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INVESTIGATING THE PERFORMANCE OF A NET-ZERO ENERGY BUILDING: AN OCCUPANCY-FOCUSED ENERGY MODELING APPROACH

Elie Azar, Maria Lamprou, and Ahmed Al Amoodi
Department of Engineering Systems and Management
Masdar Institute, Abu Dhabi, UAE

ABSTRACT

The way occupants interact in a building, use its spaces, and control its various systems, highly impact energy consumption. Using building energy modelling, this study investigates the impact of various occupancy profiles and energy use characteristics behaviours on the operation of a Net-Zero Energy (NZE) home. A scenario analysis indicates that different types of occupants (e.g., worker, student, and stay-at-home) can lead to variations in building energy consumption up to 16 percent. Such variations put the NZE operation of the building at risk, motivating the need to research and better account for human-related parameters in the design of NZE buildings.

INTRODUCTION

In recent years, there has been a growing interest in Net-Zero Energy (NZE) Homes to help reduce the energy intensity of the residential building sector (Marszal et al., 2011). While different definitions can be found in literature, a NZE building in this study refers to one that generates as much or more energy than its yearly energy demand (Annunziata et al., 2013). To reach this objective, NZE buildings are typically designed to be highly energy efficient, hence minimizing the need for large energy generation capacities (Li et al., 2013).

In practice, despite advancements in building design and technologies, buildings consistently consume higher than expected energy levels (Masoso and Grobler, 2010). Discrepancies between predicted levels, obtained during the design phase, and actual levels, observed during the operation phase, typically range from 30 to 100 percent in some cases (Azar and Menassa, 2012). Therefore, there has been a growing interest in recent years to identify and evaluate various drivers of energy consumption in buildings.

A large number of studies can be found in literature on the impact of building design parameters on energy performance (Wang et al, 2011; Lam et al, 2008; Lee and Chen, 2008; Melek, 2008; Tavares and Martins, 2007). Typical parameters include building envelope features, thermal mass, airflow rates, electrical lighting systems, Heating, Ventilation, and Air Conditioning (HVAC) systems, to name a few. In these studies, researchers typically rely on building simulation software (e.g., EnergyPlus, IES, and eQuest), which take as inputs the parameters of the building under study and predict its energy consumption levels. Then, based on the improved understanding of the interdependencies between these parameters and building performance, energy conservation measures are typically proposed (e.g., replace chiller, retrofit building envelope).

In recent years, the scope of study has expanded beyond building design parameters to include ones that reflect how people actions and energy use behaviours can impact building performance (Azar and Menassa, 2014, 2012; Lopes et al, 2012; Moezzi, 2009). For instance, Azar and Menassa (2012) studied parameters that reflect how occupants' actions in their built environment can affect its energy performance. These include thermostat set point temperature settings for occupied and unoccupied periods, lighting and equipment usage patterns, hot water consumption, and general building schedules. Results confirm the high impact of human actions on energy consumption levels, particularly changing thermostat set point temperatures, which can significantly increase cooling or heating loads.

Such findings are particularly relevant for NZE building and homes, where efficient operation by occupants is not only desired, but also vital to successfully achieve energy self-sufficiency (PNNL, 2013). Furthermore, understanding and anticipating occupancy energy use patterns is essential even at the first stages of the building design phase. This allows designers and engineers to first properly size building systems such as HVAC units, and second, size energy generation systems such as Photo-Voltaic (PV) solar panels to ensure that energy demand does not exceed supply. Therefore, human energy consumption behaviour is a highly important factor to be studied, understood, and accounted for to reach NZE goals.

PROBLEM STATEMENT

Despite the growing focus on occupancy-related drivers of energy consumption, literature on the topic remains disaggregated and limited, especially in the context of residential NZE buildings.

First, most studies in literature focus on traditional commercial or residential buildings. As a result, the impact of occupancy actions and energy use behaviours on the energy consumption of NZE buildings remains unclear. Second, different types of residential occupants (e.g., worker, student, stay-at-home) typically have different occupancy schedules (Rakha et al., 2014), potentially leading to different energy use patterns. Here again, literature lacks studies that investigate how occupancy types and profiles can affect or drive the performance of ZNE residential buildings or homes.

Finally, due to lack of understanding of the human drivers of energy use, important assumptions are made during the design phase on the energy consumption patterns of occupants. This is leading to important discrepancies between predicted and actual energy consumption levels (Azar and Menassa, 2012). Such inaccuracies can lead to excessive energy demand over the building life cycle (e.g., from inaccurate sizing of building energy systems) and insufficient energy supply (e.g., from inaccurate sizing of energy generation systems).

