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Energy audit based identification of energy efficiency improvement opportunities for existing houses

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KEYWORDS

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Energy Audit

Energy Consumption

Thermal imaging

Energy Improvements.

ABSTRACT

Energy efficiency in the building has two dimensions; efficient use of energy resources and energy conservation. Energy-efficient houses play a critical role in energy conservation and achieving sustainable built environment goals. The energy efficiency of a house depends on its building envelope (design, orientation, and energy properties of construction material) and operational characteristics (appliance efficiency, energy consumption patterns). Rather than merely ensuring new houses are energy-efficient, it is vital to energy retrofit existing houses. Energy audits can assist in evaluating the energy efficiency of existing houses and identify improvement measures. The main objectives of this study were to identify efficiency improvement opportunities through an energy audit of houses and apartments in Karachi. A detailed energy audit checklist was prepared using literature, standards, expert review, and code requirements. Data was collected through physical and owner-assisted virtual audits of 58 houses in six districts of Karachi. Architectural plans, information about doors, windows, air ducts, thermal images, historical data, and material properties were collected. Audit tools included; an anemometer and thermal imagining camera during physical audits. Android applications were used during owner-assisted audits. Data were analyzed for developing descriptive graphs, U and R-values, Pareto charts, and district-wise mapping of energy properties of the material. As a result, energy improvement opportunities were proposed. These are focused on building envelope aspects, including; window orientation, minimizing air infiltration, and using heat-resistant paint. Improvement measures were confirmed through thermal imaging of selected buildings.

1. Introduction

Energy consumption has increased globally due to the increase in population and limited opportunities for making existing structures energy efficient. Pakistan is among countries having high energy domestic energy use, despite having an energy deficiency. Pakistan's annual total final consumption (TFC) of energy by sector indicates that the residential sector consumed 43651 Ktoe energy in 2018, which is significantly more than the industrial sector usage, i.e., 24116 Ktoe in the same year. Residential share of TFC consumption has decreased from 1990 to 2018 (i.e., from 55.4% to 45.6%). It is predicted to remain around 45.6% in 2021. However, the residential sector's TFC has increased from 20047 Ktoe in 1990 to 43651 in 2018 [1]. Forecast results show the demand will keep on increasing by 2030.

Energy efficiency in energy outlook has two dimensions; efficient use of energy resources and energy conservation. Energy-efficient houses play a critical role in energy conservation and achieving sustainable built environment goals.

The rapid advancement of energy-efficient housing is crucial not only to address the worsening energy crisis but also to meet a key objective of the United Nations Sustainable Development Goals, which is to double the global rate of improvement in energy efficiency. [2]. According to the recent population and housing census of Pakistan, out of the total 32 million residential units in 2017, rural housing was 63.62% and urban housing was 36.38%. Significant efforts are required to improve energy efficiency in residential houses and buildings in urban areas, which use a significant portion of the residential sector's energy share.

The energy efficiency of a house depends on its building envelope (design, orientation, and energy properties of construction material) and operational characteristics (appliance efficiency, energy consumption patterns). Rather than merely ensuring new houses are energy-efficient, existing houses must also be focused on energy retrofitting. Energy audits can assist in evaluating the energy efficiency of existing houses and identify improvement measures. An energy audit is a tool to evaluate buildings' energy performance to highlight deficiencies and propose improvements. Energy bills, architectural plans, meteorological data, and occupant profiles, combined with analysis of different activities, are part of energy audit data. Such audits can establish a helpful database that describes the study area's overall energy consumption and efficiency parameters. It also assists in identifying opportunities to improve efficiency.

Based on the above discussion, this paper provides details of an energy audit conducted in Pakistan with a geographical focus on the biggest city Karachi. The study's primary objective was to identify efficiency improvement opportunities through an energy audit of existing houses and apartments.

