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From Certification to Performance: Quantifying the Energy, Environmental, and Economic Returns of Green Buildings in Rapidly Urbanizing Regions

Dr. Eahya Al Huda

Department of Earth Science, University of Science and Technology, Meghalaya.

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*Corresponding Author

Dr. Eahya Al Huda

E-Mail Id: ea.huda@gmail.com

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Abstract: This study quantifies the energy, environmental, and economic returns of certified green buildings compared to conventional buildings in rapidly urbanizing metropolitan regions. We employed a comparative quantitative research design across five urban zones, analyzing 100 buildings (50 certified green and 50 conventional) through building energy simulation, Life Cycle Assessment, and statistical analysis. Ten sustainable technologies were evaluated, including solar photovoltaics, green roofs, and smart Building Management Systems. Green buildings demonstrated a 36% reduction in annual energy consumption, a 40.4% decrease in carbon emissions, and a 32.0% reduction in water consumption. The sustainability index for net-zero energy buildings reached 99 out of 100, versus 62 for conventional buildings. Renewable energy contribution increased nearly fivefold, from 8% to 39%. Economically, annual operating costs fell by 30.7%, property values rose by 17%, and occupancy rates increased from 82% to 95%. Pearson correlation analysis revealed strong positive associations among all performance variables, with the highest correlation between energy efficiency and sustainability index (r=0.95). Major adoption barriers included high initial construction costs (mean score 4.39 out of 5) and limited technical expertise. The findings conclusively demonstrate that integrated green building technologies significantly outperform conventional practices across energy, environmental, and economic metrics. This research provides empirical evidence to inform urban development policies, building certification standards, and investment decisions, supporting the widespread adoption of green buildings as a viable strategy for sustainable urban growth.

Keywords: Green Buildings, Energy Performance, Environmental Sustainability, Economic Returns, Rapid Urbanization.

Introduction

The process of urbanisation poses unprecedented challenges on global energy resources and environmental systems particularly on highly populated metropolitan areas characterised by high population and economic activity (Akram et al., 2026). Buildings are one of the largest contributors to the urban infrastructure systems, accounting for an estimated 30 – 40 % of all global greenhouse gas (GHG) emissions and total energy consumption, in the building sector (Hamilton et al. 2024). Concurrently, in response to this, the green building certificates are significant tools for awareness and dissemination of sustainable practices in the construction industry and the minimum environmental impact of buildings (Cordero et al., 2019). There are few and fragmented examples of empirical evidence of real performance differences between certified green buildings and their counterparts in conventional buildings, especially under the wide-ranging climates and operating conditions in rapidly urbanizing regions.

The key conclusion of this study is that a building system that incorporates renewable energy technologies and smart management technologies that are green certified and integrated, can achieve significant improvement in energy efficiency, environmental and economic performance compared to the average building system. The goal is to make a detailed and comprehensive comparison based on a broad sample of buildings in various building and architectural typologies (commercial, residential, institutional, smart city and mixed-use) in five large urbanising cities. In order to achieve this, we use a full range of quantitative methods that include building energy simulation, Life Cycle Assessment (LCA) (Cole & Kernan, 2019), Building Performance Evaluation (BPE) (Preiser & Vischer, 2006) and statistical analyses to assess energy use, carbon emissions, water use, indoor environmental quality, occupant satisfaction, and operational costs.

The major importance of the study is that it adopts a large scale and cross-context approach. Previous works are mostly carried out at a single case study or specific building types and the generalizability of previous works results into other case studies and building types is limited (Zuo & Zhao, 2014). This work will compare 100 buildings (50 green and 50 conventional) of the 5 urban typologies considering a complete level of comparison without breaking the rules for the different regional and climatic conditions. Moreover, by measuring eight different performance parameters - annual energy consumption, carbon emissions, water use, indoor air quality index, percentage of renewable energy, occupant satisfaction, operational cost savings, and a composite sustainable building performance index - this study creates a multidimensional perspective on the performance of green building, which are not always measured together in a single study. The results show a 36% reduction in energy consumption, 40.4% reduction in carbon emissions, and a reduction in operating costs by 30.7% with an increase in property values by 17%, provide tangible and measurable data to support policy makers, developers and investors in the push towards more sustainable building technologies.

Existing literature papers on green building performance are discussed and a focus on areas where this study has gaps is given in Section 2. The research methodology, which consists of criteria in the choice of study sites, building samples, measurement parameters and analytical methods is detailed in Section 3. The empirical evidence is presented throughout the discussion based on the whole set of the metrics measured in Section 4, which not only compares the performance of green buildings with conventional buildings, but also analyses the correlation between the measured performance variables. In Section 5 the implications for urban sustainability policy and practice, the barriers to introducing green buildings identified in the investigation and any shortcomings of the research itself are discussed. Last but not least, Section 6 is a summary of the main contributions with a proposal of possible future research paths.

Literature Review

Many studies have been conducted on green building performance but most both focus on one building element (such as energy consumption) and concentrate on only a few different contexts (only specific urban areas). Findings in this study have been confirmed by a number of previous studies that have shown that green certified buildings are more energy efficient than conventional buildings, between 20% and 40% depending on the level of certification and climate zone (Gil-Ozoudeh et al. 2024). Newsham et al. (Newsham et al., 2009) performed an influential study of U.S. LEED certified buildings that compared their energy use to non-LEED certified buildings, and determined that they averaged 18-39% less energy use per floor area than conventional buildings, but the performance of individual buildings was quite variable. This finding serves as a reminder that certification does not necessarily predict performance and actual outcomes in the real world are essential.

Other studies have also been conducted on green buildings and their environmental attributes using the approach of LCA. Sharma et al. (Sharma et al., 2011) compiled a variety of life cycle assessment (LCA)-based studies of different types of buildings and concluded that the embodied carbon of adopted "green" building materials or design approaches can be reduced by 20-40% from the more "conventional" construction of buildings. Similarly, another research (Nwodo & Anumba, Khasreen et al.,2019) determined that operational phase is the phase with the highest impacts from the life cycle of buildings, with a particular emphasis on the importance of energy efficiency and integration of renewable energy in buildings during this phase. However, most of these studies have relied on information at either a modeling site or a specific site, making it difficult to know if the conclusions would be relevant to other rapidly developing cities with different building types and climatic characteristics.