OBJECTIVES

This study aims to fill the identified gap in literature by investigating the impact of various occupancy profiles and energy use characteristics on the operation of a NZE home. Specific objectives include (1) developing energy consumption profiles (i.e., occupancy diversity factors) for different types of occupants, (2) understanding the impact of these profiles and their energy use patterns on the performance of a NZE home, and (3) providing insights and recommendations on the design and operation of future NZE buildings.

METHODOLOGY

The proposed methodology is composed of three phases. The first phase describes the development of occupancy diversity factors for three common types of occupants. The second phase details the development of a building simulation model for a NZE home located in Abu Dhabi, United Arab Emirates (UAE). The third and final phase describes a scenario analysis performed on the model to determine the impact of occupancy profiles and other occupancy-related actions on the performance of the building under study.

Diversity factor profiles

Three common types, or profiles, of occupants are defined in this study: "Worker", "Student", and "Stay-at-home". This classification is based on the work of Rakha et al. (2014), who categorized building occupants' types based on extensive travel surveys. Then, diversity factor profiles are developed in this paper to characterize the energy consumption patterns of each occupancy type. More specifically, four sub-types of diversity factors are defined for each profile, based on a review of various studies and building codes (Deru et al., 2011; Davis and Nutter, 2010; ASHRAE, 2010a, 2004). A description of these sub-types is provided in Table 1.

Table 1
Diversity Factor Sub-Types

DIVERSITY FACTOR SUB-TYPES	**DESCRIPTION**
Sub-type 1: Occupancy Presence Diversity Profile (**OPDP**)	Represents the patterns of occupancy presence in the building over a period of 24 hours. A value of zero means that no occupants are present, while a value of 1 represents maximum occupancy level.
Sub-type 2: Lighting Use Diversity Profile (**LUDP**)	Represents the patterns of lighting energy use over a period of 24 hours. A value of zero means that all lighting systems are turned-off, while a value of 1 represents maximum lighting use.
Sub-type 3: Equipment Use Diversity Profile (**EUDP**)	Represents the patterns of equipment, or plug-loads, energy use over a period of 24 hours. A value of zero means that all equipment are turned-off, while a value of 1 represents maximum equipment use.
Sub-type 4: Thermostat Temperature Diversity Profile (**TTDP**)	Represents the variation of the HVAC temperature set point over a period of 24 hours. In residential buildings, it is common to link this profile to the OPDP. More specifically, one temperature (e.g., 24°C) is typically assigned to periods when the building is occupied (i.e., OPDP different than 0), and another temperature (e.g., 26°C) is assigned to unoccupied periods (i.e., OPDP equals 0) (ASHRAE, 2010a).
Note: It is important to distinguish between weekdays and weekend days or holidays when developing each of 4 diversity sub-types above. For instance, for ODDP, a common practice is to develop one ODDP for a typical weekday and another for a typical weekend day or holiday, given the expected differences in occupancy patterns. The same distinction applies for LUDP, EUDP, and TTDP.	

In summary, three occupancy types are defined (i.e., “Worker”, “Student”, and “Stay-at-home”), each requiring four diversity profiles to be developed for a typical workday, and four other for a typical weekend day or holiday. This results in a total of 24 diversity factors to be developed. This was achieved in this study by compiling and fusing the results of various sources of information. These mainly include building energy standards (ASHRAE, 2010a, 2010b, 2004), a study on people daily travel patterns (Rakha et al., 2014), and an initiative by the United States Department of Energy (DOE) on typical schedules for equipment and lighting energy use (Deru et al, 2011).

The process of obtaining the needed information from the mentioned sources is illustrated in Figure 1. Solid lines indicate cases where diversity profiles were directly obtained from the mentioned sources. Dashed lines indicate cases where the authors combined the results of multiple sources to generate the diversity profiles. For instance, the weekday *LUDP* for the “Student” profile was obtained by combining the LUDP of the “Worker” profile, obtained from the DOE initiative (Deru et al., 2011), with the travel schedule of a typical student, obtained from Rakha et al. (2014). More specifically, knowing that a student returns home on average two hours earlier than a worker on a workday (Rakha et al., 2014), the LUDP of the student is generated by copying that of the worker and shifting it two hours earlier. Similar data fusion processes were used to generate the remaining of the 24 profiles identified in Figure 1.