2. Literature Review

2.1 Context

Pakistan locates between 24 N and 36 N on a geographic coordinate. Pakistan lies in a temperate climatic zone. It’s having arid climate and is categorized as hot summers and cool or cold winters, haing widespread variations between extremes of temperature at given locations. Typically, 70% of the nation remains in a hot climatic zone for a significant part of the year [3]. Thus, in hot summers, a significant amount of energy is required for cooling, specifically in urban areas like Karachi, which should be a primary concern in the building envelope design. This should encompass improved building envelope design, the use of energy-efficient construction materials, and the incorporation of energy-saving electrical appliances. Building Energy Code 2011 of Pakistan Energy Provisions exist, however, guidelines for energy efficiency in existing housing is yet to be developed.

2.2 Energy Audits

An energy audit can assist in ensuring energy efficiency as this process leads toward the understanding of total energy consumption, and identifying opportunities for reducing the consumption [4]. The energy audit process typically implies (1) ensuring commitment towards energy conservation and environmental consideration, (2) exploring possible ways to reduce consumption, and (3) continuous improvement by promoting energy efficiency [5]. Analysis of the primary inputs like; utility bills, architectural plans, relevant metrological data, consumption profiles, and patterns can lead to identifying possible improvement measures for energy efficiency. The analysis and hence reduction of heat losses in the building is also directly related to improving the building's energy efficiency [6]. Therefore, heat losses through walls, roofs, and floors shall be analyzed in detail. Walls are the most considerable portion of the surrounding area of a building and can contribute up to 35% of the total heat losses of the building. Losses through roofs can be up to 25%, and poor insulation of the floor can cost up to 15% of the total heat losses of the building [7].

2.3 Building Envelop Performance Thresholds

The building code of Pakistan Energy Provisions [8] specifies threshold performance parameters for different building envelope components. It provides threshold U (Conductivity) of outer (exposed) walls and roofs. The provisions specify thresholds for heat (warmth) transmission coefficient (conductivity U), and concealing coefficient (SC) a measure of the thermal performance of a glass unit (panel or window) in a building.

These are proposed for two scenarios: structures where the external glass area does not exceed 40% of the outer wall surface, and structures where the external glass area exceeds 40% of the outer wall surface. Furthermore, provisions also specify threshold values for the convective surface coefficient in upward, downward, and horizontal directions as a measure of allowed heat flux (density). All of the aforementioned parameters’ values as specified in PEC’s building code of Pakistan energy provisions are shown in Table 1.

Table 1

Ranges for walls, roof, and glass area and values of convection surface coefficient

Energy Parameters	U- Values	Equivalent R Values
External Walls and Roof		
Divider U	0.57 W/m^2.K (0.100 Btu/h.ft^2. °F)	1.754
Rooftop U	0.44 W/m^2.K (0.078 Btu/h.ft^2. °F)	2.727
Outer Glass Area (≤40%)		
Warmth Transmission Coefficient (U)	3.5 W/m^2.K (0.44 Btu/h.ft^2.°F)	0.286
Concealing Coefficient (SC)	0.76	
Outer Glass Area (>40%)		
Warmth Transmission Coefficient (U)	2.5 W/m^2.K (0.37 Btu/h.ft^2.°F)	0.4
Concealing Coefficient (SC)	0.35	

For air leakage or infiltration, the code provisions mandate that the building envelope must be securely sealed, caulked, gasketed, or weather-stripped to minimize air leaks where potential gaps exist. Additionally, lobbies and doorways should be designed to reduce air penetration through revolving, sliding, or swinging doors.

3. Research Objectives, Scope, and Methodology

The main objectives of this research were to conduct energy audits of houses and identify possible energy efficiency improvement opportunities. The scope of the research was limited to houses in six districts of Karachi and selected apartment buildings at the staff colony NED University. This study's limitations include climatic zone considerations. Since Karachi lies in Climate Zone 0B as per ASHRAE codes, the results are most applicable to regions with similar climatic conditions. Additionally, the findings are primarily relevant to RCC structures, potentially limiting their applicability to other building types. Despite these constraints, the study provides valuable insights into energy efficiency improvements in similar climatic zones.