One more aspect of water efficiency is another area where green buildings should excel over traditional buildings. According to the research conducted by C Cheng (Pratiwi et al 2024), it is found that potable water usage can be reduced by 30-50% if water preventing facilities such as water harvesting facility was implemented in a green building together with water efficient facility. Chua et al. (2016) found a 35% water saving for certified green buildings in their study on water conservation in office buildings in Singapore. The currently available evidence, however, is rather limited to more-developed countries and temperate latitudes and even substantially less for emerging markets experiencing change.

When it comes to an investment in a "green" building, one of the important considerations stakeholders will make is the building's economic performance. According to a study by Eichholtz, et al (Green Buildings and Economic Outcomes n.d.), the premium prices for renting and selling Green certified commercial buildings stands at 3 - 7 % and 10 - 16 % respectively using the methodology of Meta Analysis. Fuerst and McAllister (Fuerst & McAllister, 2008) presented evidence from a similar study which saw substantial gains in the property value of both LEED and Energy Star certified properties. Most studies that have been done, however, are on market transaction costs rather than operating costs—that's an additional issue—and there's still a lack of understanding of how this certification will relate to real bottom-line savings.

The other features found in the literature are occupant satisfaction and indoor environmental quality (IEQ). Abbazzadeh et al (Altomonte et al., 2017) did a study comparing clients' perception of DOE's LEED rated buildings with non-LEED conventional buildings to see how much more satisfied LEED building users were with building performance, air quality and thermal comfort. Others have shown a mismatch, however: some researchers have also found that there were significant differences across the board in comfort with lower quality air quality in buildings, but no differences in comfort with lighting or acoustic performance of a greener building (Altomonte & Schiavon, 2013). This imbalance may suggest that the value (where value is defined as the value added by green building certification) may not be distributed evenly across the IEQ components.

There have been a number of reviews that have brought together the information pertinent to the state of knowledge in green building performance. In an inclusive review of over 100 empirical studies, Geng et al. (Depauw et al., 2024) concluded that overall, green buildings provide improved energy consumption, water conservation and satisfaction results when compared to conventional buildings, though the level of benefit varies from one certification system to another, building type to type and geographical area to geographical area. The authors called for additional standardisation regarding environmental and social-economic studies, with the use of multiple metrics. Similarly, in other review, Zuo & Zhao (Fan & Li, 2025) indicated the need for long-term observations and the absence of real-time post-occupancy test of the performance, which needs to be conducted after the simulation models to make an assessment of the performance of systems.

Though this is a considerable body of work, there are some key missing pieces. Firstly, the majority of research is undertaken in countries of the 'total urban' world, such as the USA, UK and Australia, and only a handful of countries in Asia, Africa and Latinamerica with high levels of rapid urbanisation. Second, most of the studies are limited to one building typology or a few case studies, thus providing relatively low external validity of the findings. Thirdly, the available literature has typically not made direct, simultaneous comparisons by buildings, simultaneously comparing all five of the typically examined key performance metrics—energy, carbon, water, IEQ, and occupant satisfaction and operational costs—in the same buildings within the same urban context, across a large sample of both green and conventional buildings. This research aims to address these limitations by analyzing 100 buildings across 5 urban typologies of fast growing metropolitan areas using a multi-metric, comparative research. Based on direct measurement and statistical analyses, sound, generalizable evidence is generated with regard to how certified green and conventional buildings perform and contributes to the support of policies and investments to support sustainable urban development.

Methods

The method of comparison had been based on quantitative approach; Building energy simulation has been used to compare the performance difference between LEED certified green buildings and conventional buildings; Environmental Impact Assessment (EIA) and statistical analysis were used as part of a comparative quantitative method of research to assess the performance difference between LEED certified green buildings and conventional buildings. The study comprised five fast urbanising metros with different climatic conditions and urban development attributes. The findings represent Community Business District, Residential Urban Area, Institutional Campus, Mixed-Use Development and Smart City Zone, ensuring the findings are representative of a broad spectrum of urban areas.

Study Sample and Building Selection

There were a total of 100 green and conventional buildings selected as targets for this study (50 in each category). A common bottom line of sustainable design and operation is LEED, BREEAM or local organisational-certifications, which were all the case for all the Green certified buildings. The buildings used in the conventional and the green case studies were selected as one would expect: climate zone, building type, building size, building age were selected to be as close as possible to the buildings in the green to isolate the effect of the green building design and technologies. For each building detailed design documents and energy performance certificates (EPCs) and occupancy records were collected for further analysis.

Green Building Technologies Evaluated

Ten technologies were identified to contribute toward the overall building performance, and then evaluated based on sustainability in buildings. They included Solar PV system, Rain Water harvesting system, HVAC system (heating, cooling and ventilation) which is high efficiency, Smart Building Management System (BMS), Natural ventilation system, Water efficient plumbing fixtures, Green Roof and High performance insulation (HP). Technology units were each appraised for the amount of technology and its operation, as well as for the technology's measured effect on the improvement of the building's indoor environmental quality (IEQ), and the measured impact on the energy and water. Green buildings were discriminated from conventional buildings by the number and presence of these technologies in a green building "type" was created that contained at least 6 of the 10 technologies being considered.

Data Collection and Measurement Parameters

Building energy audits, indoor environmental quality testing, questionnaires, reviewing utility bills, building inspections and smart sensor monitoring were used to collect primary data. An audit of energy was performed to confirm energy installed, operation schedules and maintenance activities. The indoor environments in all of the buildings were monitored continuously by installing the portable sensors at representative locations throughout the buildings,and analysing parameters include particulate matter,CO_2 concentration, temperature and relative humidity. Three key areas (comfort, air quality, lighting) and overall satisfaction were measured by a 5-point Likert scale ranging from 'not at all satisfied' to 'very satisfied', using the same survey tools for each of the three areas. All the relevant building design records, Energy Performance Certificates, urban development reports, green building certification databases, and municipal environmental statistics and published scientific literature were used to support the secondary data to provide the building design as a full basis of comparison.

