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Windows of Opportunities: Orientation, Sizing and PV-Shading of the Glazed Area to Reduce Cooling Energy Demand in Sub-Sahara Africa

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Abstract: In hot climates, such as sub-Sahara Africa, window sizing and orientation pose challenges as they add, through solar insolation, to the building cooling energy demand and thus the cause of indoor overheating risk. This risk can be reduced through passive building-design-integrated measures, e.g., optimizing the window size, orientation and solar shading strategies. Through an IDA-ICE building performance simulation tool, the current study explores the impact of window size, optimization and building-integrated PV panels as shading strategies on cooling energy demands in three cities (Niamey, Nairobi and Harare) in sub-Sahara Africa. Results show that thermal comfort and cooling energy demand are sensitive to a window-to-wall ratio (WWR) > 70%, while the need for artificial lighting is negligible for a WWR > 50%, particularly in the north for cities in the Southern hemisphere and the south in the Northern hemisphere. A WWR > 70% in the east and west should be avoided unless shading devices are incorporated. Internal blinds perform better in improving occupant thermal comfort but increase artificial lighting while integrating PV panels, as external shading overhangs reduce cooling energy but also produce energy that can be utilized for building services, such as air conditioning. In this study, the results and implications of the optimization of window size, orientation and building-integrated shading and operation are discussed.

Keywords: glazing area; window shading; cooling energy demand; thermal comfort; building-integrated photovoltaics

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1. Introduction

Buildings account for about 40% of the total global energy use and contribute as much as 36% of the anthropogenic carbon dioxide emissions [1–3]. Indoor climate control requires about 50% of the total building energy use, and regions with high cooling requirements adopt electricity-driven technologies, such as air conditioning, which are cumulatively energy-intensive and have a high impact on the climate [4]. Unfortunately, projections show that energy use in buildings will increase to 67% of the total global energy use by 2030 [5]. This undermines the declared urgent race to Net-Zero emission systems reinvigorated at the 26th Conference of the Parties (COP26 as commonly known) and also the ambitions of the 2015 Paris climate agreement to reduce global energy use and increase energy efficiency in buildings [6,7]. Therefore, the building sector remains an area of interest to reduce global energy use and greenhouse gas emissions.

When focusing on the building sector, the major determinants of energy use in buildings include the building size, location, regional climate, building envelope, building energy systems, architectural design, economic level of occupants, occupant behavior, building operation and maintenance [8–12]. Location and regional climate are important factors that inform and guide architectural design. These parameters inform passive design factors that influence the heating and cooling demands of the building when in operation. This understanding is emphasized in traditional architecture, where bioclimatic design is at the center of decision making during the design phase. However, modern architecture has brought on an appeal for the broader application of glass envelopes or large windows (glazed areas) in modern buildings [13], but in the hot season, these do not offer the energy-saving advantages afforded by bioclimatic design. For example, unoptimized windows can cause overheated indoor climates due to high solar insolation, which necessitates a large cooling energy capacity. For many of these buildings, particularly in predominantly hot climates, the solar radiation heat load is even higher than the convection heat transfer, which aggravates the role of windows in increasing building cooling energy use [14]. This is problematic, especially now that the increase in heatwaves is escalating the overheating of indoor environments. Thoughtful considerations should be made during design so that buildings can adapt to the changing climate, especially in regions with a high cooling demand throughout the year. Optimizing the glazed area of the building envelope could be a starting point for reducing the cooling energy requirements.

The building envelope plays a significant role in regulating heat loss or gain and improving the indoor environment. For instance, proper insulation reduces infiltration, eliminates thermal bridges, and optimizes the glazed area, leading to reduced heat transfer across the building envelope [15]. Windows are an important part of the building envelope as they additionally offer psychological benefits to occupants by creating a link between the indoor and outdoor environments. While the cooling and heating energy demand of a building is mainly affected by the internal heat load (solar insolation, equipment, occupants etc.), ventilation rate and regional climate [16], windows are a key component that affects a building's energy usage. Their influence depends on their size, type (window characteristics) and orientation (i.e., are the windows facing north, south, east or west).

The size and material composition of the window regulate the amount of solar insolation admitted indoors [17]. Large windows allow for greater solar radiation indoors, resulting in increased internal heat gains, which could be desirable or problematic depending on the local climate and season [18]. For example, in cold climates, poorly oriented large windows can cause significant heat loss and poor thermal comfort due to downdraft, but if the windows are well integrated into the design and the correct type of glass is used, they can result in reduced building heating demands [19]. Additionally, the high amount of daylight indoors reduces the demand for artificial lighting while offering occupants the benefits of the biological process of circadian rhythms [20,21]. On the other hand, in hot climates, smaller windows are associated with lower cooling demands and reduced occupant visual comfort and daylight utilization [22]. Therefore, an optimum window size ensures enough natural light that reduces artificial lighting requirements, improves the biological process of the circadian rhythm, and promotes occupants' health and psychological/emotional well-being [23–25].