Name of home owner: Fuad Ahmed Shariff | House code: 02

City: Karachi | District: East | Date: 19/02/2020 | Time of Audit: 2:00pm

Address: 148 Bangalore Town Tipu Sultan Road Karachi, block 7/8

Plot size: 500sq yard	Sunlight Direction: N.w
Season: Winter	Wind Speed: 4.16m/s
Covered Area: 250sq yard	Wind Direction: W-NW, 300º from N

Architectural Plan attached	Yes ✓	no
Electricity Bill 12 months attached(Year 2019)	Yes ✓	no

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Units	375	285	344	471	779	995	972	940	764	924	763	434

`Gas Bill 12 months attached(Year 2019)	Yes ✓	No

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MBTU	3.72	3.72	3.36	3.36	3.36	3.36	3.36	3.36	3.35	3.43	3.74	3.74

Orientation of Building (Tick box)	NE	NW ✓ 340º from N	SE	SW

Outdoor Temperature: 30º C	Design Temperature:
No. of occupants:7	Area per person: 35.5 yards
Building Type: Residential	Building Operating Schedule:

24/7	24/6	24/5	12/7	12/6	12/5
✓					

No. of Rooms: 6

Room	FLOOR	Floor Area	Volume
01	First	336ft^2	4032ft^3
02	First	172.5ft^2	2070ft^3
03	First	203ft^2	2436ft^3

EXTERIOR WALL

Room no.	Type of Wall	Wind Speed (m/s)	Thicknes s (in)	Inside Temp (ºC)	Outside Temp (ºC)	R-value (m^2K/W)
01	Masonry	0.7 0.7 0.2	8" 8" 8"	29 ºC 29 ºC 29ºC	32.7ºC 32.9 ºC 32 ºC	0.3515 0.3513 0.3674
02		1.31	8"	27.5 ºC	28.3 ºC	0.3435
03		0.3	8"	27.3 ºC	28 ºC	0.3692
04		0.22	8"	27.2 ºC	27.8 ºC	0.3723
05		0.82	8"	27.5 ºC	28.1 ºC	0.3541
06		0.84	8"	27.6 ºC	27.8 ºC	0.3539

INTERIOR WALLS

Room no.	Type of Wall (Material of Wall)	Wind Speed (m/s)	Thickness of Wall (in)	Inside Temp (ºC)	Outside Temp (ºC)	R-value (m^2K/W)
01	masonry	0.2	7.5"	22.1	23.5	0.3515 0.3513 0.3674
02	masonry	0.31	7.5"	25.7	25.9	0.3435
03	masonry	0.31	7.5"	23.6	23.7	0.3692
04	masonry	0.18	7.5"	23.1	22.1	0.3723
05	masonry	0.31	7.5"	23	21.9	0.3541
06	masonry	0.25	7.5"	22	22.5	0.3539

Fig. 1. Snapshots Of The Audit Checklist

First, a detailed literature review was conducted to understand the building energy audit requirements, different standards for the energy audit, building codes' energy provisions, and prior studies. The different possible energy efficiency of improvement measures was also reviewed as found in prior studies or recommendations. The audit checklist was meticulously developed through a multi-step process to ensure its comprehensiveness and relevance to the study's objectives. The initial step involved a detailed literature review of existing building energy audit standards, building codes' energy provisions, and prior studies on energy efficiency. This review provided a foundation for identifying key parameters critical to assessing energy efficiency in residential buildings.

Based on this literature review, the checklist was designed to cover four main categories: 1) building geometry, including the shape, layout, and wall construction; 2) thermal properties, such as windows, walls, doors, and roofs; 3) building services that consume energy, including air conditioners, fans, and lighting systems; and 4) climatic parameters, such as sunlight direction, airflow, and ventilation.

To ensure the checklist's accuracy and applicability, it was reviewed by an expert energy auditing consultancy firm. The experts provided feedback on the checklist's content, suggesting conformance to industry standards and recommending additional improvement measures where necessary. The engagement with the consultancy firm was crucial to refine the checklist, making it a robust tool for conducting energy audits.

The checklist was then applied during both physical and virtual audits, ensuring consistent data collection across all the houses studied. The incorporation of expert review and the iterative development process ensured that the checklist was both comprehensive and aligned with the latest energy audit standards and practices.