These parameters were measured and their unit were indicated as follows: Annual energy consumption (kWh m-2 year-1), carbon emissions (kg CO2 m-2 year-1), water consumption (L m-2 year-1), indoor air quality index (dimensionless with a score from 0-100), shares of renewables content per annum (%), as compared to total building energy use (BEU), and occupants' satisfaction level (%) of satisfied occupants, operational costs savings (USD m-2). To develop the sustainable building performance index, the normalized values of and were combined along with the rest of the five weighted factors of overall building performance properties: , , , , and . The normalized values of and were then given weights by Principal Component Analysis (PCA) in order to maximize the existing data-set variance. Table 1 gives a summary of the parameters taken and the corresponding scoring units.

Table 1. Parameters measured and their respective units.

Parameter	Unit
Annual Energy Consumption (E)	kWh m^{-2} $year^{-1}$
Carbon Emissions (C)	kg CO_2 m^{-2} $year^{-1}$
Water Consumption (W)	L m^{-2} $year^{-1}$
Indoor Air Quality Index (I_Q)	Score
Renewable Energy Contribution (R)	%
Occupant Satisfaction (S_o)	%
Operational Cost Savings (S_c)	USD m^{-2}
Sustainable Building Performance Index (I_S)	Score (0–100)

Experimental Procedure and Statistical Analysis

The seven phases of the experimental procedure consisted of selecting representative buildings from each urban zone; conducting baseline assessments with the building performance premise using archival data analysis and done preliminary tests on site, measuring energy and water consumption for a continuous 12-month period (taking into account seasonal variations), carrying out control and sample monitoring in order to check the indoor air quality while interviewing the occupants of the buildings, identifying contribution of the green building technologies using regression modeling, executing descriptive and inferential analysis between conventional building and green building, and finally carrying out statistical analysis based on the analysis of trends for prediction of the buildings' sustainability in the future using trend extrapolation.

Descriptive statistics (mean, standard deviation, range) have been used to summary the collected data, independent sample t-test to compare the mean values between two different groups (green or conventional building) and one way ANOVA to analyse the differences between the measured parameters of five different urban zones. Pearson correlation analysis has been used to show the relationships between the parameters measured while multiple linear regression has been performed to identify the parameters most important in the influence on the overall building performance. Multiple linear regression was also performed to select the most important parameters in the influence on the overall building performance and to formulate the composite sustainability index. Dimensionally reducing the collected data with Principal Component Analysis (PCA) was also done in this process. All statistical tests significance are evaluated at . The analytical framework was designed to allow to make comparisons at the single variable level as well as insights at the multivariate level, to be used for the overall assessment of the performance differentials from green building practices.

Results

One hundred buildings were selected in 5 urban zones, 50 of which were green and 50 of which were non-green, multiple elements influenced all of the results shown here, and various analyses were performed for the buildings. These findings are presented in six sub-sections starting with a broad-based comparative answer, and then focusing in each subsequent section to specific energy, environmental, economic, and correlative outcomes for building performance.

Comparative Performance of Green Buildings

Again, as hypothesized, the level of performance of green buildings significantly outperformed conventional buildings in the domain of Environment and Energy. Table 2 offers detailed performance comparisons of eight important performance measures for five different building types, covering conventional buildings, certified and three types of advanced green building configurations.

Table 2. Comparative Performance of Green and Conventional Buildings

Building Type	Energy Consumption (kWh m^{-2} yr^{-1})	Carbon Emissions (kg CO_2 m^{-2} yr^{-1})	Water Savings (%)	Sustainability Index
Conventional	228	94	0	62
Certified Green	146	56	38	91
Solar Integrated	132	49	41	94
Smart Green	125	45	43	96
Net-Zero Energy	98	28	47	99

Buildings with integrated renewable energies and buildings where smart energy management is applied received the highest sustainability score. Net zero energy buildings had the lowest annual energy consumption (98 kWh m-2 yr-1) and carbon emissions (28 kg CO2 m-2 yr-1) as compared to conventional buildings (228 kWh m-2 yr-1; 94 kg CO2 m-2 yr-1). This took place in comparison with the highest and lowest points of every category, thereby raising the energy efficiency by 57% and lowering the carbon emissions by 70%. The overall sustainability performance of a net zero energy building was calculated as nearly 60% better than a conventional building as the sustainability index was over 99.

Buildings with a typical recognised level met the requirements for the certified green building category, whose energy use comes to 146 kWh m-2 year-1, a reduction of 36% compared to the energy use of conventional buildings. The CO2 savings were determined as 56kgCO2 m-2 yr-1 (40.4%) and water savings as 38%. The sustainability index of certified green buildings (91) was significant but less than the index for buildings that are more well-integrated technologically. New results for the energy use for solar integrated buildings further reduced (132 kWh m^{-2} yr^{-1}), and the carbon emission decrease further increased (49 kg CO_2 m^{-2} yr^{-1}) and water saving at 41% and sustainability index at at 94 respectively.

Building Energy Management Systems and renewable energy installations together allowed smart green buildings to save energy, achieve carbon emissions of 45 kg CO_2 per m^2 per year, use less water (with a 43% saving) and have a sustainability index of 96. The findings showed that the use of a smart control system in combination with design principles had synergy components in addition to the individual use of the technologies or the design principles. They could be built conventionally, up to their qualified green rating; then with the renewable energy integrated building system they would reach their smart green rating; then with the number of renewable energies generated, the net zero energy status would be reached, revealing a clear monotonic improvement structure for all parameters as measured, supporting the central hypothesis largely assumed that green buildings with renewable energy integrated building systems and the smart management technologies would exhibit more advantageous environmental performance.

In the five urban zones comparative patterns of performance were uniform while there were differences in the amount of improvement to be seen depending on building typology and climate. The relative energy reductions for commercial buildings (Business District) were the highest for these buildings, possibly indicating a higher energy demand, or lower optimization potential in HVAC and/or lighting conditions. The incentive effect on the Residential buildings in the Urban area was more modest, as buildings' energy loads in that sector are more diffuse and the effects of one's building-level (centralized) smart and efficient energy management systems are smaller. The large-scale rain water harvesting system yielded good performance in terms of water savings in the institutional buildings at the Campus while the performance of mixed use development was a reasonable increase in all parameters. Buildings designed from the start of their construction to incorporate sustainability solutions and features in their design had an average sustainability index of 97 in the newly created "Smart City Zone" buildings, which is approaching the best in the “Net zero energy” building category.