Figure 2 illustrates some of these profiles, namely the occupancy presence (OPDP), lighting (LUDP), and equipment (EUDP) profiles for a typical weekday. The TTDPs are not shown in Figure 2 as they depend on the occupied and unoccupied thermostat temperatures for the particular building under study. These are discussed in the upcoming sections. Also, and for space limitations, the profiles for a typical weekend day or holiday are not shown, and can be found in ASHRAE (2004). It was assumed that all occupancy types share these same non-working day schedules given the lack of data to differentiate between them for weekend days and holidays.

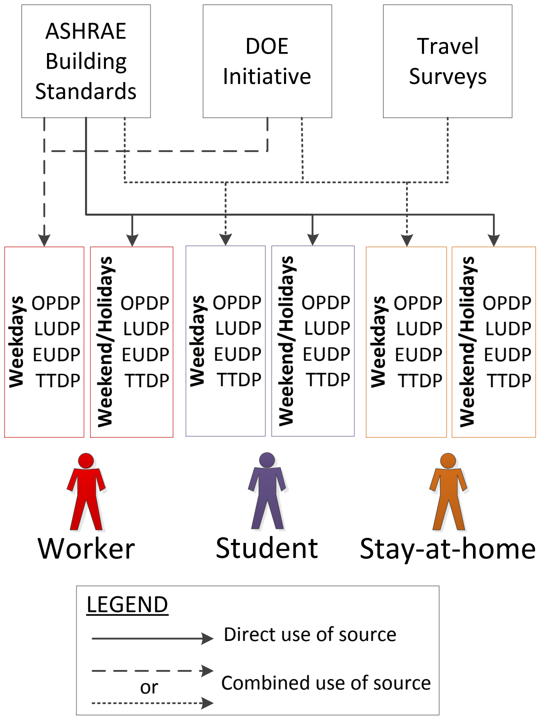

Figure 1 Diversity Factor Development

Building characteristics and base case energy model

The building used in this study is the “Solar NZE House” project, a NZE residential building that will be constructed in the last quarter of 2015 in Masdar City, Abu Dhabi, UAE. The house is designed to be entirely power by solar Photo-Voltaic (PV) panels installed on its the roof or/and in its near vicinity. The system does not have any battery energy storage capacity. On the other hand, the house is connected to the grid, allowing it to buy from and sell back electricity to the grid. The NZE terminology used in this case refers to a total amount of energy generated over a period of one year (i.e., supply) that is equal to or higher than the energy required to operate the house during the same period (i.e., demand).

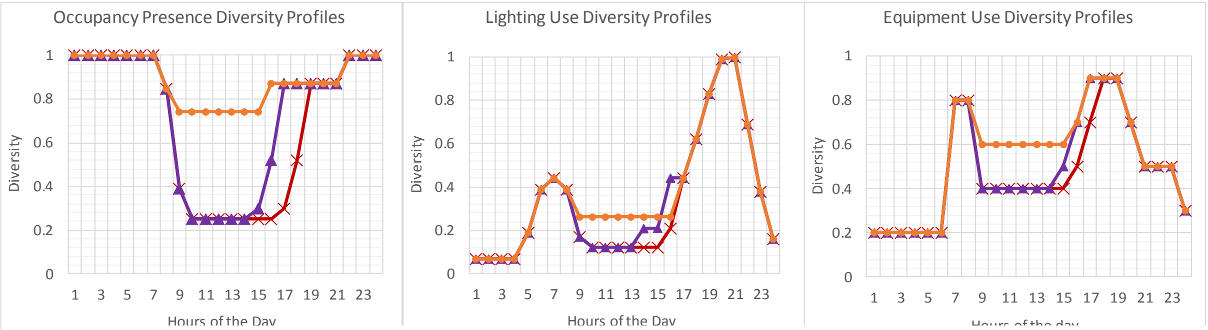

Figure 2 Diversity Factors for a typical weekday

Figure 3 illustrates a 3D model representation of the house, generated using the IES building energy simulation software (IES, 2015). This energy model was used through the design phase to test, choose, and size different civil, electrical, and mechanical systems. Several international and local building standards were used to guide this design process. These mainly include building standards such as ASHRAE 90.1, 90.2, 55, and 62.1, the Dubai Green Building Regulations, and the solar decathlon building design rules (Emirates GBC, 2014; US DOE, 2014; ASHRAE, 2010a, 2010b, 2010c, 2010d).

Figure 3 3D model of the Solar NZE House.