The orientation of the window determines the quantity/quality of the incident solar insolation and, consequently, the heat gain through the windows [26]. For example, for the temperate climate in the Northern hemisphere, windows oriented towards the south allow for the high penetration of solar radiation indoors during winter, consequently reducing the heating demand. At the same time, there is a minimal impact on the cooling demand during the summer since the sun affects the south-orientated façade [16]. The design and effect are opposite for temperate climates in the southern hemisphere. Thus, in temperate regions, depending on the hemisphere, north or south window orientation is recommended because it allows for the penetration of good daylight with minimal influence on glare, a low risk of overheating during the cooling season and reduces the heating demand in winter [27]. This shows that window orientation is a critical factor when dealing with buildings' heating and cooling demands.

The key is to strike a balance, optimize window size, or to use energy-efficient window designs/technologies that offer a trade-off between building energy use and good daylight utilization [28]. Window designs/technologies, such as shading, tinted glazing, reflective coatings and double or triple glazing, are incorporated into the design to address the sustainability and conservation needs associated with the trend of "highly glazed buildings" in modern architecture [29]. For instance, triple glazed windows reduce indoor heat loss compared to double and single glazed windows due to their low heat transfer coefficient, but they also cause indoor overheating in summer [16]. On the other hand, integrating shading allows for the use of bigger window sizes and regulates solar radiation, which reduces internal heat generation. Shading can be integrated in various ways, such as built-in blinds between the panes of glass, venetian blinds or curtains inside the room, or external shades in the form of shutters and overhangs incorporated into the exterior envelope [21,30,31]. However, shading can affect visual comfort and the optimal utilization of natural lighting. Therefore, a well-integrated shading system is recommended because it contributes significantly to indoor illumination from daylight and enhances thermal and visual comfort. It also controls solar heat gains, reduces glare, saves energy and improves the thermal performance of the building [32–34].

The current study investigated, through numerical simulations, the effects of window size, shading and orientation on the cooling energy demand, lighting electricity use and thermal comfort in a cellular office located in three cities with different latitudes in Sub-Sahara Africa. These cities were Niamey in Niger, Nairobi in Kenya, and Harare in Zimbabwe. The effect of window shading, with internal blinds, and building-integrated photovoltaic (PV) panels, as external shading devices, on building energy use and thermal comfort are examined.

To the authors' knowledge, there are few studies on the influence of the glazed area on the cooling energy demand in the context of Sub-Sahara Africa, e.g., [35,36], but this region is important particularly because it has a predominantly large cooling requirement. A literature search shows that most the studies on this topic have focused on the northern hemisphere [37,38] and most of the studies have considered passive shading strategies without accounting for the opportunity of integrated PV panels as shading devices. Additionally, since the relative performance of any energy building system or indoor climate control system is related to the local climate, this study emphasizes the importance of strategic and regional planning for the successful implementation of sustainability and conservation measures in the building sector [39]. This paper contributes to the general framework of optimizing the glazing area in the tropical climate of Sub-Sahara Africa, but more importantly, it contributes to the definition of a reference for building codes, policy and decision making. It also informs architects and provides options for sizing/handling the glazing area to the stakeholders in the building development sector in Sub-Saharan Africa.

2. Method

IDA-ICE 4.8 (IDA Indoor Climate and Energy) simulation software [40], a whole year detailed and dynamic multi-zone simulation software, was used to model the room, its systems and controllers. The software is versatile in building a simulation analysis for building energy use, indoor air quality (including indoor carbon dioxide modeling) and the evaluation of occupant comfort. The software was developed in Sweden at the Royal Institute of Technology and the Swedish Institute of Applied Mathematics. The Software was written in neutral model format that uses differential algebraic equations to model dynamic systems and environments [41,42]. Energy balance in the software considers the climatic variations and a dynamically varying time-step in accordance with model geometry, construction materials, HVAC conditions, occupant behavior or routines and internal heat loads (occupants, equipment and solar radiation). IDA ICE software has been validated by several studies, see Section 3.1 in [41], and has been used in various studies related to building energy and indoor thermal comfort, as well as air quality evaluations [43,44].

2.1. Room and HVAC Description

A cellular office occupied by one person doing sedentary work and with an internal equipment heat load of 100 W/m^2 was simulated. The room had a floor area of 3 m × 4.2 m and a ceiling height of 2.5 m. The external building envelope was made of a 0.15 m medium-weight concrete wall with a 0.01 m render on both sides, resulting in an overall U-value of 1.8 W/(m^2·K). All other walls except the outer envelope wall were considered adiabatic during the simulations. The room had a single window with a U-value of 1.78 W/(m^2·K) in which the frame area had a U-value of 2 W/(m^2·K) and the glazing area had 1.72 W/(m^2·K). The glass had a solar heat gain coefficient of 0.56, solar transmittance of 0.55 and visible transmittance of 0.81.

The room had a dedicated ventilation system operating with an air-conditioned supply temperature of 18 °C through the air-handling unit (AHU), although only sensible cooling was performed on the supply air temperature, and no heating was performed. The room had air temperature setpoints at 23–26 °C, an internal cooling unit with a coefficient of performance (COP) of 3 and unlimited cooling capacity to keep the room temperature within the specified air temperature limits. Mechanical ventilation was used with an airflow rate of 0.7937 L/(s·m^2), operating on weekdays between 6:00 a.m. and 7:00 p.m. For simplicity, all simulated cases were assumed to be fully occupied during this period, and artificial lighting followed the occupancy schedule but was automated only to switch on when daylight (natural light) in the room was below 500 lux. The ventilation was offline at night and during weekends, but the model was built with an infiltration leakage equivalent to 0.012 m^2, which amounted to an air change rate of about 0.52, for a pressure difference of 4 Pa across the building envelop.