A comparison then provided solid empirical evidence that the impact of certified green buildings on the environment and energy performance is considerably better than that of conventional buildings-and a good correlation could be demonstrated between the amount of technological integration on the one hand, and the environmental and energy performance of buildings on the other hand. The results served as a reference for the analysis of the energy efficiency, environmental and economic impacts of these various energy efficiency measures in the subsequent sections.

Energy Efficiency Improvement

The Energy performance analysis revealed that there was a wide difference between the categories of building in the energy performance and that the buildings recorded an improvement in all parameters measured. Table shows a reduction of 36.0% in energy use per m² per year with green buildings (146 kWh m-2 yr-1) in comparison with conventional buildings (228 kWh m-2 yr-1). This discovery concurred with previous studies which have found comparable energy savings for green building certifications (Gil-Ozoudeh et al., 2024). The increase achieved in the case of the present study is however much bigger than that of some of the previously mentioned meta-analyses which, on average, rate between 20 and 30 per cent. This can be attributed to the inclusion of much more current building fabric together with increasingly sophisticated energy management technologies.

Table 3. Building Energy Performance Metrics

Parameter	Conventional Building	Green Building	Improvement (%)
Annual Energy Consumption (kWh m^{-2} yr^{-1})	228	146	36.0
Peak Electricity Demand (kW)	328	236	28.0
Renewable Energy Contribution (%)	8	39	387.5
HVAC Energy Consumption (%)	48	30	37.5

For example, the peak electricity use in conventional buildings decreased by 28.0% when compared with the peak electricity use in green buildings from 328KW to 236KW. This demand reduction has widespread repercussions on the stability of the existing electricity grid and electricity facility planning since electricity capacity will be expanded according to demand, therefore electricity pricing structure. The measured reduction confirms the feasibility of using green building technologies to reduce the peak loads by (re)shifting and/or modulating energy use during peak time periods, such as employing a Smart Systems Building Management System (SBMS) or high efficient building HVAC equipment. Laverge and Janssens (Wang et al., 2024) showed that optimised control strategies enabled to lower the peak demand by 20–35% in office buildings.

The most significant growth was in the contribution of renewable energy in green buildings for a 387.5% increase (as compared to the 8% in conventional buildings). This amount of increase is representative of the work that is done in an organized manner towards integrating solar photovoltaic systems, activated in 42 of the 50 green buildings sampled. Average installed capacity of the green buildings was 85 kW/bldg; direct savings of purchased grid electricity (and thus carbon emissions) due to the installation of these green buildings. This renewable energy share is more than the previous studied (15-25%, Sayigh, 2013), likely due to the project selection strategy that took into account only buildings in locations with favorable conditions for solar insolation, as well as countries with positive attitudes towards net metering.

The HVAC use was down 37.5% and from the conventional buildings to green buildings from 48% to 30% of total building energy use. This had several reasons which were linked with each other. High performance insulation and minimising thermal loads through the building envelope coupled with the low emissivity glazing and the high Coefficient of Performance (COP) HVAC equipment led to the high efficiency of the thermal loads through the building envelope and HVAC system conditioning air delivery. 36 of the green buildings employ the natural ventilation and enabled regressive reduction in mechanical cooling loads in moderately weathered conditions. The energy share reduction for HVAC systems is similar to the results reported by Pérez-Lombard et al. (Kumar et al., 2026), which found that

HVAC typically consumes 40-60% of building energy and improvement measures that involve improving the HVAC system can save 10-20% of the energy share.

In terms of buildings as a whole, this translates to substantial absolute reductions in annual energy use of 36.0%. This translates to an annual energy savings of 820,000 kWh for the average green building in the sample (with an area of around 10,000 m^2), or to 420 mteCO_2 per building per year, if the grid emission factor is taken to be 0.512 kg CO_2/kWh. This type of results can provide quantitative strong evidence of integrated green building technology benefits in measurable energy efficiency improvements.

This diversity in energy performance amongst the 5 urban zones can be attributed to a variety of factors and reasons. Buildings in Smart City Zone also exhibited the lowest energy consumption (132kWh/m^2/yr) of all the green buildings surveyed, likely because of district energy and central smart grid management systems installed in the buildings. With house-hold use averaging 158 kWh m^{-2} yr^{-1}, the Residential Urban Area's buildings demonstrated more moderate gains, when considering green-building consumption.The energy load in the Residential Urban Area was less decentralised and the limited applicability of large scale renewable energy systems for the individual building resulted in smaller improvement of the average consumption of 158 kWh m-2 yr-1. The highest relative reduction of Peak was observed on the "Campus" category, as an institutional building generally has a central HVAC system in a larger building, or a Building Management System that sequentially schedules HVAC for several buildings in the campus, thus decreasing HVAC running time overall. In this category, the PGDR of the green buildings was 32% less than that of green buildings.

Environmental Benefits

Generally, results of the environmental performance of Green buildings showed significant improvements, compared to conventional buildings, with consistent results in all the measured indicators. The main environmental parameters that were reduced namely reduction in carbon emission, reduction in water consumption, and improvement in IEQ are then highlighted in detail in Table 4.

Table 4. Environmental Performance Indicators

Indicator	Conventional Building	Green Building	Improvement (%)
Carbon Emissions (kg CO_2 m^{-2} yr^{-1})	94	56	40.4
Water Consumption (L m^{-2} yr^{-1})	1,420	965	32.0
Indoor Air Quality Index	71	91	28.2
Urban Heat Island Reduction (%)	0	19	—

There is a large disparity in that carbon emissions were decreased by 40.4 per cent from 94kg CO_2 m-2 year-1 in conventional buildings to 56kg CO_2 m-2 year-1 in green buildings. This is in line with energy consumption's slowdown as seen in Section 4.2 and is reflective of the enormous correlation that exists between energy and carbon emissions. This has been attributed directly to the decrease in the electricity supplied to the grid share of the total spatial energy demand as the emission factor for this supply dropped from 360kgCO_2/kWh to 175kgCO_2/kWh, and to a higher share of on-site renewable energy (ORS), both types, rising from 8 % of the total spatial energy demand share to 39 % of the total spatial energy demand share while renewables became more dominant with a rise from 56 % to 69 % of the total and on-site energy demand. Similar reduction in carbon from operating buildings has been documented by Sartori and Hestnes (Sartori & Hestnes, 2007), who report operating carbon reductions of between 40 and 60 percent with low energy buildings. However, the present study broadens the scope of the earlier study and demonstrates this to be possible in many different urbanenvironments, and not only in particular climatic conditions.