Data was collected through physical and owner-assisted virtual audits of 58 houses in six districts of Karachi. Architectural plans, information about doors, windows, air ducts, thermal images, historical data, and material properties were collected. Audit tools included; an anemometer and thermal imagining camera during physical audits. Android applications were used during owner-assisted audits. Both physical and virtual audit datasets were logged into Google form developed for audit checklist to compile data set for analysis efficiently. During the virtual audits, participants were assisted through Zoom meetings and different video tutorials logged in the online audit form.

Data collected through the audit was analyzed for developing descriptive graphs, U and R-values, Pareto charts, and district-wise mapping of energy properties of the material. As a result, energy improvement opportunities were proposed. These are focused on building envelope aspects, including; changing window orientation, minimizing air infiltration, and use of heat-resistant paint. Improvement measures were confirmed through thermal imaging of selected buildings.

4. Audit Checklist Development, Structure, and Conformance Development

A detailed energy audit checklist was developed based on a thorough literature review. The literature review included (a review of); standards such as, which relates to the thermal performance of buildings [10], which relates to thermal resistance and transmittance through building components; and [11], which relates to hygrothermal properties of building materials and products. The review also included a detailed study of Building Codes of Pakistan: energy Provisions [8] to identify the minimum necessary energy efficiency conditions (thresholds) for buildings and identify improvement opportunities in the audited houses. In addition to these standards and codes, several relevant prior studies were also reviewed in detail, as discussed in the literature review section earlier in the paper. These studies specifically helped develop a checklist for guidelines for possible energy improvement measures, along with other essential aspects of the checklist. The key findings from standards, code's energy provisions, and prior studies were input in designing a detailed energy audit checklist.

4.1 Audit Checklist Structure

The audit checklist was structured into five sections. These included basic information, thermal properties-related data, data related to the energy profile of appliances, a checklist of the type of construction of building elements, and a checklist for guidelines. A snapshot of the checklist is provided in Fig. 1.

The first section of the checklist consisted of requesting essential characteristics about the house, including; the name of the resident, address, electricity unit consumption (KWh) for the last 12 months, house orientation, sunlight direction, wind speed and direction, outdoor temperature, building operating schedule, number of occupants, site/architectural plan of house, covered area.

The second section included; data related to the thermal properties of the building envelope elements, i.e., walls, roofs, windows, doors, and ventilators. The audit checklist also included data collection for the type of element and its material, thickness or depth of the element, the surface area of the element, the element's global direction (window direction), wind speed at/or near the element's surface, inside, and outside temperature at the surface of the element. During the audits, these datasets were collected for each wall, window, door, ventilator, and ceiling. As a result of this collected data, the thermal performance of building elements in terms of resistivity and transmittance values was evaluated in line with the ISO standards' calculation mechanism. The calculations and outputs will be discussed later in the paper in the energy audit analysis section.

The third section of the checklist included data collection related to the energy profile of appliances, including; amperes/watts, operating hours and the number of appliances used in each room. Although this portion was not entirely related to the building envelope-related information, which is the primary scope of this study's audit, it was necessary to develop Pareto charts. Pareto charts illustrate energy consumption patterns for different types of appliances in a house.

The fourth section included a checklist of the type of construction of building elements, i.e., interior walls, exterior walls, roof, ceilings, windows, and doors. It also included a checklist for identifying possible heating and cooling load infiltrations based on walkthrough analysis.

The fifth and final section of the audit checklist included a checklist for guidelines to identify possible energy efficiency improvement opportunities in an audited house. The list of comprehensive guidelines was made part of this section and was used to identify preliminary potential improvement measures for audited houses.

4.2 Checklist Review and Conformance

To get the conformance of the checklist before it could be used for the conduct of energy audits, an energy and environmental consultant firm was engaged. The firm is one of Pakistan's most prominent environmental and energy consulting companies. The firm has over 25 years of experience in energy and the environment. It is involved in energy audits, environmental audits, and environmental impact assessments. The company has conducted more than 100 energy audits in the industrial sector. The Consultants' team included experienced professionals having expertise in human settlement, city planning, environmental, and civil engineering.

Changes were made, and errors were removed from the checklist based on the expert review. Furthermore, the consultant identified that energy efficiency for existing houses could be categorized into two main categories (1) behavior changes and (2) using energy-efficient appliances based on behavior changes. The consultant also suggested techniques to graphically analyze and illustrate data (such as Pareto Charts) to stakeholders for making appropriate decisions. Another valuable input from consultants was also incorporated into the final audit list.