2.2. Simulated Cases

Figure 1A illustrates the investigated cases. Three cases of window characteristics were investigated: (1) plain window, (2) window integrated with internal blinds, which activated when the incident light hitting the windows was higher than 100 W/m^2 and (3) window with photovoltaic (PV) panels integrated as an external shading system (overhang). For each of the first two window characteristics, 10 cases of variation in the Window-to-Wall Ratio (WWR) (representation shown in Figure 1B) from 10 to 100% in successions of 10%, with 100% representing a totally glazed façade, were considered to represent the window size. In the third scenario, the PV panel (generic PV) was used as an overhang, which had a projection of 1 m long from the wall outwards (or shading length), while the length varied depending on the window size.

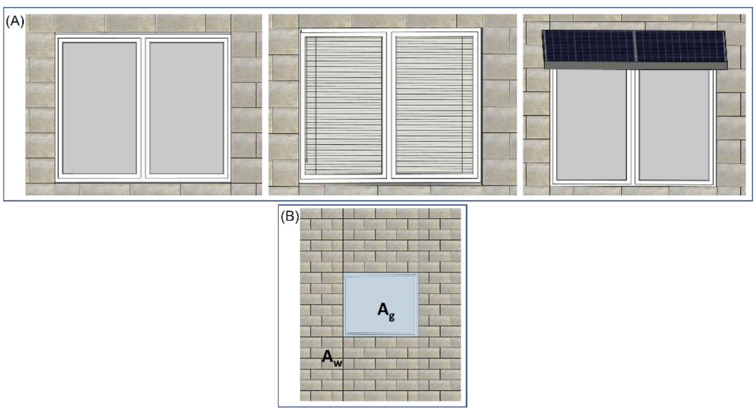

Figure 1. (**A**) Illustration of investigated cases: plain window, window with blinds and PV system as external shading overhang; (**B**) window-to-wall ratio: area of glass (A_g)/area of an external wall (A_w).

The simulated cases with PV shading overhang were dependent on the results from the plain window with poor thermal comfort and a high cooling energy demand. Thus, only window sizes of 50–100% WWR and in unfavorable orientations were simulated. A software built-in generic PV panel was used and had a conversion overall effective efficiency of 20% corresponding to a power rating of 200 W/m^2. Table 1 shows the simulated WWR with PV overhang panel areas and corresponding power rating capacity on each overhang. Tilt or latitude angles used for installing PV panels with respect to the horizontal plane were 4° for Kenya, 6° for Niger, and 22° for Zimbabwe. These tilt angles were maintained in all orientations of interest.

Table 1. Simulated WWR with PV overhangs and the corresponding power ratings.

WWR (%)	Panel Area [m^2]	Panel Capacity [W]
50	2.12	424
60	2.32	464
70	2.51	502
80	2.68	536
90	2.85	570
100	3.00	600

2.3. Approach and Analysis

This research adopted thermal comfort concerning the cooling energy as an assessment criterion to determine the optimal size and window characteristic for each orientation that would give a minimal cooling energy demand in the respective region. The criterion to consider thermal comfort as the most important factor in choosing the optimum WWR for hot climates was recommended by [34,45]. The rationale was that the occupant comfort conditions must guide any building energy calculations of heating and air-conditioning systems. For this reason, the percentage of occupancy hours with acceptable thermal comfort was used.

Aspects of thermal comfort in IDA-ICE software are estimated according to ISO 7730 and used the PMV/PPD model, i.e., Predicted Mean Vote and Predicted Percentage of Dissatisfied [40]. Metabolic rate and clothing were specified as 1.2 met for sedentary work and 0.75 CLO as standard indoor clothing. The analysis did not include occupant exposure to direct solar radiation based on thermal comfort since the PMV/PPD model does not account for it. Real indoor environments are complex and transient, while comfort modeling in IDA-ICE is non-transient, and this may overestimate the percentage of occupancy hours with acceptable thermal comfort.

The cooling energy needed to meet the specified ventilation conditions are defined, as cited by Schiavon et al. [46], from CEN/TR 15615-2007, as the sum of energy needed to cool the supply air (AHU cooling) and to cool the room air (room cooling) in order to obtain and maintain the specified conditions for a given occupancy period. The use of the “Room cooling demand” in the current analysis is critical because the predicted results are independent of the specific characteristic of the HVAC system [46]. For example, the current study does not account for the influence of equipment performance, duct system characteristics and chiller part load curves. In applied practice, delivered energy is considered so that the HVAC system characteristics are all included in the analysis.

3. Results

The results of scenarios simulated are presented in this section. The energy used by fans and the HVAC system is not shown in the graphs because it is almost the same for each city in all window orientations, thus having no basis for a comparison. The average fan energy for all the cities in all the orientations at all WWRs was 4.6 kWh/m^2. The average energy use by the HVAC system (supply air temperature conditioning) in all orientations at all WWRs for Niamey, Nairobi and Harare was 24.3 kWh/m^2, 5.2 kWh/m^2 and 6 kWh/m^2, respectively. It is large for Niamey because it has high outdoor air temperatures and thus requires more energy use to satisfy the supply temperature condition.