Conventional buildings had an average water use of 1420 liters per meter along a year while the green buildings had an average water use of 965 liters/m/yr, which is a reduction of 32.0%. The majority of the significant decrease was related to the following use of water-efficient construction: 44 out of 50 green buildings in the sample used low-flow toilets, faucets, and showerheads. In addition, 26 green buildings installed rainwater harvesting systems to use the water collected on roofs in landscape irrigation or for toilet (public buildings with restrooms only) flushing. The water savings recorded in this study are also consistent with the findings of other studies on water-efficient buildings which found a water saving between 20% to 50% (Pratiwi et al., 2024) and the empirical water savings obtained in this study support the observations that water savings can be achieved in real life conditions instead of only in theoretical models.

So the overall test result of IAQ (recorded) was improved by 28.2%, 71 with conventional buildings, and 91 with green buildings. This improvement came from mechanical systems with higher outdoor air fractions, use of low-emissivity materials and furnishings in the buildings to reduce outgassing of volatile organic compounds (VOCs), and making natural ventilation strategies a part of 36 of the 50 green buildings. The continuous monitoring proved green buildings maintained better average concentrations where CO_2 was always lower than 800 ppm level in occupied buildings this is compared with 1100 ppm, showing the effectiveness of the ventilation. The IAQ enhancements realized throughout the current area may be higher than usually reported in literature, ranging between 10-20% improvements; this enhancement can be explained and justified by the introduction of smart sensor-based demand-controlled ventilation (DCV) systems, which actually provide optimize air change rates as a function of real time occupant presence levels and pollutant concentration control.

The green roof and the plant reduce the temperature difference between the surface of the green building roof and the dark-colored roofs by 19% compared to that between dark-colored roofs and night time air temperature.The surface of green roof and the plant material decrease the modern heat island surface temperature difference by 19% under roof surface and dark-colored roof compared to the surface with dark-colored roof and night air temperature. The surface temperature of the vegetated surfaces installed on 31 (out of 50) green buildings was determined at their peak temperatures in summer which was 8.5°C cooler than conventional roofing materials, reducing the coefficient of heat transfer into the building at its peak summer condition to just an estimated 12% of the cooling load. The observed reduction in UAT aligns with the 15-25% urban heat island mitigation achieved by the green roofs as reported by the green roofs (Santamouris, Ziaeemehr et al., 2023) which reported an UAT reduction of 1-3 °C by implementing a green roof in the urban canyon. In addition to the benefits that the green roofs provide at the building level, the cumulative effect of the multiple green roofs provided in the study areas helped to bring about local microclimate improvements as demonstrated by a 1.2°C difference in the average ambient temperature measured in the Green Roof area of the Smart City Zone versus the conventional Commercial Business District.

A comparison of the environmental performance based on the five urban areas showed rather that the "goodness" of the environmental performance changed in terms of amounts. Institutional building at Campus had the highest water consumption reduction of 38% which resulted from large scale rainwater harvesting at the Campus, application of centralized irrigation controls for institutional buildings. Business District commercial buildings had the most carbon emission reduction (43%), when considering the higher baseline energy use and higher energy use potential of HVAC systems compared to other building types. The improvements offer the lowest levels of enhancement to the IAQ in residential buildings in the Urban Area, which could contribute to the more varied use of individual dwelling units and the absence of commoned ventilation systems for air. The generalizability of these observations is supported by the fact that the general trend of a large amount of environmental improvement occurred in all zones.

Empirical evidence of the benefits of certified green buildings includes the energy and resource savings listed in Section 4.2, and the environmental benefits listed here. The results of these findings directly impact urban sustainability policies, as the 32.0% reduction in water consumption and 40.4% reduction in carbon emission from the inventory are direct steps towards achieving that city's climate action target and water conservation. As described earlier in Section 4.6, if energy efficiency relates to carbon reduction (—), then this can be used again to reinforce the interrelatedness of these environmental benefits, which in turn gives greater credence to any integrated approach to design that the green building certification schemes follow.

Economic Performance

The economic performance evaluations found there were significant economic benefits to green buildings when compared to conventional buildings in a variety of measures of operational costs, maintenance costs, asset value and market occupancy. A summary of the overall comparison of the main economic indicators measured becomes apparent in the following Table 5.

Table 5. Economic Benefits of Green Buildings

Indicator	Conventional Building	Green Building	Improvement (%)
Annual Operating Cost (USD m^{-2})	34.8	24.1	30.7
Maintenance Cost (USD m^{-2})	8.2	6.6	19.5
Property Value Increase (%)	0	17	—
Occupancy Rate (%)	82	95	15.9

Further, the annual operating costs significantly decreased by 30,7%, with the annual operating cost of conventional buildings as 34,8 USD m-2 and that of green buildings as 24,1 USD m-2. With an annual saving of 10.7 USD m-2 of buildings, the economic benefits of this cost saving on an average building of 10,000 m-2 is calculated to be 107,000 USD/annum. This reduction can be directly attributed to the energy efficiency improvements reflected in Section 4.2 where the energy use annual savings reported for green buildings was a reduction in energy use of 36%, and water use savings was 32% as reflected in Section 4.3. The energy cost element alone has been reduced by 18.2 USD m^{-2} of energy in conventional buildings to 11.9 USD m^{-2} of energy in green buildings, and this is the biggest individual cost driver to operating cost savings. This aligns with the results of the meta analysis performed by Eichholtz et al. (Green Buildings and Economic Outcomes, n.d.) which concluded that these energy and water savings could save the cost of operation by as much as 20% – 35% in a green building.

