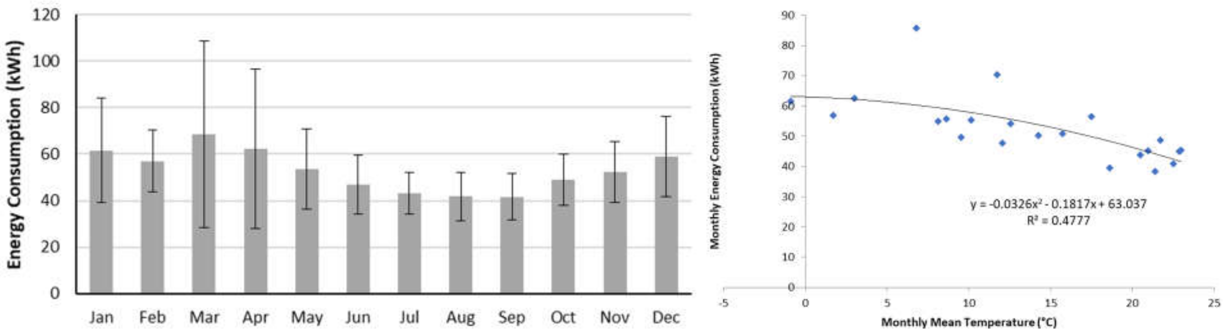


Fig. A.2. a) Monthly energy consumption for water heater in sample mean in a typical year (average of both 1-year periods) b) Regression result for monthly energy consumption for water heater and average outdoor air temperature.

1.3.3 A.3.3 MELs

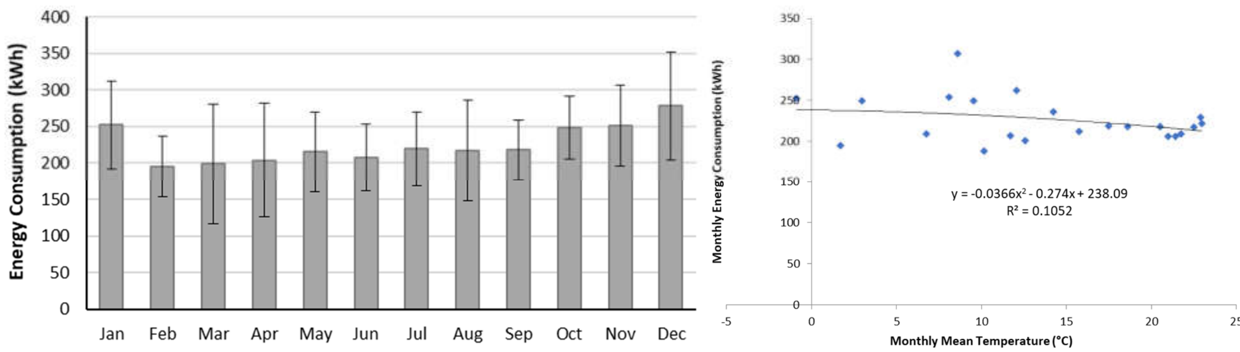
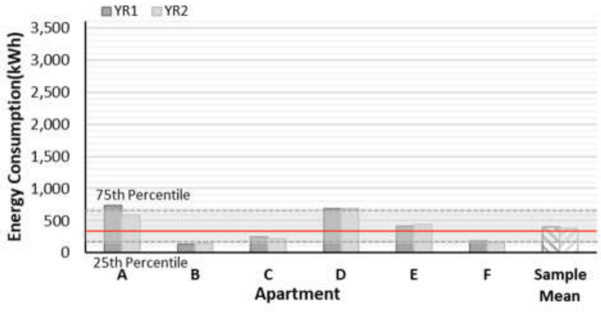
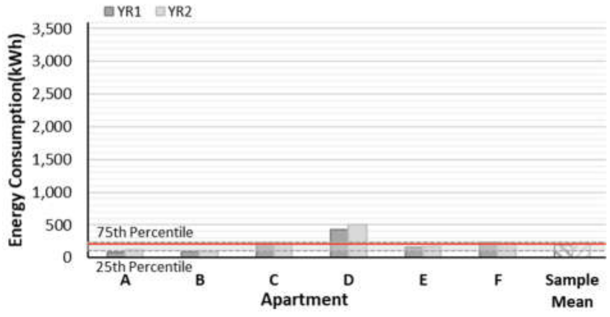


Fig. A.3. a) Monthly energy consumption for MELs in sample mean in a typical year (average of both 1-year periods) b) Regression result for monthly energy consumption for MELs and average outdoor air temperature.

1.4 A.4 Annual Energy Consumption for Dryer and Range



(a)



(b)

Fig. A.4. a) Annual energy consumption for a) dryer and b) range in six units and sample mean.