3.1. Plain Window (Without Any Shading)

Figure 2 shows the results of the building energy use in terms of the annual cooling energy demand, artificial lighting requirement and the percentage of hours with the acceptable thermal comfort level. The general trend is that the energy used for artificial lighting decreases with an increase in WWR for all cities. However, increasing the window size increases solar insolation, which consequently increases the room cooling demand.

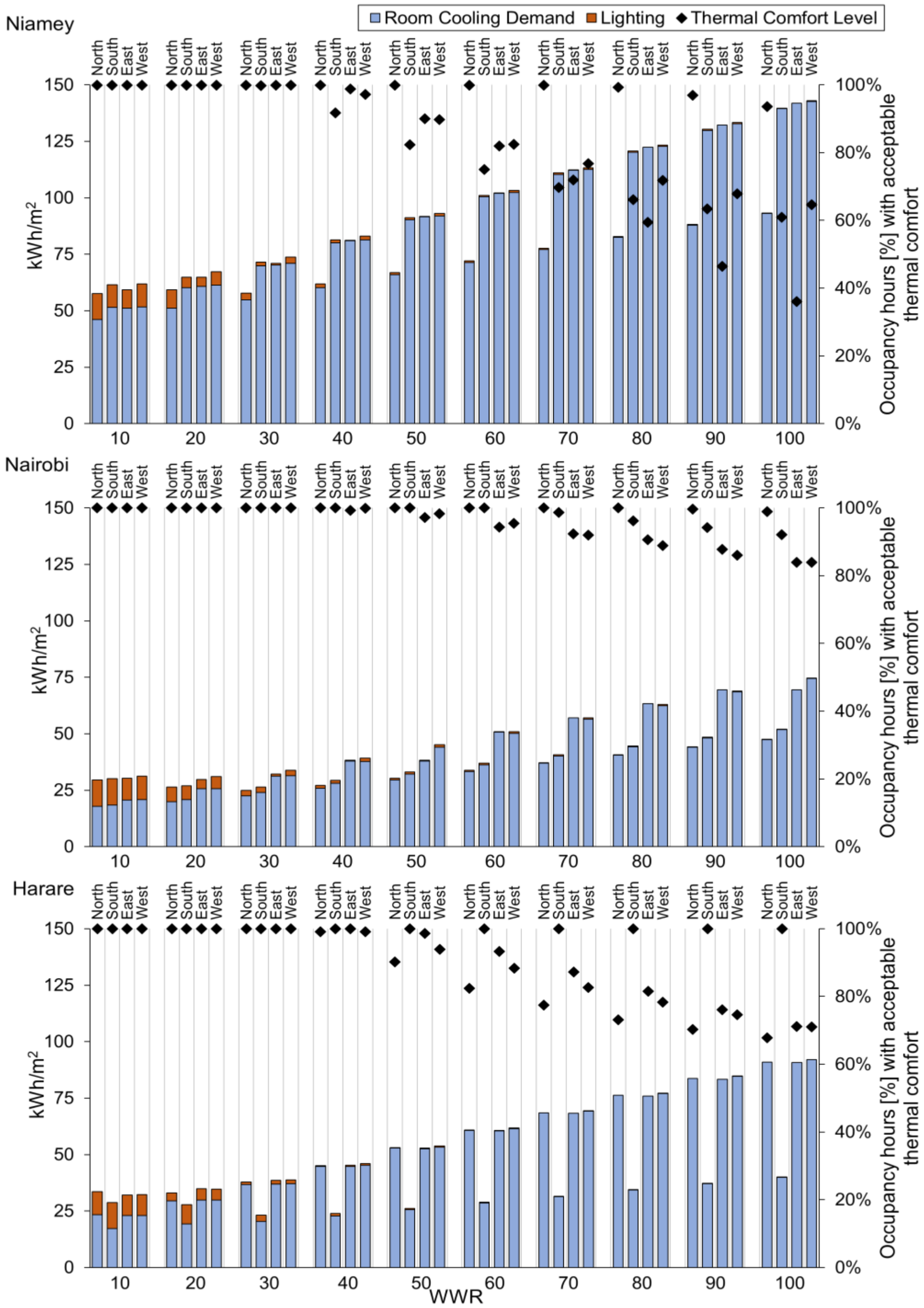

Figure 2. Annual cooling energy demand and occupancy hours with an acceptable thermal comfort level for different WWRs for a plane window.

For Niamey, the occupancy hours with an acceptable thermal comfort level decline for WWR beyond 30% for all window orientations except for the north orientation where it remains at 100% up to a WWR of 80%, above which it drops to about 90%. The north orientation also offers the lowest annual cooling energy demand compared to other orientations with an increase in WWR. For example, a WWR of 100% has an annual cooling energy demand of 93.1 kWh/m^2, while other orientations average around 141.3 kWh/m^2. The east is the worst orientation beyond a WWR of 60%, as there is a fast decline in occupancy hours with an acceptable thermal comfort level as the WWR increase. The latter could be because of the influence of diffuse solar radiation and high temperatures from the Sahara Desert. At a WWR > 40%, the south orientation is the first to decrease in occupancy hours with an acceptable thermal comfort level, but there is a steady decline as the WWR increases. One can deduce that occupancy hours with an acceptable thermal comfort level are sensitive to WWR in the east orientation.