5. Conducting Energy Audits

5.1 Audit Procedure

Five Civil Engineers were trained to perform the energy audits of the selected houses and apartments. Data was collected from building walk-throughs and audit instruments i.e., anemometer and thermal imaging camera. Architectural plans and electricity bills for the past 12 months were also collected. Owner-assisted virtual audits were also devised where access to the physical team was not possible. In these virtual audits, owners were contacted through online video call sessions. An online form to collect required information was developed and data was collected through owner-assisted virtual walk-throughs aided by the Android application Zephyrus Lite Wind Meter and thermometer for calculating U and R values as shown in Fig. 2.

Fig. 2. Snapshots From Energy Audit Exercise

5.2 Sample Characteristics and Reliability

A total of 58 audits were conducted based on a simple random sampling of houses in 6 districts of Karachi. From district-wise geographical coverage of the audited houses, 44% of the houses were from District East, 19.3% houses were from District Malir, 17.5% of the houses were from District Central, 8.8% of the houses were from District South, 7% were from district Korangi, while the rest were from district West. Mainly, residents' acceptance and house sizes were the critical criteria in selecting houses for audits. The house sizes range between 80 to 500 sq. yds houses and apartments. 36% of audited houses ranged between 80 to 100 sq. yds in size, 34% of audited houses ranged between more than 100 to 200 sq. yds in size, and 22% of houses ranged between more than 200 to 300 sq. yds in size, while 4% houses each were audited in the range of more than 300 to 400 sq. yds and 400 to 500 sq. yds. Most audited houses (i.e., 92%) were between 80 to 300 sq. yds. These are typically 1-

3 or in some cases 4 rooms houses. According to Pakistan Bureau of Statistics data, 1 to 3 or 4-room houses in Urban Sindh, of which Karachi is the biggest, are approximately 93.29% of the total houses. Out of this 93.29% of houses, 84.46% are termed as (Pucca) structured houses. Therefore, 78.79% of the houses can be considered structured houses of 1 to 3 or 4 rooms, typically having a size range between 80 to 300 sq. yds. in Urban areas of Sindh [12]. Hence, 92% of the data set collected in this research (80 to 300 sq. yds.) is statistically from the 78.9% mentioned above of houses that establish satisfactory reliability and acceptance of energy audit results in this research.

6. Energy Audit Analysis

6.1 Basic Characteristics

6.1.1 Covered area

For the covered area (constructed area) of the audited houses; 27.6% of the audited houses were in the range of 40 to 80 square yards. 31% of the houses were in the range of >80 to 120 square yards. 25.9% of the audited houses were in the range of >120 to 160 square yards. 5.2% of the audited houses were at >160 to 200 square yards. And 10.3% were in the range of >240 to 500 sq yds.

6.1.2 Surrounding weather conditions

The energy audits were mainly conducted from May to September. The outdoor temperature around the houses was measured to be 24oC to 38OC, with an average temperature of approx. 29OC. The wind speeds around the audited houses was measured in the range of 0.22 m/s to 14 m/s. An average wind speed is approximately equal to 3 m/s. These weather parameters indicate typically hot to mild weather (in between summer and winter) season; therefore, audited measurements and results reliably represent the measured energy parameters due to average seasonal conditions.

6.1.3 Operation and occupancy

100% of the houses had an operating schedule of 24/7. The number of occupants in the audited houses ranged between 2 and 8. While the average occupancy was found to be approximately five persons per house. It indicates that audited houses are mainly comprised of dwellings from medium-sized families, with some exceptions. Hence, the operational data collected, such as energy consumption, will be a true and accurate representation of typical energy consumption patterns in medium-sized family houses in Karachi.

6.1.4 Energy source

About 67% of houses did not have any alternative energy source. Among the houses that were found to have an alternative energy generation source, 74% were equipped with fuel-based generators with a power range between 2 to 5 kV, and 11% were equipped with Solar Photovoltaic Technology having a power range of around 4 to 5 kV. While 16% of the house were equipped with battery-based electricity-powered Uninterruptible Power Supply (UPS) systems as a backup for power outages.