Following a thorough iterative design process, a projected Energy Intensity (EI) of 132.5 kWh/m2/year was obtained for the house, which is around 50% less than what an average building in Abu Dhabi consumes (Abu Dhabi Municipality, 2011). A summary of the main building characteristics is presented in Table 2. These are the same parameters used to develop the model in IES, which is considered the base case model for the scenario analysis presented in the next section.

Figure 4 illustrates the predicted energy consumption by end-use for this base case model over a period of one year. The highest and most variable end-use is the HVAC system. This was expected given the extreme hot weather conditions of Abu Dhabi, especially in the summer months. In contrast, and also due to the hot climate, the building does not require any air heating energy.

In parallel to the energy model development, a solar PV generation system was designed for the house with a net energy production capacity of 9.54 MWh/year. This value represents the useful energy out of the converter (i.e., after deducting different types of losses such as PV-array or inverter losses). A summary of the proposed PV system is presented in Table 3. It is important to note that in addition to the mentioned PV panels, solar thermal panels will also be installed for domestic water heating purposes. These are not included in this paper given the main focus on electricity consumption.

Table 2
Building characteristics and base case model parameters

PARAMETER	VALUE
Design weather conditions (Location)	Abu Dhabi International Airport, UAE
Building floor area	70.2 (m^2)
Building volume	189.5 (m^3)
Number of floors	1
Number of bedrooms	1
Cooling type	Packaged DX Cooling with Constant Volume Fan Coil Units (FCUs)
Heating type	Not required due to Abu Dhabi hot climate
Water heating system	Solar thermal panels-Hot Water (HW) Boiler
Glazing type	Double
Infiltration rate	0.25 ACH (air changes per hour)
People density	23.4 m^2/person
Minimum fresh air	10 L/s-person
Equipment intensity	5.4 W/m^2, applied to all the non-common areas of the ground and middle floors
Lighting intensity	11.8 W/m^2
Chiller COP	5 (constant)
Heat recovery	sensible only, 70% effectiveness
Envelope U-values	0.11 W/m^2-K for the wall, 0.09 W/m^2-K for the roof
Thermostat Cooling Set Point Temperatures	23.9°C (for occupied periods) and 24.6°C (for unoccupied periods), as per ASHRAE (2010a)

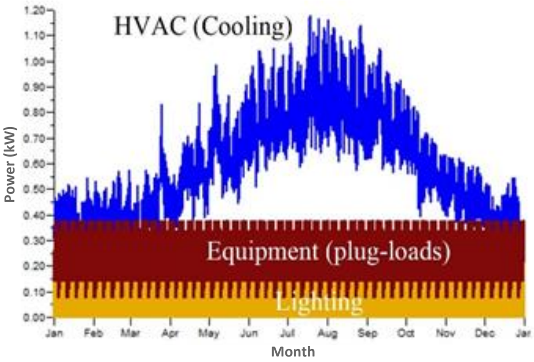

Figure 4 Base case energy consumption by end-use.

Table 3
PV system characteristics

PARAMETER	VALUE
Number of modules	22
Cell type	Poly-crystalline, 6 inch
Nominal power	5.5 kW at peak
Total area	35.4 m^2
Tilt angle	24 degrees
Performance ratio	73.5 %
Produced energy (useful)	9.54 MWh/year

Scenario analysis

In accordance with the objectives of this study, a scenario analysis is conducted to understand the impact of different occupancy profiles and energy use characteristics on building performance. This is achieved by varying the parameters of the base case energy model and tracking the resulting impact on its energy predictions (i.e., IES model simulation results). The proposed scenario analysis consists of three main phases.

Phase 1: The specific goal of this phase is to compare the influence of the different types of occupants identified earlier on the energy consumption of the base case model. This is done by running 3 iterations of the base case model, each iteration using the diversity profiles previously developed for a "Worker", "Student", and "Stay-at-home" occupant, respectively (Refer to Figures 1 and 2). All other model parameters, such as the ones listed in Table 2, remain constant in this phase.

In practice, several of the assumptions made during the design phase do not necessarily reflect the actual situation during operation. This is particularly the case for occupancy actions such as setting thermostat temperatures, which can be hard to predict during design. This guided the design of Phases 2 and 3 where a preliminary sensitivity analysis was conducted on key model parameters to identify influential parameters to test. Results indicate that thermostat set point temperatures have a significant impact on building performance, which is in accordance with previous studies on the topic (Afshari et al., 2014; Azar and Menassa, 2012). As a result, thermostat set point temperatures for occupied and unoccupied periods were selected for variation in Phases 2 and 3, as shown next.