Thus, building designers should avoid putting windows with a WWR > 30% in the east orientation but rather optimize the glazing area in the northern orientation. However, this comes at the cost of more energy use based on artificial lighting for a WWR < 50%; as noted, the northern orientation recorded the highest annual energy demand for artificial lighting of about 2.9 kWh/m^2 compared to 0.6 kWh/m^2 for the eastern orientation.

For Nairobi, the occupancy hours with acceptable thermal comfort is 100% for all WWRs with windows facing north, but it declines to a WWR > 50% for west and east orientations; the decline is noted for the WWR > 70% for the south-facing windows. The annual cooling energy demand is lowest for north- and south-facing windows as seen at a WWR of 50%; it is 25 kWh/m^2, while for the west and east orientations, it is over 35 kWh/m^2. At a WWR of 50%, the lowest demand for artificial lighting is 0.2 kWh/m^2 for windows facing east. Taking the occupancy hours with acceptable thermal comfort as the selection criterion, the optimum WWR is 50% for the west and east but can be as high as 70% for the south or cover the whole façade for the north. For Harare, the occupancy hours with acceptable thermal comfort dip beyond 40% of the WWR for all orientations except those facing south, where it is maintained at 100%. The greatest reduction in occupancy hours with an acceptable thermal comfort level and highest annual cooling energy demand is observed for north-facing windows. The annual cooling energy demand is lowest for south-facing windows (about 15 kWh/m^2) compared with 50 kWh/m^2 for the remaining orientations. The annual energy demand based on artificial lighting is negligible; it is highest for the south-facing windows at 1.2 kWh/m^2 for a WWR < 40%. Based on the occupancy hours with acceptable thermal comfort, the optimum WWR for the south orientation can cover the whole façade, but it can only be as high as 40% for the remaining orientations.

For all cities, it is observed that windows facing the west and east had lower occupancy hours with acceptable thermal comfort beyond a WWR of 40%. In all of these orientations, the larger the window-to-wall ratio, the higher the chances of indoor overheating, and the fewer the hours of occupancy with a comfortable indoor climate, consequently the higher the cooling energy demand. However, the lowest cooling demand is observed for windows facing the north for cities in the northern hemisphere (regions above the Equator). Meanwhile, south-facing windows had the lowest annual energy demand for the city in the southern hemisphere (Harare).

3.2. *Window Integrated with Internal Blinds*

Internal blinds were implemented to assess their influence on the annual cooling energy demand and thermal comfort. Figure 3 shows the annual cooling energy demand, artificial lighting requirement and the percentage of hours with an acceptable thermal comfort level when internal blinds are integrated.

