Energy Consumption Performance Using Window-to-Wall Ratio Factor in a Hot, Dry Climate in Office Buildings: A Case Study in Khartoum City, Sudan

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Abstract--**This study investigates energy consumption in office buildings, which are among the most energy-intensive building types and significantly contribute to overall energy demand and associated environmental impacts. The research aims to evaluate the role of energy-efficient design strategies, with particular emphasis on the window-to-wall ratio (WWR), in reducing cooling energy consumption in office buildings located in Khartoum City. Three contemporary office buildings were selected as case studies. The adopted methodology integrates parametric building modeling and energy simulation using Rhino, Grasshopper for Rhino, and DIVA to assess the influence of different WWR configurations on building energy performance. Simulation results were analyzed using descriptive statistical methods to identify trends and performance variations. The findings reveal that WWR was not sufficiently considered during the early design stages of the investigated buildings, leading to increased solar heat gains, higher indoor thermal loads, and consequently elevated cooling energy demand. The study demonstrates that appropriate control of WWR can play a critical role in improving energy performance in office buildings situated in hot, arid climates. The results underline the importance of integrating energy efficiency considerations at the design stage and provide evidence-based guidance for architects and decision-makers to support the adoption of passive design strategies in similar climatic contexts.**

Index Terms--**Building energy efficiency, Cooling energy demand, Energy simulation, Hot arid climate, Office buildings, Passive design strategies, Window-to-wall ratio.**

المستخلص--تبحث هذه الدراسة استهلاك الطاقة في المباني المكتبية، التي تمثل أحد أكثر أنواع المباني استهلاكًا للطاقة وتسهم بدرجة كبيرة في الطلب الكلي عليها وفي الآثار البيئية المرتبطة بذلك. وتهدف الدراسة إلى تقييم دور استراتيجيات التصميم الكفؤة في استخدام الطاقة، مع التركيز بوجه خاص على نسبة مساحة النوافذ إلى مساحة الجدران (WWR)، في خفض استهلاك طاقة التبريد في المباني المكتبية بمدينة الخرطوم. واختيرت ثلاثة مبانٍ مكتبية معاصرة بوصفها حالات دراسية. وتدمج المنهجية المعتمدة بين النمذجة البارامترية للمباني ومحاكاة الطاقة باستخدام Rhino وGrasshopper for Rhino وDIVA لتقييم أثر التكوينات المختلفة لنسبة النوافذ إلى الجدران في أداء الطاقة بالمبنى. وحُللت نتائج المحاكاة باستخدام أساليب إحصائية وصفية لتحديد الاتجاهات وتباينات الأداء. وأظهرت النتائج أن هذه النسبة لم تحظَ بالاعتبار الكافي في المراحل المبكرة من تصميم المباني المدروسة، مما أدى إلى زيادة الكسب الحراري الشمسي وارتفاع الأحمال الحرارية الداخلية، ومن ثم زيادة الطلب على طاقة التبريد. وتبين الدراسة أن الضبط الملائم لنسبة النوافذ إلى الجدران يؤدي دورًا حاسمًا في تحسين أداء الطاقة في المباني المكتبية الواقعة في المناخات الحارة الجافة. كما تؤكد النتائج أهمية دمج اعتبارات كفاءة الطاقة منذ مرحلة التصميم، وتقدم إرشادات قائمة على الأدلة للمعماريين وصنّاع القرار لدعم تبني استراتيجيات التصميم السلبي في السياقات المناخية المماثلة.

I. Introduction

Khartoum has witnessed rapid urban expansion in recent decades, particularly in the development of office buildings. This expansion is reflected in the increasing number, scale, height, architectural forms, finishing materials, and widespread use of modern construction technologies. Although these developments indicate economic and urban growth, they have led to a substantial increase in energy demand, especially for cooling, due to the hot climatic conditions of the region.