The significant reduction in maintenance cost was also not as great but was still impressive at 8.2 USD m-2, down to 6.6 USD m-2 (a 19.5% decrease). This is less maintenance for green buildings and can be attributed to several reasons. Moisture intrusion and thermal stresses were the least likely cause of repair, due to high performance building envelope insulation and strong materials. In addition, with the incorporation of a smart Building Management Systems (BMS), it was possible to create a predictive maintenance schedule which helped the Building Managers to anticipate, prevent and manage any issue that could occur with the building's equipment without turning into a costly failure. Water efficient plumbing fixtures, located in 44 out of 50 green buildings, also helped to reduce water leakage and repairs as a result of water damage. This reduction in maintenance costs is 19.5% and confirms other findings by Newsham et al (2009) that show that the overall range of maintenance cost savings of green buildings over conventional buildings is 15-25%.

The difference in property values was a staggering 17% in favor of green buildings, compared with non-green buildings with the same amount of square footage and neighborhood. This appreciation has emerged because of the market recognition of sustainability credentials, as well as better indoor environmental quality and costs savings. The premium is in the range of 10-16 % which has been found by Fuerst and McAllister (2008) in the study of LEED certified commercial buildings. Most important, the increases found in this study (17%) were a difference between matched green and conventional buildings in the same area (city blocks, census tracts, and neighborhoods) in the same size and time of construction. Increases in property values were greatest in the Commercial Business District and Smart City Zone, where tenant demand for sustainable space was highest—at 22% and 20%, respectively.

There was an increase of 15.9% from 82% to 95% of those who occupied conventional buildings to those in green buildings. The 22.5 percentage point difference in overall tenant and occupant satisfaction reported in the occupant satisfaction survey (OS) reinforced by the facts from the 92% of green building tenants/occupants that reported being "satisfied" or "very satisfied" with their building performance versus 74% of the tenants and occupants of conventional buildings that reported being "satisfied" or "very satisfied" in their building, shows that green customers/tenants are pleased with their green building environment. The shorter vacancies indicate less concern about vacancy for building owners and investors and thus benefit long-term profitability. This 95% market uptake in the green buildings was near the top of the pie chart for the commercial real estate market where even in buildings with frictional vacancies of 2-5% are at the upper end. The discovery suggests that green building certification is a tool to help establish a market differentiation in attracting tenants that prefer the other attributes of sustainability and are willing to extend their lease at the end of the day.

The economic benefits of green buildings were seen to exist in all five urban zones with the magnitude varying depending upon the urban context and building typology. Commercial buildings with the highest operating energy costs without going green (baseline) (Business District) had the largest absolute reductions in energy costs at Green buildings reduced energy costs by 12.5 USD m^{-2} when compared to conventional buildings, which indicates that these buildings' energy costs were high and have a significant potential to reduce energy costs. The premium that property developers enjoyed for properties in the Mixed-Use category, 21%, is perhaps the most driven due to the versatile marketability of such properties, and their attractiveness to commercial and residential tenants. While energy efficiency gains were lower than in the energy service projects, most cost savings were for operational savings (RESUA 8.0 USD m-2) and cost increases, or investment gains, were largest with energy service projects in other types of buildings; the energy cost optimization possibilities in the buildings' dwelling units were smaller, and the energy costs in the residential sector were lower.

The economic results which are covered in this subsection are evidence that there are tangible economic advantages to green buildings and development, and that these advantages are not limited to environmental considerations. The savings in operating costs of 30.7% combined with the positive growth in property values of 17% and occupancy of 15.9% has a very strong investment argument for building owners and developers. Based on the 50 green buildings in the sample, the estimated payback period for the extra up-front cost of green building technologies is 4.6 years, and the net present value of 156 USD m^{-2} is positive for a building's life cycle of 20 years. Last, the financial results are comparable with what this research found when arguing for better economic profits and for reducing operating risks, on which the policy arguments in this research can be based.

Major Challenges

While the results of empirical studies are overwhelmingly consistent on the positive results of green buildings in terms of energy, environmental and economic aspects, the actual uptake of these technologies are confined in fast-growing urban areas by some serious obstacles. But if the transition to sustainable building practice is to be pushed, these barriers need to be identified, understood and addressed to adequately inform policy interventions and investments to catalyze the transition. To this end, a comprehensive survey was undertaken with the building developers, architects, engineers, facility managers and policy makers for buildings in the sample, in which they were asked to note how significant they considered the various issues to be on a five-point Likert-scale (1 = not significant, 5 = extremely significant). There are 6 barriers that are cited most often with the mean and mean rank listed in Table 6 below.

Table 6. Major Challenges to Green Building Adoption

Challenge	Mean Score (1–5)	Rank
High Initial Construction Cost	4.68	1
Limited Technical Expertise	4.39	2
Lack of Financial Incentives	4.18	3
Limited Public Awareness	3.97	4
Regulatory Barriers	3.82	5
Technology Maintenance Complexity	3.61	6

This was the first barrier namely (high initial construction cost) which received the highest mean barrier score (4.68, 1st. barrier/5). The finding follows the findings of previous studies, which found that the main obstacle to take up green buildings is the capital cost premium (A. Darko et al., 2017). The supplementary cost of going green on average is 12.5% in the sample, and varies between 8% for basic certified building, up to 18% for net zero energy building. This figure for payback period, of 4.6 years (as calculated in Section 4.4), shows that these upfront costs are offset by the operational cost reduction, however access to cheaper finance can be a challenge, especially in urbanizing areas where developers or building/asset owners may need to cut down on the initial capital cost. The high upfront costs were discussed by a few of the survey respondents citing their not being very confident in the energy savings they were able to achieve, but questioning the predicted energy savings from simulation.

The second highest scored barrier for participants was also limited technical expertise with a mean score of 4.39. A shortage of skilled manpower including Passive Design trained architectural professionals, experienced engineers in system integration of renewable energy systems and experienced operators in the field of facilities in running advanced Building Management Systems is the challenge. This was particularly the case for the Residential Urban Area and Institutional Campus zones – specifically both less than 30% of construction firms reported to have formal green building training staff in either zone. The results are consistent with findings by Zhang et al. (Ahn & Pearce, 2007) which indicated that one of the significant issues in emerging countries is that of competent personnel. The reduction does not only occur in the construction and design phases, but also during the use of the technology - partly due to substandard commissioning and partly due to maintenance.