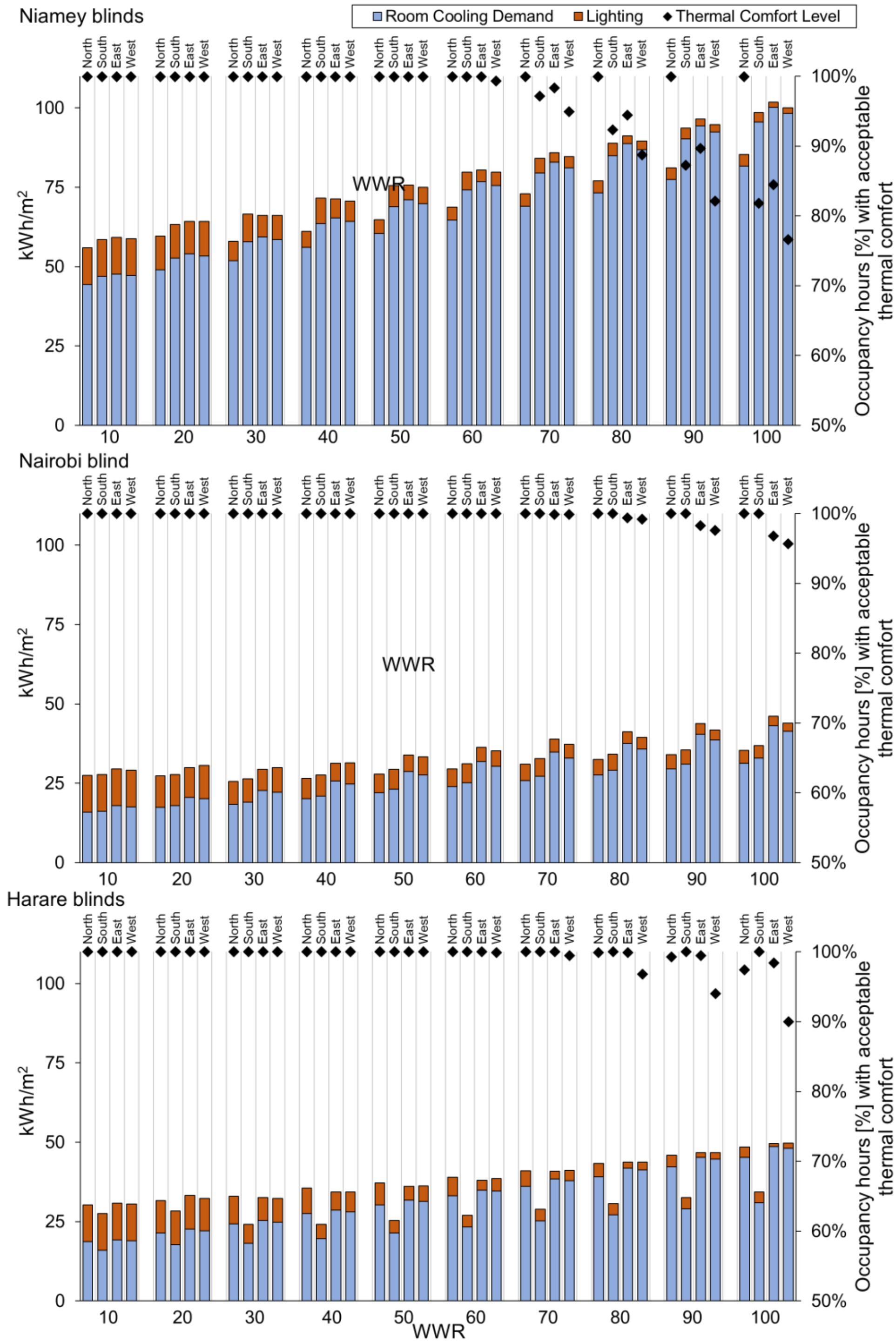

Figure 3. Annual cooling energy demand and occupancy hours with an acceptable thermal comfort level for different WWRs for a window with internal blinds.

Unlike in the case of unshaded windows, where the annual cooling energy demand was high for a larger WWR, there is a significant reduction in annual cooling energy demand with shading using internal blinds for each respective WWR. For example, for a WWR of 50%, the annual cooling energy demand is reduced by 37%, 24% and 41% for windows facing the west for Nairobi, Niamey and Harare, respectively. The reduction is 24%, 22% and 39% for the east-facing windows, 25%, 8% and 42% for the north-facing windows and 28%, 23% and 16% for the south-facing windows for Nairobi, Niamey and Harare, respectively.

Implementing internal blinds has a huge effect on the percentage of occupancy hours with an acceptable thermal comfort level. Niamey registers 100% of occupancy hours with an acceptable thermal comfort level for the north orientation, while this is observed only for a WWR up to 60% for other orientations. Even then, there is a significant improvement in the percentage of occupancy hours with acceptable thermal comfort at larger WWRs in these orientations. Nairobi has almost 100% occupancy hours with acceptable thermal comfort levels in all orientations with only a slight reduction in east and west at a WWR $\geq$ 90%. A similar observation is made for Harare, with only west-facing windows showing a reduction in occupancy hours with an acceptable thermal comfort level at a WWR $\geq$ 80%.

Integrating internal blinds reduces the amount of sunlight into the building, consequently increasing the annual energy demand for artificial lighting. There is more than an 80% increase in annual energy demand for artificial lighting in all cities and all orientations compared to that with the plain windows (unshaded) for a WWR greater than 50%. However, the internal blinds offer cooling energy saving and widens the comfort zone as compared to plain windows, so bigger windows can be used.

3.3. Windows with PV Panels as Shading Overhangs

External shading devices are employed to avoid the social–technical implications of internal blinds. It offers occupants opportunities to experience natural lighting while also being linked to outdoor views. For this reason, photovoltaic (PV) solar panels were employed as an overhang to provide external shading for the window. Figure 4 shows the annual cooling energy demand, photovoltaic electricity production, artificial lighting and percentage of occupancy hours with acceptable thermal comfort levels for buildings with PV solar panels as external shading overhangs. Here, only results for a WWR greater than 50% and only in orientations with an effect on the thermal comfort level registered in Figure 2 (scenario with a plain window) are assessed for each location.

When comparing PV overhangs against internal blinds, the results show that for Niamey, there is an average annual cooling energy demand increase of about 15.3%, 14.6% and 17.7% when the window is facing east, south and west, respectively. However, the annual energy demand for artificial lighting is reduced by about 97.6%, 85% and 72% in the east, south and west orientations, respectively. No significant changes in thermal comfort are observed based on the west orientation but the south exhibits significant changes at a WWR $\geq$ 70%, and for the east, it is at a WWR $\geq$ 80%. Generally, in all cases, an increase in a WWR > 50% significantly decreases the percentage of occupancy hours with acceptable thermal comfort levels. On the other hand, the use of solar PV overhangs introduces local power production, which gives an annual electricity production averaging about 52.35 kWh/m^2 of the room area for the east and west orientations and 64.6 kWh/m^2 of the room area for the southern orientation.

For Nairobi, PV overhangs show, on average, an increase in cooling energy demand of about 24%, 13.9% and 26.4% for east, south and west, respectively, as compared to internal blinds. However, energy demand for artificial lighting is reduced by about 97.8% in the east, 87% in the south and 83.4% in the west. The need for a level of artificial lighting in south- and west-facing windows could be due to the overshadowing of the direct sunlight by the PV panels since Nairobi is very close to the Equator, where the sun is somewhat directly overhead. Regarding thermal comfort, there were minor differences based on performance, although internal blinds provided a better statistical description of comfort performance, e.g., the worst thermal comfort level was based on the west orientation but the difference between conditions with internal blinds and PV overhangs was only about 3%. On the other hand, PV panels had an annual electricity production ranging from 33.3 to 54.4 kWh/m^2, with the south orientation dominating and the west having the least production for all considered WWR.