Buildings are among the major consumers of energy worldwide, and office buildings exhibit high operational energy use. Energy-efficient buildings aim to reduce energy consumption while maintaining or improving indoor environmental comfort compared to conventional building types. Such buildings contribute to minimizing environmental impacts, reducing operational costs, and enhancing long-term economic sustainability and resilience.

In response to growing global concerns regarding climate change, carbon emissions, and occupant comfort, energy efficiency has become a fundamental principle in the design and construction of office buildings in the 21st century [1]. Consequently, the integration of passive design strategies at the early design stage is increasingly recognized as a key approach to achieving significant reductions in building energy consumption.

A comprehensive understanding of energy-efficient design strategies is therefore essential for effective energy conservation in buildings. Among these strategies, the window-to-wall ratio (WWR) plays a critical role in controlling solar heat gains, daylight availability, and cooling energy demand. Within this context, this study focuses on evaluating the impact of WWR on the energy performance of office buildings in Khartoum City, aiming to provide evidence-based guidance to support energy-efficient design practices in hot, arid climates.

II. Literature Review

This literature review examines key concepts, theories, and previous studies related to energy efficiency in buildings, with a focus on sustainable design principles and environmental performance.

A. Energy Efficiency Concept

The principle of energy conservation in buildings is one of the fundamental concepts that supports sustainable design, promotes the efficient use of renewable energy resources, and reduces the negative environmental impacts of the built environment. To clarify the concept of energy use and efficiency in buildings, energy efficiency can be defined as the amount of energy consumed for heating, ventilation, and lighting, measured in standardized units that comply with established performance criteria for buildings over time [2].

Furthermore, several studies have emphasized that improvements in energy efficiency have the potential to foster economic growth and social development, while simultaneously enhancing occupant health and well-being, as well as increasing competitiveness and investment opportunities [3], [4]. In addressing global climate change, it has been explained that the international community has increasingly advocated standardized design solutions that mandate higher levels of energy efficiency in buildings, particularly given that buildings are responsible for approximately one-third of global CO_2 emissions [5].

In addition, energy-efficient design strategies in office buildings have become increasingly critical, as they are essential for developing office environments that enhance user comfort through effective energy conservation [6]. Similarly, a study conducted in the United States examined the relationship between improved indoor environmental quality, building energy efficiency, and gains in occupant health and productivity [7]. Overall, previous studies indicate that, despite limited empirical evidence, existing technologies and design practices can significantly improve indoor environmental conditions and enhance workers' performance in office buildings.

B. Energy Efficiency Design Strategies

The principle of energy conservation in buildings is a fundamental concept that supports sustainable design, promotes the efficient use of renewable energy, and reduces the environmental impacts of buildings. Energy efficiency in buildings can be defined as the amount of energy consumed for heating, ventilation, and lighting, measured according to standardized units in compliance with established performance criteria [2].

Improvements in energy efficiency have been shown to support economic growth and social development while enhancing occupant health, well-being, competitiveness, and investment opportunities [3], [4]. In addressing global climate change, the international community has increasingly emphasized standardized design solutions that require buildings to achieve higher energy efficiency, particularly since buildings contribute approximately one-third of global CO_2 emissions [5].

Energy-efficient design strategies are especially important in office buildings, as they are essential for creating environments that enhance occupant comfort while conserving energy [6]. Additionally, studies have shown that improved indoor environmental quality, in combination with energy-efficient building design, can lead to significant gains in occupant health and productivity [7]. Overall, previous research indicates that, although empirical evidence is limited, current technologies and design practices can effectively improve indoor environments and enhance worker performance in office buildings.

C. Climatic Conditions

Khartoum has a subtropical desert climate, characterized by a distinct rainy season from July to September. From November to May, the climate is predominantly hot and dry, with a cooler period occurring between December and February. The rainy season lasts approximately three months, spanning from June to October [8].