6.1.5 Energy consumption

The data gathered during the energy audit includes electricity bills from houses in different districts of Karachi. Four categories of houses were considered in the analysis concerning their areas. The analysis also incorporates the data separately for the summer and winter periods. The ranges of houses include houses with areas less than and equal to hundred square yards (H1), greater than a hundred to two hundred square yards (H2), greater than two hundred to three hundred square yards (H3), and greater than three hundred to four hundred square yards (H4). For the summer period, months from April to March were considered, and for winter, months from November to March were considered in the analysis. For district east, data on energy units for fourteen houses of category H1 were collected and separately analyzed for summer and winter by taking their average. In the same pattern, analysis for H2, H3, and H4 categories with ten, two, and zero houses, respectively, was performed, as shown in Fig. 3. It can be depicted from Fig. 3 that energy consumption is more in the summer period than in winter. With a greater area of houses, their consumption increases except that for category H3, energy consumption in winter is lesser than the energy consumption of categories H2 and H1 in the winter period. A similar process was carried out for district Malir where two houses for category H1 were considered; no data were available for category H2, nine houses were considered for category H3, and no data was available for category H4. However, for the graph of district Malir in Fig. 3, it can be depicted that more energy is consumed in summer than in winter, and the amount of energy consumption increases as the area of the house increases. For the analysis of District Central, two houses were considered for category H1; six houses were considered for category H2; one house was considered for category H3, and one house for category H4 was considered. Electricity units on the electricity bills for the houses in other districts of Karachi were not legible clearly. Therefore, those houses were not considered in this analysis, which is shown in Fig. 3.

Another analysis for developing the overall trend of electricity consumption in an entire year was done by taking the average of all the energy units of the houses each month and drawing a curve against the months so that the apparent trend of the energy consumption can be visualized. 'Low unit consumption zone' has been identified for November to March and high units consumption zone was identified for April to October as shown in Fig. 3.

6.2 Thermal Properties and Performance

The thermal performance of building elements in terms of thermal resistance and transmittance properties was calculated using data collected through the second section of the audit checklist. As reviewed and discussed earlier, the following sub-sections discuss detailed calculation mechanisms for thermal properties based on ISO standards. Next, district-wise results have been discussed in detail due to the energy audit conducted in this research.

6.2.1 Thermal resistance

The thermal resistance (R-value) measures how well a given material can withstand the conductive heat flow based on its thickness. Four variables decide the efficacy of a home's insulation. Conduction, convection, air penetration, and radiation are all four factors. The factor determined by the R-value is conduction. It allows for determining the impact of adding thicker layers of the same insulating material. The following graphs show the R-values of different houses in each district.

The following analytical graphs show the variation of R-values of different materials. Thermal resistance is mathematically defined as the ratio of the temperature difference across a material's two surfaces to the rate of heat flow per unit area.