Phase 2: In this phase, the set point temperature for occupied periods is changed from 23.9°C, which is recommended by ASHRAE (2010a), to a value of 22°C, which is commonly observed in the UAE (Afshari et al., 2014). The set point temperature for unoccupied periods remains unchanged (i.e., 26.7 °C) in this phase. Then, a process similar to Phase 1 is repeated where the model is run for a "Worker", "Student", and "Stay-at-home" occupant.

Phase 3: In this phase, the set point temperature for unoccupied periods is also set to 22 °C, illustrating a scenario where the indoor house temperature remains constant independently of the occupancy status or time of the day. This is another possible and commonly observed scenario, which can occur due to faults in HVAC control systems, lack of occupancy knowledge on how to programme set points for different time of the day, or lack of occupancy motivation to adjust the set points to save energy (Colmenar-Santos et al., 2013; Duarte et al., 2013; Azar and Menassa, 2012). Here again, and similar to the previous phases, three runs are performed to compare the three studied occupancy types.

RESULTS AND DISCUSSION

This section presents the results of the scenario analysis. Starting with Phase 1, Figure 5 illustrates an important difference in energy consumption for different occupancy profiles. A maximum difference of 8 percent is observed, particularly between a "Stay-at-Home" occupant (10.3 MWh/year) and a "Worker" (9.5 MWh/year). This difference is due to the longer hours spent in the house by a Stay-at-home occupant, which results in more frequent use of equipment and lighting (Refer to Figure 2).

More importantly, Figure 5 also highlights that the increased energy demand for "Student" (9.8 MWh/year) and "Stay-at-Home" occupants (10.3 MWh/year) exceeds the energy supply from the PV panels (9.54 MWh/year) (Refer to Table 3). The results of this phase confirm that occupancy type can have a significant impact on the energy performance of the studied building, jeopardizing its NZE operation.

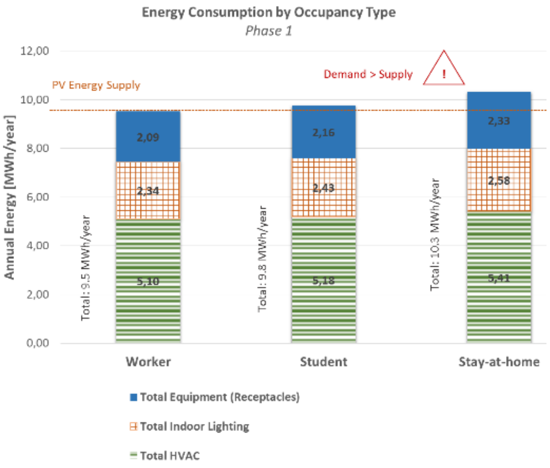

Figure 5 Phase 1 Results.

In phases 2 and 3, some of the assumptions in the base case energy model were challenged. More specifically, the thermostat set point temperature for occupied periods was changed to 22^0C in Phase 2, followed by a change in the set point temperature for unoccupied periods also to 22^{0}C in Phase 3. Results are summarized in Table 4, showing the energy consumption for each run of the model, as well as the average energy consumption level obtained for the three phases of the scenario analysis.

Starting with the later, the average energy consumption of Phase 2 runs is 6 percent higher than that of Phase 1. This shows that a thermostat set point temperature of 22^{0}C for occupied periods, instead of 23.9^{0}C, results in a 6 percent increase in energy consumption. As discussed earlier, it is very common to observe set point temperatures of 22^{0}C in buildings, especially in the UAE. Therefore, and while ASHRAE standards suggest the use of 23.9^{0}C, the authors recommend the use of more conservative set point temperatures during design (e.g., 22^{0}C) to avoid higher than expected energy consumption levels. In parallel, educating building occupants to raise their set point settings by few degrees can significantly help reduce energy, without compromising their thermal comfort levels (ASHRAE, 2010c).

As for the comparison between the averages of Phase 3 and Phase 1 runs, a difference of 8 percent was observed. In fact, changing temperatures for both occupied and unoccupied periods to 22^{0}C has shown to further increase energy consumption levels. Here again, the authors recommend a careful consideration of the assumptions made regarding set point settings during design.

In addition, results highlight the importance of educating building occupants on how to control set point temperatures between occupied and unoccupied periods to minimize cooling loads (e.g., raise temperature when leaving the house to reduce cooling loads). Educating building or facility managers on how to operate and maintain HVAC systems is also essential as faults can lead to excessive energy loads and uncomfortable thermal conditions.