Wind patterns in Khartoum are generally predictable [9]. During the dry season, winds primarily originate from the north, while in the brief wet season, they shift to the south. The months of May and June are notable for their weather variability, which is often associated with the occurrence of the "Haboob" winds. Additionally, from May to September, the sun is visible for an average of 95% of daylight hours [10].

III. Materials And Methods

A. Design Approach

This study was guided by an analytical descriptive–quantitative approach. A descriptive method of data analysis was adopted to evaluate existing office buildings in terms of applying effective window-to-wall ratio (WWR) design strategies, to reduce energy consumption related to thermal performance. The research methodology employed a combination of building modeling using RHINO and GRASSHOPPER, along with DIVA simulation tools, to assess building energy consumption.

B. Computational Simulation Using RHINO and DIVA

For this case study, the Virtual Environment (IES-VE) was utilized in conjunction with RHINO through DIVA energy performance simulation tools. DIVA is a widely used software that integrates DAYSIM for climate-based daylighting analysis using the Radiance engine [11]. EnergyPlus is incorporated into the program for single thermal zone energy modeling. The simulation was performed using the Khartoum Airport climate file in combination with actual energy consumption data. The software calculates the energy demand associated with the building's cooling processes under the existing window-to-wall ratio (WWR).

C. Modeling and Simulation

The evaluation of the effectiveness of the window-to-wall ratio (WWR) constituted the first step of this research. In this phase, the building envelope was analyzed, and the performance of the existing WWR was assessed to establish a baseline for comparison with a proposed alternative WWR. A detailed building model was developed, and advanced virtual modeling software was employed to simulate temperature and ventilation performance.

TABLE I
Energy modelling inputs

Category	Source
Weather file	Geographical location (climate)
Geometry: Plans, Sections, elevation	Architectural drawings
Construction: Wall, Roof, Window Overhangs	Architectural drawings
Actual energy consumption	Bills-
Internal Load: Usage (e.g. number of hours) Schedule People, equipment, lighting	Client, Energy modeler Benchmarking data, Nameplate data

D. Assessment Criteria

The study was conceived to identify The relationship between the area of the window to the area of the solid walls and the effect of this relationship on the high rate of energy consumption in cooling and finally, to reach out the effective window to wall ratio office buildings in Sudan in particular, and in the hot- dry climate in general. effective window-to-wall ratio is the measure of the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area.

Fig. 1. Buildings location

IV. Buildings As Case Studies

To achieve the aim of this study, a case study approach was adopted. Three major office buildings in Khartoum city (Table 1), notable for their construction and operational significance, were selected to assess the impact of window-to-wall ratio (WWR) on energy consumption.

The selection criteria included construction period (2003–2015), building height (10–26 floors above ground), built-up area (2,800–5,500 m²), and location within the same microclimate zone. Buildings below ground level were excluded. Tables 3, 6, and 9 summarize the general characteristics of the selected buildings.

The analysis revealed that the design of openings and curtain walls was driven primarily by aesthetics—such as views, transparency, luxury, and modernity—while environmental considerations were secondary. This finding directed the study's focus toward evaluating the environmental impact of these design choices.

TABLE II
Case study buildings

N0	Buildings
1	Greater Nile Petroleum Operating Company (GNPOC)
2	Petrodar tower (PDOC)
3	National Telecom Corporation Tower (NTC

V. Analyses And Discussion

The facades of the buildings were analyzed first by the research method of assessment (modeling and simulation programs) to measure the WWR for buildings, the ratio was 98, 90, 70, It is very high in the climate which the buildings under study are located, to that indicate that principle of facades designing is aesthetical reasons, providing view, transparency, luxury, modernity, and finally environmental aspect, so this principle had a great impact in raising the rate of the energy consumption for cooling, following is a detailed presentation of the case study buildings:

A. GNPOC Greater Nile Petroleum Operating Company

GNPOC Tower; Cross-section; Site plan; Typical layout plan

Fig. 2. Greater Nile building

TABLE III
GNPOC Percentage of Energy Consumption Reduction

Month	Baseline WWR 98%	Proposed WWR 56%	Reduction	Reduction
	kWh	kWh	kWh	%
Jan.	358,000	318,000	40,000	11%
Feb.	355,000	315,000	40,000	11%
Mar.	392,000	358,000	34,000	9%
Apr.	445,000	400,000	45,000	10%
May	486,000	451,000	35,000	7%
Jun.	499,000	452,000	47,000	9%
Jul.	456,000	425,000	31,000	7%
Aug.	496,000	448,000	48,000	10%
Sep.	485,000	431,000	54,000	11%
Oct.	492,000	445,000	47,000	10%
Nov.	441,000	395,000	46,000	10%
Dec.	375,000	339,000	36,000	10%
Total	**5,280,000**	**4,777,000**	**503,000**	**10%**

TABLE IV
Greater Nile Building: General description

Project Data:	Ventilation Overview	Design Strategies	Daylight Overview	Mass design Strategy
Structural Material: composite (Concrete and steel) structure Plan Depth:12 meters (from central core) Location of Plant Floors: Ground floor –outdoor area.	Ventilation Type: Mixed-Mode, 90% mechanical, 10% natural ventilation; natural strategy ventilation Wind-Driven Single-Sided ventilation	Double-skin façades (95% Glazing curtain wall) Double-Skin Façade Cavity: Depth: 500 mm Horizontal Continuity: 2 meters Vertical Continuity: 3.5 meters (floor-to-floor) Approximate Percentage of Year Natural Ventilation can be Utilized: 20% Percentage of Annual Energy Savings for Cooling: Unpublished Typical Annual Energy Consumption (Cooling): Unpublished	Good natural lighting is provided by opening up the space that gives the 'atrium', with three floors, large porches and terraces.	Widest possible point of view. Aerodynamic shape to allow wind flow around the building and its façade. Flexibly serviced, high specification 'user-friendly' column-free office spaces. The smooth flow of wind around the building was one of the main considerations.

The building envelope of the GNPOC Tower was first evaluated to quantify its window-to-wall ratio (WWR), which was determined to be approximately 98% (Table 4). This extremely high proportion of glazing substantially increased solar heat gains, leading to elevated cooling loads and an annual cooling energy consumption of about 5,280,000 kWh

TABLE V
Case 1: GNPOC Facade details

Item	Total	North	East	South	West
Gross Wall Area [m2]	9674.31	1751.81	2737.98	2007	3177.52
Above Ground Wall Area [m2]	9674.31	1751.81	2737.98	2007	3177.52
Window Opening Area [m2]	8692.46	1710.26	2674.56	1205.06	3102.57
Gross Window-Wall Ratio [%]	89.85	97.63	97.68	60.04	97.64
Above Ground Window-Wall Ratio [%]	**89.85**	97.63	97.68	60.04	97.64

To enhance the building's energy performance, an alternative façade design was proposed, reducing the WWR to 56% while preserving architectural quality and visual transparency. Simulation results indicate that this modification resulted in a significant reduction in cooling energy demand, decreasing annual consumption to approximately 4,777,000 kWh. This corresponds to an energy saving of nearly 10% compared to the baseline scenario (Figure 3).