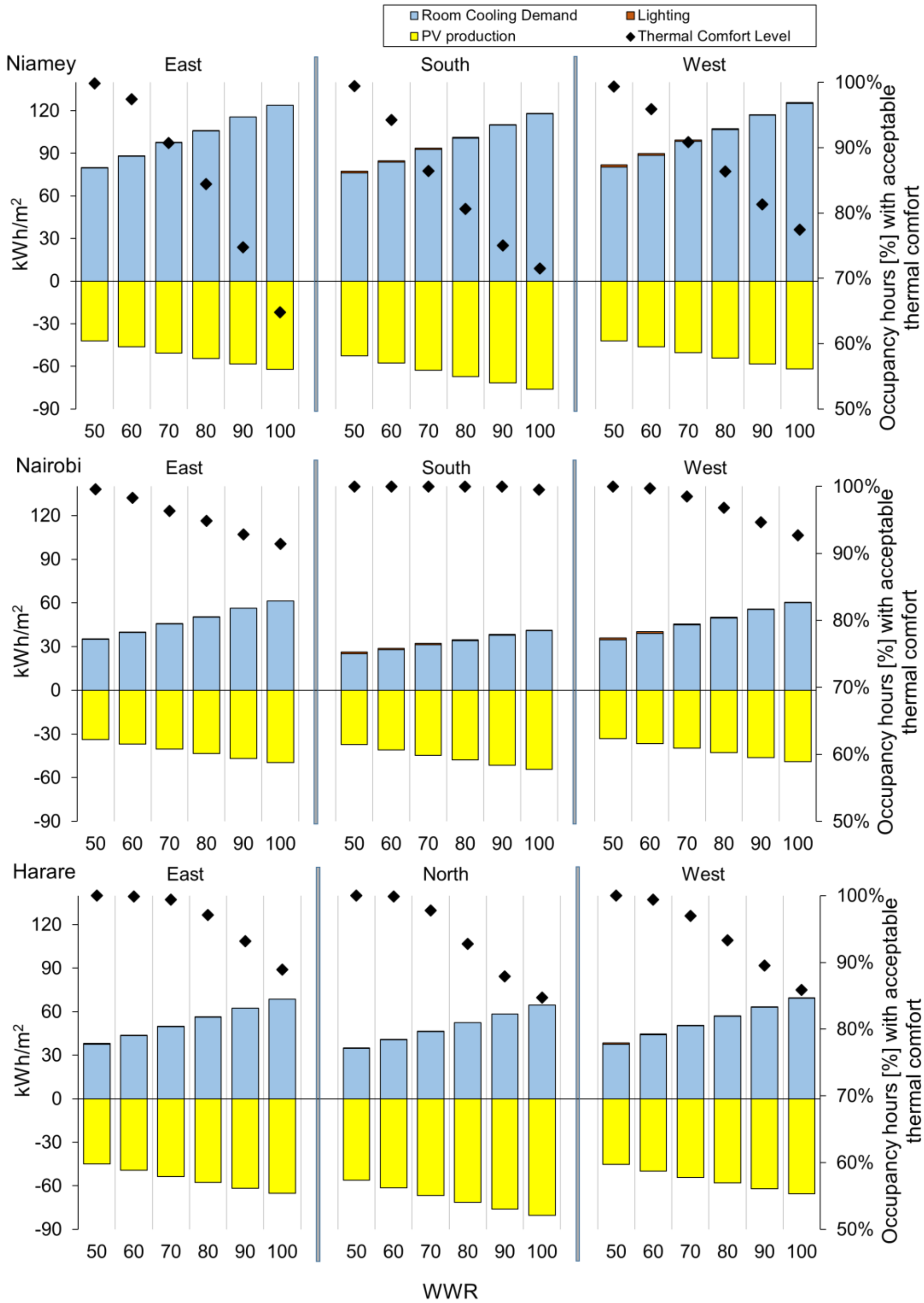

Figure 4. Annual cooling energy demand, photovoltaic energy production, artificial lighting and percentage of occupancy hours with acceptable thermal comfort levels when PV solar panels are integrated as external shading overhangs.

Similarly, comparing PV overhangs and internal blinds, Harare had an average annual cooling energy demand increase of about 23.4%, 22.7% and 24.9% when the window was facing east, north and west, respectively. There was a tremendous reduction in the energy demand for artificial lighting averaging about 95.1%, 98.1% and 88.3% for the east, north and west orientations, respectively. No significant differences were observed in the percentage of occupancy hours with acceptable thermal comfort levels, although a slight drop was registered for north orientations with a WWR $\geq$ 80% and east and west orientations with a WWR $\geq$ 90%. PV panels as overhangs had an annual electricity production averaging 55.6 kWh/m^2 for the west and east orientations and 68.7 kWh/m^2 for the northern orientation in all considered WWRs.

A general trend is that there is a large reduction in energy demand based on artificial lighting in the considered window orientations for all the cities when PV solar panels are introduced as shading overhangs when compared against the window with internal blinds. However, internal blinds show better performance for annual cooling energy demand and has a small improvement in thermal comfort.