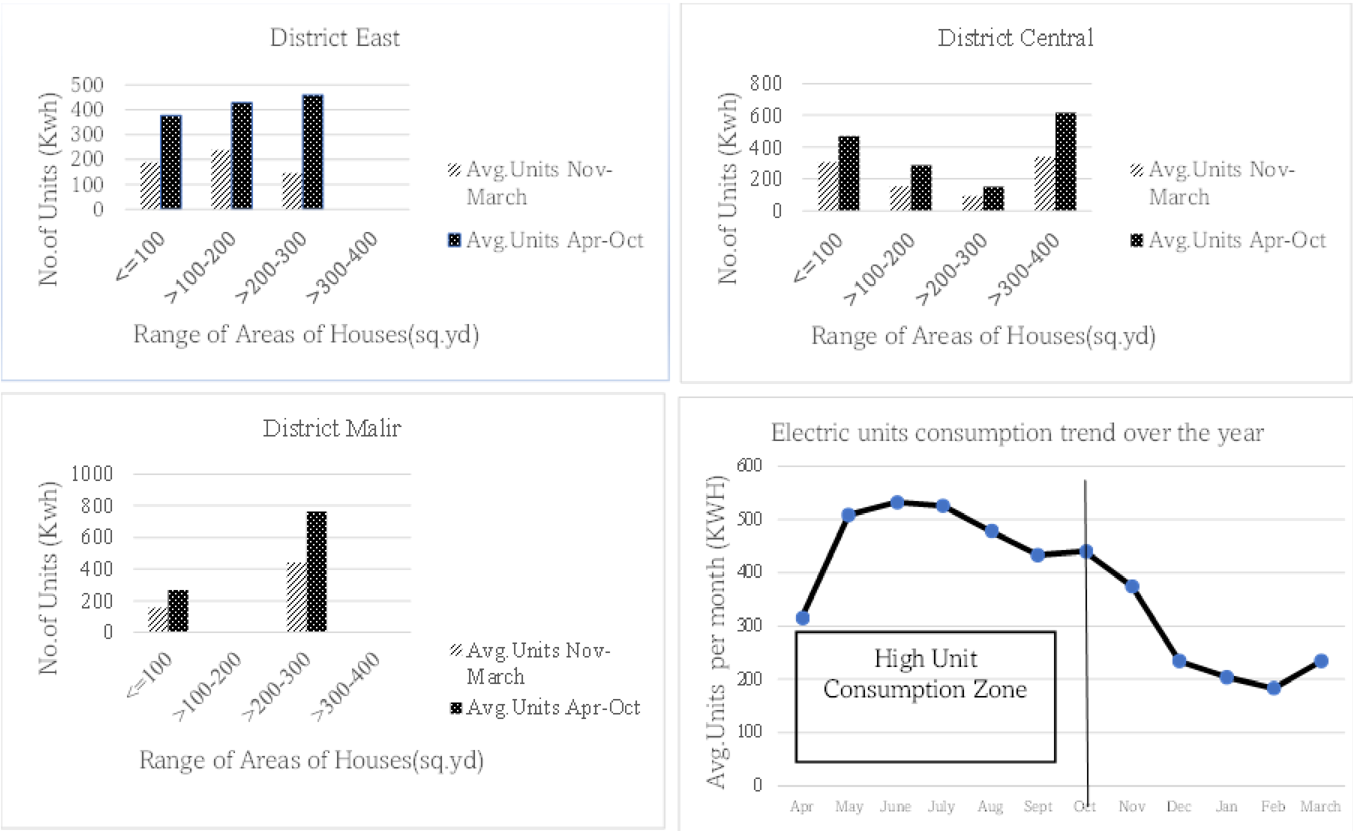


Fig. 3. Avg. No. Of Units Consumed By Different Districts And Electricity Unit Consumptions' Trend In Different Districts Of Karachi

To calculate the thermal resistance (R) of a material layer when the thermal conductivity (λ) is provided,

$$R = \lambda/d \quad \text{Eq. 1}$$

Where:

R is the thermal resistance in $m2{\cdot}K/W$, d is the thickness of the material layer in meters (m), λ is the thermal conductivity of the material in $W/(m{\cdot}K)$

The value for λ can be obtained from relevant standards, such as ISO 10456 (2007), which provides thermal conductivity values for construction materials.

Surface resistance is given by $Rs=1/(h_c+h_r)$ Eq. 2

Where;

R_s is the surface resistance in $m^2{\cdot}K/W$;

h_c is the convective coefficient in $W/(m^2{\cdot}K)$; hr is the radiative coefficient in $W/(m^2{\cdot}K)$. $h\,r = \varepsilon\, h_{ro}$

$$h_{ro} = 4\sigma \, [\![T_{mn}]\!]^3 \qquad \text{Eq. 3}$$

where,

hr is the radiative coefficient in W/(m^2·K)

ε is the hemispherical emissivity of the surface

hro is the radiative coefficient for a black-body surface in W/(m^2·K)

σ is the Stefan-Boltzmann constant: 5.67 × 10^{-8} W/(m^2·K4)

Tmn refers to the mean thermodynamic temperature of a surface and its surroundings, measured in Kelvin (K). The emissivity (ε) of a surface, which affects heat transfer, is often taken as 0.9 for both internal and external surfaces, as this value is generally suitable for most building materials in thermal analysis.