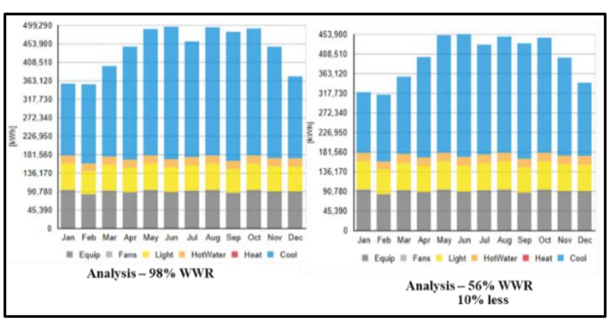

Fig. 3. GNPOC adjusting WWR helped to reduce 10% of the total

These findings demonstrate that optimizing the window-to-wall ratio represents an effective passive design strategy for reducing cooling loads and improving energy efficiency in office buildings located in hot-arid climates

B. Petronas Tower (PDOC)

Design consultant: Engineering Consulting Group

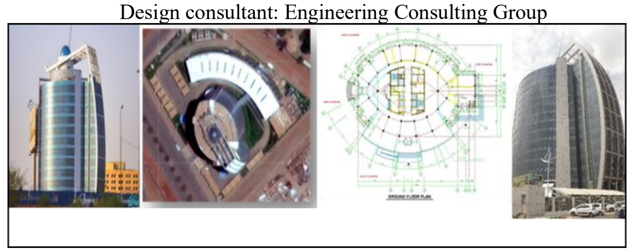

Fig. 4. PDOC building

TABLE VI
CASE 2: PDOC adjusting WWR helped to reduce 12% of the total Energy Consumption

Month	Baseline WWR 90%	Proposed WWR 63%	Reduction	Reduction
	kWh	**kWh**	**kWh**	**%**
Jan.	337,000	308,000	29,000	9%
Feb.	335,000	305,000	30,000	9%
Mar.	370,000	338,000	32,000	9%
Apr.	398,000	363,000	35,000	9%
May	469,000	410,000	59,000	13%
Jun.	461,000	408,000	53,000	11%
Jul.	425,000	375,000	50,000	12%
Aug.	467,000	407,000	60,000	13%
Sep.	458,000	402,000	56,000	12%
Oct.	461,000	405,000	56,000	12%
Nov.	405,000	364,000	41,000	10%
Dec.	353,000	316,000	37,000	10%
Total	**4,939,000**	**4,401,000**	**538,000**	**12%**

TABLE VII
Case 2: PDOC Detailed building description

Project Data:	Ventilation Overview	Design Strategies	Daylight Overview	Mass design Strategy
Structural Material: Composite (Concrete and steel) structure Plan Depth:8 meters (from central core) Location of Plant Floors: Ground floor –outdoor area.	Ventilation Type: Mixed-Mode: 85% mechanical, 15% natural ventilation 2. Natural Ventilation Strategy: Wind-Driven Single-Sided Ventilation	Double-skin façades (98% Glazing curtain wall) Double-Skin Façade Cavity: Depth: 300 mm Horizontal Continuity: 2 meters Vertical Continuity: 3.2 meters (floor-to-floor) Approximate Percentage of Year Natural Ventilation can be Utilized: 25%; Percentage of Annual Energy Savings for Cooling: Unpublished. Typical Annual Energy Consumption (Cooling): Unpublished	Good natural lighting is provided by opening up the space that gives the 'atrium', with three floors, large porches and terraces.	Widest possible point of view. Aerodynamic shape to allow wind flow around the building and its façade. Flexibly serviced, high specification 'user-friendly' column-free office spaces.

TABLE VIII
Case 2: PDOC Facade details

Item	Total	North	East	South	West
Gross Wall Area [m2]	13146.14	1557.35	3401.08	3841.26	4346.45
Above Ground Wall Area [m2]	13146.14	1557.35	3401.08	3841.26	4346.45
Window Opening Area [m2]	9165.45	329.53	3111.79	3104.72	2619.4
Gross Window-Wall Ratio [%]	69.72	21.16	91.49	80.83	60.27
Above Ground Window-Wall Ratio [%]	**69.72**	21.16	91.49	80.83	60.27