4. Discussion

The general observations from the simulation results are that increasing the WWR increases the need for cooling requirements, reduces the need for artificial lighting and impacts thermal comfort in all cases. For the simulated cities in the northern hemisphere of the tropics (Nairobi and Niamey), the results in this study are similar to [34] in that north-facing windows receive less solar insolation and radiant heat during the cooling seasons than any other orientation. However, local climatic conditions should also be considered as they have a strong influence on the results. For example, in Niamey, the east window facing the Sahara Desert received more radiant heat than the south-facing window, which is expected to receive more direct solar radiation than any other orientation, consequently affecting annual energy use and the percentage of occupancy hours with acceptable thermal comfort levels. In this study, it is shown that the south-facing windows receive less solar insolation and radiant heat than any other orientation for a building in the southern hemisphere.

The introduction of shading devices on the building windows caused a significant reduction in solar insolation, reducing the annual energy cooling demand and improving thermal comfort, which resonates with the recommendation in [28]. It further confirms the role of shading devices in reducing cooling demands and improving thermal comfort levels, as reported by other researchers [47,48]. However, considerations should be made during the design and optimization of the glazing area to account for local climatic conditions and the type of shading devices. For example, in this study, internal blinds are more effective in reducing cooling energy although energy demand for artificial lighting increases. However, the current study did not quantify the value of visual comfort, which seems to be more favorable for PV overhangs.

The demand for artificial lighting is negligible for WWRs greater than 50% for the plain window and the window with PV shading overhangs, which conforms to the results of [28]. However, it comes with a reduction in the percentage of occupancy hours with acceptable thermal comfort levels as the WWR increases. In the case of Niamey, perhaps using internal blinds for the windows facing east, south and west would be better than using shading overhangs for a WWR $\geq$ 80%. On the other hand, integrating internal blinds will affect occupants' exposure and the experience of natural lighting. Integrating internal blinds implies that there will be limited exposure to natural lighting, which will have psychological and biological effects on the occupants [20,21]. Although the amount of daylight was not examined in this study, it can be deduced that the visual environment is improved through the action of the PV shading overhangs. Freeman [49] found that shading overhangs improved the visual environment, in addition to reducing the use of curtains and artificial light. Shading devices improve the daylight quality by enhancing the uniformity level, controlling excessive sunrays, protecting the working plane from direct sunlight and eliminating sources of glare. This study further confirms that external shading devices (for example, overhangs) could be more effective for visual comfort, but internal blinds are more effective in reducing the annual cooling energy demand and improving indoor environmental quality [32,34].

In this study, the authors assessed integrating PV panels as external overhangs to optimize local energy generation. The advantage of this approach is that while the PV panels work as shading devices for the windows, they also produce electricity. The produced electricity can be used to power other building services, including lighting or providing electricity to operate a suitable heat pump that will cover the cooling demand. An example would be that a ground-source heat pump system with a typical coefficient of performance (COP) of 3 to 4 can be used [50]. $COP_{cooling} = COP_{heating} - 1$; thus, 1 unit of electrical energy produced by the PV panels could meet 2 or 3 units of the cooling demand. Solar PV glazing is increasingly being incorporated within the fenestration system to offset modern buildings' cooling, heating and artificial lighting demands [51].

Modern windows are incorporated with low emissivity coatings (Low E) and sunshade coatings that reflect the wavelengths of NIR (near-infrared). This means larger windows can be installed with a reduced risk of overheating or low annual cooling energy demand and good thermal comfort. These windows are expensive and will likely take time to gain popularity in developing countries. In this study, the use of the Low E windows was not considered.

5. Conclusions

The effect of the window size and orientation on cooling energy and thermal comfort level in an office building has been studied. It has been observed that the window size and orientation significantly affect the cooling energy and occupancy hours with acceptable thermal comfort. While the demand for artificial lighting decreases, the annual cooling energy demand increases with an increase in the WWR. Based on the results and simulation setup, windows facing the east and west in sub-Sahara Africa have a high influence on the annual cooling energy demand. Thus, the use of large windows in buildings with these orientations should be avoided unless shading devices are incorporated to alleviate the overheating problem that ensues. However, the choice of shading devices comes with trade-offs; for example, shading devices as blinds significantly lower the annual cooling energy demand but increase the need for artificial lighting compared to overhangs. However, building-integrated PV overhangs have a similar effect on thermal comfort as internal blinds but also offer benefits of locally produced electric energy that can be used to offset the cooling demand by using heat pumps. Buildings in the northern hemisphere in sub-Sahara Africa should utilize north-facing facades for large windows, while those in the Southern hemisphere should utilize the south side.

Employing shading strategies can significantly reduce the cooling demand, and PV panels offer more benefits in the form of locally produced electricity that can help offset the cooling demand by powering a heat pump or reducing the imported power for other building services. This has direct and indirect implications on building sector-related emissions and primary energy use and imported power for building services. Thus, integrating PV systems with the building envelope, even as shading devices, as shown in this study, could help reduce the environmental impact of buildings.

To truly develop a sustainable built environment, it is important for future buildings to take advantage of options that increase local power/energy generation. One such option is to use PV panels as shading devices in building design and operation.

The current study has the following limitations: it did not consider the economic aspect of buying, installing, and maintaining these PV panels, and it did not consider aspects, such as the return on investment or an environmental assessment.

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