Generally the least favourable mean score was the lack of financial incentives (4.18). Despite the positive economic impacts identified in this study, the survey respondents believed that existing financial awards (tax relief, lower interest loans and grants) were not as significant as the perceived risks associated with higher set up costs. The city governments are unclear about direct subsidies for green building certification, and slightly more than half (54%) provide any of these subsidies.Direct subsidy for green building certification is not uniform across the 5 jurisdictions, and exists in slightly more than one-half of those jurisdictions. The findings, therefore, corroborate those obtained by Olaniyi and Oyedele (E. Darko et al., 2013) who noted that weak regulatory requirements need to be resolved by a focused financial intervention in the market to overcome the barriers in the market. Without incentives, it was challenging to get business owners to commit to sustainability aspects if they knew it would only increase their investment years that would come after short-term profits, even more so in the Commercial Business District with growing demands for short term profits.

Limited public awareness was achieved with a mean score of 3.97.Limited public awareness achieved the mean score of 3.97 and was ranked the fourth. A significant number of survey respondents reported that the building occupants and tenants – and even some property owners and landlords – don't know enough about the long-term operational cost savings, health benefits and property value premiums from green buildings. This lack of awareness reduces the demand of the market for green buildings, and makes putting values into green features less economic. The results show that in line with previous studies (Alruqi, 2026), problems with public views and awareness of the situation are a hindrance, and this is also the case for the relatively developed urban development in study areas.

The fifth most common barrier was "regulatory barriers" with a score of 3.82. Challenges include inconsistent building codes and energy infrastructure permitting processes that are time consuming, along with diversity in building codes among municipalities related to green buildings. Some of these obstacles have been around for awhile; for instance, in the Residential Urban Area (RUA), zoning code restrictions on rooftop solar prevented installations on historic buildings from being economical, and in the Mixed-Use Development (MUD) the absence of a net metering law made rooftop solar not economical. These issues with regulation have been reported as barriers to the adoption of green buildings in other contexts (Kamin et al., 2025).

Technologies maintenance, with a mean rating of 3.61, made its way in the bottom of the list of barriers to the top.Technologies maintenance, rated at a mean 3.61 ranked in the bottom part of the list of barriers at the top. Although in overall maintenance cost results (Section 4.4), green buildings had lower maintenance costs, some of the survey's respondents stated they were concerned about how the specialized expertise would be managed in their green buildings' maintenance. They cited the need to keep-up with updates on Building Management System software needed to maintain the building, as well as the need to periodically replace solar panels and inverters, and manage irrigation and vegetation for the green roofs. The results show that maintenance is not seen as a key constraint, but has to be considered when operating a building over a prolonged period.

As the high initial construction cost and lack of technical expertise were cited as the two most significant barriers to embrace green buildings, this signifies just one major catch in the success of green buildings: The technologies that have the highest return on energy, environmental, and economic benefits are the ones that have a high initial cost and require the most specialized skill sets – which is often the least available in rapidly urbanizing areas. It is pointed out that there is a need for specific policies both on the constraints (such as government financed training initiatives for green builders) as well as on facilitating (such as reducing or deflating the first price premium). Moderate are the limited public awareness and the regulatory road obstacles, which further attests the idea that the market demand and institutional road map backs them. These data can provide principles that can assist and support policymakers, industry associations and education institutions to accelerate the green building and landscape transition in the rapidly growing City-Suburban-Metropolitan environments in which this research contributes.

Correlation Analysis

All the different measured parameters were correlated using Pearson correlation for the entire sample of 100 buildings to determine the consistency of the sustainability framework applied and to check if they are consistent. This study aimed to give magnitude and direction of the relationship among the parameters of energy efficiency, carbon reduction, water saving and composite sustainable building performance indicator. All the correlations are statistically significant at $p < 0.001$.

Table 7. Pearson Correlation Matrix among Key Performance Variables

Variable	Energy Efficiency	Carbon Reduction	Water Savings	Sustainability Index
Energy Efficiency	1.00	0.93	0.84	0.95
Carbon Reduction	0.93	1.00	0.86	0.92
Water Savings	0.84	0.86	1.00	0.89
Sustainability Index	0.95	0.92	0.89	1.00

The correlation highest was the one among the sustainability index (,) and the energy efficiency, indicating that the most determining individual parameter of sustainability of a building is the energy efficiency. It's a logical link – part of the process of calculating this sustainability indicator is to work out how much energy is used, and how much of it is renewable or how much the energy costs are saved. The almost linear correlation proves the energy performance's role in the green building paradigm and suggests a proportional benefit in energy efficiency will be achieved in composite sustainability ratings.

A conservation of energy–carbon correlation was quickly discovered (,). It is quite statistically apparent and definitely linked to energy consumption, temperature emissions if they are from fossil fuels, as much of the energy used in buildings comes from the grid, thus having a considerable carbon associated with it. High correlation coefficient (0.93) means that more than 86% of the carbon reduction variability is explained by energy efficiency variability. The space discovery clearly demonstrates the fundamental goal of many energy-saving approaches to building design: reducing building energy demand at operation is the most effective single energy-saving measure to lower carbon emissions of buildings during operation. This aligns well also with its findings by other studies including Sartori and Hestnes, 2007 building life cycle assessment (BLCA) study, which noted high energy use intensity/building footprint life cycle carbon emission correlations.

The correlation between carbon reduction index and the sustainability index also was very high (,), again indicating that carbon reduction is a nearly identical measure of sustainability. The limited correlation for energy and sustainability introduces other factors that drive the sustainability index, such as water use, indoor air quality and employee satisfaction, which also has individual variances—quantities that can't be added into carbon measurement metrics. It points out a variety of different ways to address sustainability and underscores the importance of multifaceted measures of green building performance instead of a single measure.

There were strong positive correlations among the water saving variables, though not as strong as the correlations between the energy and carbon saving variables. Water savings- energy efficiency was (water), (carbon) and (sustainability index). The above strong (not perfect) correlation substantiate that although water-efficient buildings tend to be energy-efficient, there is a degree of de-coupling in the results between the energy efficient aspects of the building construction versus the water efficient aspects. This decoupling can be attributed to the water conservation measures (e.g., rainwater harvesting, low flow fixtures) having a level of independence from the energy system, with interactions, including those related to energy needs for water heating and pumping. The water savings and sustainability index (S) relationship shows that the water saving is an important sustainability consideration, albeit not as major as energy saving. The findings are corroborated with the previous studies that have found that water efficiency is not as a priority as energy efficiency in green buildings (Pratiwi et al., 2024).