C. National Telecom Corporation Tower (NTC)

Fig. 5. NTC building

TABLE IX
Case 3: NTC Facade details

Item	Total	North	East	South	West
Gross Wall Area [m2]	8368.04	2634.34	1504.48	1800.02	2429.2
Above Ground Wall Area [m2]	8368.04	2634.34	1504.48	1800.02	2429.2
Window Opening Area [m2]	8201.52	2581.91	1474.54	1764.2	2380.87
Gross Window-Wall Ratio [%]	98.01	98.01	98.01	98.01	98.01
Above Ground Window-Wall Ratio [%]	**98.01**	98.01	98.01	98.01	98.01

As a result of the analysis of the envelope of this building, it was proven that its WWR is equal to 90%. The energy consumption rate is equal to 4,939,000 kWh . The outer cover was redesigned using the same procedures as the first building; the WWR percentage was reduced to 63%, so the rate of energy consumption corresponding to the cooling process was equal to 4,401,000kWh, which means that the average energy consumption is reduced by 12% (Figure5). Adjusting WWR helped to reduce 12% of the total Energy Consumption. The WWR for the last building was 70% (Table 10), and the energy consumption rate corresponding to the cooling process was equal to 5,541,000kWh (Table 9).

TABLE X
Case 3: NTC detailed building description

Project Data:	Ventilation Overview	Design Strategies	Daylight Overview	Mass design Strategy
Structural Material: composite (Concrete and steel) structure Plan Depth:10 meters (from central core) Location of Plant Floors: Ground floor –outdoor area	Ventilation Type: Mixed-Mode, 90% mechanical, 10% natural ventilation 2. Natural Ventilation Strategy: Wind-Driven single-sided ventilation.	Double-skin façades (96% Glazing curtain wall) Double-Skin Façade Cavity: Depth: 200 mm Horizontal Continuity: 2 meters Vertical Continuity: 3.5 meters (floor-to-floor) Approximate Percentage of Year Natural Ventilation can be Utilized: 25% Percentage of Annual Energy Savings for Cooling: Unpublished Typical Annual Energy Consumption (Cooling): Unpublished	Natural lighting is provided by opening the space.	Reduced energy consumption by use of natural ventilation whenever suitable, low façade heat gain, and smart building control systems. Maximum use of public transport for the occupants of the building. Flexibly serviced, high specification 'user-friendly' column-free office spaces with maximum primary space adjacent to natural light.

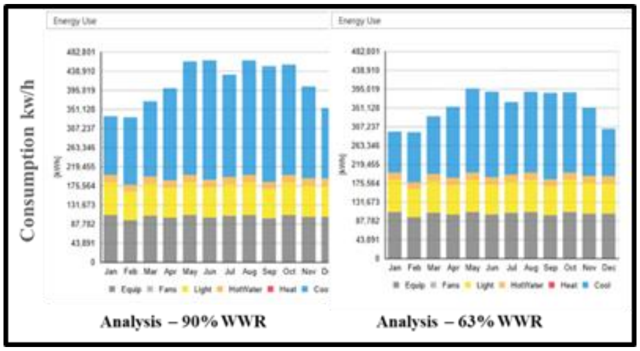

Fig. 6. PDOC adjusting WWR helped to reduce 12% of the total Energy Consumption.

TABLE XI
Energy consumption reduced according to reduction of WWR

Month	Baseline WWR 70%	Proposed WWR 55%	Reduction	Reduction
	kWh	kWh	kWh	%
Jan.	364,000	305,000	36,000	11%
Feb.	362,000	303,000	37,000	11%
Mar.	386,000	322,000	39,000	11%
Apr.	455,000	384,000	46,000	11%
May	522,000	440,000	55,000	11%
Jun.	532,000	446,000	59,000	12%
Jul.	483,000	405,000	53,000	12%
Aug.	520,000	437,000	57,000	12%
Sep.	511,000	425,000	60,000	12%
Oct.	521,000	435,000	60,000	12%
Nov.	465,000	386,000	54,000	12%
Dec.	420,000	351,000	45,000	11%
Total	**5,541,000**	**4,641,000**	**601,000**	**12%**