Table 4 also illustrates the maximum differences obtained between all runs. This helps capture the possible variability in building performance due to occupancy-related assumptions. As shown in the table, the maximum differences are observed between a "Worker" occupancy profile from Phase 1, and a "Stay-at-home" profile from Phases 2 or 3. These differences are significant, reaching a maximum of value of 16 percent.

Put differently, inaccurate assumptions made during the design phase regarding occupancy type and thermostat settings can lead to a 16 percent discrepancy between predicted and actual energy consumption levels. This can here gain alter the balance between energy demand and supply level, putting the NZE performance of the house at risk.

Prior to concluding, it is important to highlight some of the limitations of this study, which can guide future research efforts. First, the scope of this study was limited to one specific NZE house. Future research can cover more types (e.g., apartment or office buildings), sizes and locations.

Table 4
Results for all phases

	OCCUPANCY PROFILE	ENERGY CONSUMPTION [MWH/YEAR]	AVERAGE ENERGY CONSUMPTION PER PHASE [MWH/YEAR]
Phase 1	*Base case model used without modifications*		
	Worker Student Stay-at-home	9.53 *(Minimum value observed)* 9.76 10.32	9.87
Phase 2	*Occupied set point temperature changed from 23.9 ^{0}C to 22 ℃*		
	Worker Student Stay-at-home	10.01 10.31 10.98	10.43 *(6% higher than Phase 1 average)*
Phase 3	*Occupied set point temperature changed from 23.9^{0}C to 22 ℃* *Unoccupied set point temperature changed from 26.7^{0}C to 22 ℃*		
	Worker Student Stay-at-home	10.40 10.61 11.07 *(16% higher than minimum value)*	10.69 *(8% higher than Phase 1 average)*

Second, only one occupancy energy use action was included in the scenario analysis, which is varying thermostat temperatures. Future research can investigate additional uncertainties in occupancy behaviours related to lighting and equipment usage. This is expected to increase the observed variation in energy consumption levels and further support the findings of this paper.

Third, this study did not study any hybrid occupancy types such as having both a worker and a student living in the house. In addition, diversity profiles were generated using resources mostly originating in the United States. This was mainly due to the lack of data on travel behaviours in the UAE, which can also be the subject of future research on the topic.

CONCLUSION

This study investigates the impact of occupancy profiles and energy use characteristics on the performance of NZE house in the UAE. The proposed methodology involves (1) developing diversity profiles for common types of residential building occupants, (2) emulating the energy performance of the NZE house using building energy simulation software, and (3) conducting a scenario analysis on the model, varying occupancy profiles as well other human-related parameters (i.e., thermostat set point temperatures).

Results confirm the significant influence that occupants can have on building energy performance. First, different types of occupants can have different schedules and as a result different energy use patterns. For instance, results indicate that a “Stay-at-home” occupant is likely to consume 8 percent more energy than a “Worker” occupant. Such an increase results in energy demand exceeding supply from PV panels, compromising the NZE operation of the house. Second, even a single occupancy action can highly affect energy use levels. For instance, a 2-degree change in temperatures set points can lead to an 8 percent increase in energy consumption levels. Finally, when testing different combinations of occupancy types and thermostat set point temperatures, a maximum of 16 percent in energy consumption was observed.

As a result, several recommendations can be made to support the design and operation of NZE buildings. First, during the design phase, it is crucial to properly account for occupancy-related parameters to avoid discrepancies between energy model predictions and actual energy use levels during operation. Adequate time and resources need to be particularly allocated to study influential parameters such as the profile of future tenants of the building. Furthermore, it is also essential to account for uncertainty in occupancy-related parameters in order to design and size energy generation systems accordingly. Second, regarding building operation and maintenance, the authors recommend a continual maintenance and commissioning strategy to ensure an efficient operation of building systems, especially the HVAC system. Programmable thermostats can also be used to control thermostat settings and avoid unnecessary cooling loads during unoccupied periods. This is particularly relevant to regions with extreme weather conditions such as the UAE, where a proper control of the HVAC system can lead to significant energy reductions. Finally, this study sheds the light on the human role in energy conservation. The authors would like to emphasize the importance of educating building occupants and facility managers on best practices to operate their buildings efficiently. While changing human behaviour can be challenging, it remains a crucial step to alter current energy consumption patterns and help achieve a more sustainable built environment.

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