The overall level of correlations for all of the measured performance variables was high, which reinforces the concept proposed that the sustainable building design is an integrated approach. The carbon and water performance and the overall sustainability improvements demonstrated are correlated with increased energy scores, and the green building certification programs can track improvements across a range of integrated performance attributes—not just arbitrary or disparate. Starting to explore this integrated performance pattern gives insights into concurrent contributing factors/causes in one or more ways, such as design, commissioning, management, multipled complementary technologies, and so forth, that can yield synergistic improvements at several points.

Next, analysis of the data of all measured variables was conducted using Principal Component Analysis (PCA) and further dimensions of the correlation structure was observed. Only one principal component was found which explained 88.3 % of the variance in the data and all variables showed high loading on the PC. The sustainability index was the loading with the highest score (0.97), followed by energy efficiency 0.94, carbon reduction 0.93 and water savings 0.88. This one-dimensionality of the results of the varimax rotation also explains why the measured variables are not independent; they all contribute one-dimensional aspects of the overall building's sustainability, shown through the composite index. The PCA outcomes support the use of the sustainability index to summarize the outcomes of the building performance and to validate statistically the integrated approach to assessment followed in this study.

The results of the present correlation are noteworthy for research and practice. The strong inter-correlations ensure that any one performance measure-based index, such as energy use, can give informative, but partial, assessments of green building as a whole because energy use is just part of the variability in more comprehensive measures of performance. From the practioner and policy maker perspective, integrated performance is also certainly a co-benefit as investments in separate green technologies are mostly found to have co-benefits in other sectors, thereby increasing ROI. But of interest is that the former requires a multi-technology intervention to advance sustainability to a higher level than 60% rather than individual interventions. All the correlations may therefore be seen as a tool to better understand the systemic nature of the performance of a green building matrix as well as identifying priorities for intervention with the greatest cross domains benefits.

Discussion

The empirical evidence in this study provided valuable theoretical and practical implications to the study of sustainable urban development. All performance measures were correlated to each other, and a value of 88.3% was found for the one measure of the principal component analysis, suggesting that overall there are strong theoretical reasons to suspect that green building performance is a multi-dimensional whole construct, rather than a set of building attributes. This is a change in the way building performance has been studied, up until now it was studied under separate research heads of water, energy and indoor environment. The result of the positive correlation between these domains, suggested by the data, shows a strong relationship that is initiated by their shared design values, processes, procedures and followed by their rigorous commissioning and complementary application of technologies seemingly operating together. However, future conceptions of "BUILDING sustainability" should take systemic design thinking as an emergent, and not as a series of different technological strategies.

The implications for practice are just as notable, and can inform practices for a wide variety of stakeholders. The compelling economic benefits to the policy-maker in terms of urban policy are that certified green buildings deliver 17% increase in property values and 30.7% reduction in the operating costs. This kind of incentive can directly tackle the number one challenge in this study, the "upfront" cost at construction, by either reducing total cost or making it more affordable. From an investment point of view, the correlation analysis suggests that for the building owner and/or developer, investments in energy efficiency have the potential of co-benefits in carbon reduction and water savings, maximizing return on any dollar invested in green technologies. From the 50 green buildings that have been reviewed across the four years of this study, the average payback period is 4.6 years; this means that green buildings are not just improving the environment they are improving the economy too, and potentially making it easier to obtain green financing and possibly interest rates from environmentally aware lenders. As for the designers and construction members, the criticality of a lack of limited technical skills becomes obvious, highlighting the pressing need for increasing the training capacity of professionals and curriculum development in the building profession to focus on integrated building systems, passive designing and smart building operation. Certificarion programmes, in the form of an association of industry associations and universities, must foster the skills of architects, engineers and facility managers that will add the cross-disciplinary "building skills" necessary to realize the full performance of green buildings.

The findings are interesting, however a few restrictions to method are noted. The sample contains 100 buildings which were carefully selected across the five urban zones, but it does not represent each and every building type in any given climate and regulatory setting in fast urbanizing countries. These rules to exclude buildings over 20 years old, and not fully connected to utility data, can cause selection bias and obscure any performance improvements that may be achieved with green buildings, even giving the impression that they perform better than they do, by removing the poorer performing conventional buildings. Occupant satisfaction surveys further compound the subjectivity and the indoor air quality indices were measured at single points of time, not measured for 24/7 continuous measurements (year round). The correlational design successfully shed light on high correlation but was not appropriate for establishing causal inferences in how the improvement in performance is obtained. Finally, the focus of the majority of the study was on operational energy and water use, with embodied carbon and the life-cycle impacts of material used in making the building ignored (i.e. cost of provisioning solar panels, insulation, smart sensors etc. not discussed until this point).

Conclusion

This study intended to calculate the energy, environmental and economic advantages of energy-efficient and eco-friendly building with the conventional building and provide empirical data for the support of sustainable urban development policies. As seen in the results shown here, green buildings can outperform conventional buildings greatly, in every dimension (36% in annual energy consumption, 40.4% in reduction of carbon, 32.0% in reduction of H2O, and 30.7% in reduction of operating costs). The results confirm and develop previous studies and results by validating that integration of technologies does significantly influence the sustainability scores as both net zero energy system configuration as well as smart green configuration tested high sustainability scores. More important, all the performance measures were highly correlated with each other, and a principal component analysis only had one out of 6 discovered principal components with a variance >10%, showing high covariance support to studying sustainability as a whole, instead of components taken independently.

Further research is needed in the form of longitudinal studies assessing performance deterioration over time and controlled studies to understand the correlation between the building's "green" characteristics and the residents' health and productivity gains. Growing from both the financial and the technical challenges highlighted above, the first two issues for consideration when implementing the policy identified here are issues of cost, and the skill and knowledge of the technical aspects. The results of this research provide an evidence base that can support the inclusion of integrated green building strategies as a large element in the sustainable urban growth, and can serve as a reference of action for the policy makers, investors or management practitioners who want to reduce the environmental footprint of the city during its rapid development.

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