VI. Study Results

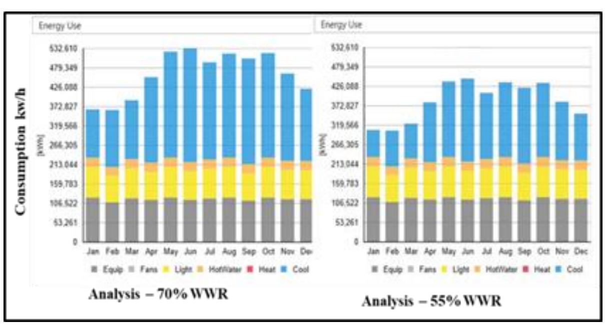

Fig.7. NTC adjusting WWR helped to reduce 12% of the total Energy Consumption.

TABLE XII
Energy consumption reduced according to the reduction of WWR.

Building	Current WR%	Current E. C.KWh	Proposed WWR%	Obtained E. C. kWh	Reducing %
GNPOC	98	5,280,000	56	4,777,000	10
PDOC	90	4,939,000	63	4,401,000	12
NTC	70	5,541,000	55	4,641,000	12

This study investigated the relationship between cooling energy consumption and the window-to-wall ratio (WWR) across three office buildings. For each case, the WWR was systematically modified, and the resulting variations in cooling energy demand were analysed and compared (Table 12).

A. Petronas Tower (PDOC)

The original window-to-wall ratio (WWR) of the Petrodar Tower was approximately 90% of the total façade area. When the WWR was reduced to 63%, while preserving key façade design objectives—including visual connectivity, aesthetics, transparency, and architectural expression—the building's total energy consumption decreased by 23%. This finding indicates that a 27% reduction in glazing area resulted in nearly one-quarter savings of the building's baseline energy use, underscoring the substantial impact of excessive glazing on cooling demand.

B. Greater Nile Petroleum Tower

The Greater Nile Petroleum Tower initially exhibited an exceptionally high WWR of 98%, as the façade was almost entirely glazed. Reducing the WWR to 65%, without compromising essential architectural and visual requirements, led to a 19.6% reduction in energy consumption. The results reveal that the additional 35% of glazing in the baseline scenario accounted for nearly one-fifth of the total energy consumption, despite offering limited additional visual or functional benefits.

C. National Telecom Corporation Tower (NTC)

In this case study, the WWR was reduced from 70% to 60%, resulting in an 8.64% reduction in total energy consumption. This outcome demonstrates that the excess 10% glazing area contributed disproportionately to energy use, consuming almost 9% of the building's total energy without serving a clearly justified functional or architectural purpose.

VII. Conclusions

This study confirms the existence of a strong relationship between cooling energy demand and the window-to-wall ratio (WWR) in office buildings. However, this relationship is nonlinear and influenced by several interrelated factors, including building height, façade geometry, surface flatness, and material properties. Based on the findings, the following conclusions can be drawn:

The results suggest that an optimal WWR should not exceed approximately 60%, as derived from the average performance of the three case studies, while still maintaining essential façade design principles related to visual quality, transparency, and architectural aesthetics.

Among the investigated façade design parameters, the WWR was found to have the most significant influence on cooling energy consumption. Reducing the WWR consistently led to a clear and measurable decrease in total energy use.

Excessively high WWR values substantially increase operational energy costs and exacerbate environmental impacts, including higher thermal loads and increased carbon dioxide emissions.

It is strongly recommended that WWR optimization be integrated into the early design stages through the use of environmental simulation tools, enabling designers to identify an appropriate balance between energy efficiency and visual performance.

This research provides valuable baseline data for local and regional studies on energy-efficient and climate-responsive architectural design and can serve as a reference for future research initiatives focused on sustainable office buildings in hot-arid climates such as Khartoum.

VIII. ACKNOWLEDGMENTS

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