At internal surfaces, $h_c = h_{ci}$

At external surfaces, $h_c = h_{ce}$

And

$$h_{ce} = 4+4.v \qquad \text{Eq. 4}$$

Where; v is the wind speed adjacent to the surface, in m/s (ISO 10456, 2007) [11].

6.2.2 The thermal resistance of a building component

The total thermal resistance of a plane-building component, made up of thermally consistent layers aligned perpendicular to the heat flow, can be determined using the following Eq: [11].

$$R_{total} = R_{\_si}+R_1+R_2+R_n+R_{se} \qquad \text{Eq. 5}$$

Where;

R_{total} is the total thermal resistance in m^2·K/W

$R_{\_si}$ is the internal surface resistance in m^2·K/W

R_1, R_2……R_n are the thermal resistances of each layer in m^2·K/W

R_{se} is the external surface resistance in m^2·K/W

6.2.3 Thermal transmittance

In the steady state, the heat flow rate per unit area, divided by the temperature difference between the surroundings on each side of a system, is determined by the reciprocal of the total thermal resistance of the structure. It is expressed as W/m^{2}K. [11].

The thermal transmittance is given by:

$$U = 1/R_{total} \qquad \text{Eq. 6}$$

Where;

U is the thermal transmittance in W/(m^2·K);

R total is the total thermal resistance in m^2·K/W.

Table 2

District-wise analysis of thermal resistance (R-Values) of building elements

Districts	R- Values				
	Door	Window	Exterior Walls	Interior Walls	Roof/ Ceiling
East	0.38-0.55	0.18-0.22	0.28-0.32	0.29-0.33	0.29-0.31
Central	0.47-0.73	0.16-0.23	0.27-0.31	0.3-0.32	0.26-0.31
West	0.49-0.57	0.20-0.21	close to 0.32	close to 0.33	0.315-0.325
South	0.41-0.54	0.19-0.20	0.28-0.307	0.28-0.35	0.28-0.34.
Malir	0.36-0.38	0.19-0.29	close to 0.29	0.26-0.28	0.31-0.32
Korangi	0.48-0.55	0.17-0.19	0.27-0.28	0.3-0.32	0.28-0.31

It can be noted that observed in Table 2, R- values for Exterior in all districts of Karachi were found to be in the range of 0.27-0.32. This value is significantly smaller than the prescribed value of 1.754 by Pakistan Building Energy Codes. Thus, walls can be regarded as efficient in maintaining the energy efficiency as expected by these elements. This gap between the recommended and observed values became even more significant in the R -Values of the Roof/ceiling where the code prescribes a higher R-value than the walls. Observed values lay between the range of 0.26-0.31 which is much smaller than the code-recommended value of 2.7. Windows are not different from this observed trend, where other than the Malir district houses, the R-values falls short that the one prescribed by the building codes.

6.3 District-Based Audit Detailing

After carefully gathering and calculating the R-values of each district detailed mapping of each district was developed, which shows the following data: Total Household of each district, the Total number of houses and flats audited in that district, R-values of doors, R-values of windows, R-values of Interior walls, R-values of Exterior walls and R-Values of Roof/Ceiling. From Fig. 4, it was determined that the total household of district east is 509238, from which audited houses and flats were 17 and 8 respectively. This map shows the range of R-values for district east. R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like Wall and Roofs were not far off. The total household of district central is 538983, from which audited houses and flats were seven and three respectively. This map shows all the ranges of R-values for district central. R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like Wall and Roofs were not far off. The total household of District South is 327518, from which five houses in district south were audited. This map shows the range of R-values for the district south. R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like Wall and Roofs were not far off. The total household of district west is 634459, from which two houses from district west were audited. This map shows all the range of R values for district west.

R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like Wall and Roofs were not far off. The total household of district Korangi is 421618, from which four houses from district Korangi were audited. This map shows all the ranges of R-values for district Korangi. R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like walls and Roofs were not that far off. The total household of district Malir is 538983, from which 11 houses from district Malir were audited. This map shows all the ranges of R-values for district Malir. R-values of doors were generally higher than the R-values of windows, and R-values of masonry and RCC structures like Wall and Roofs were not that far off.

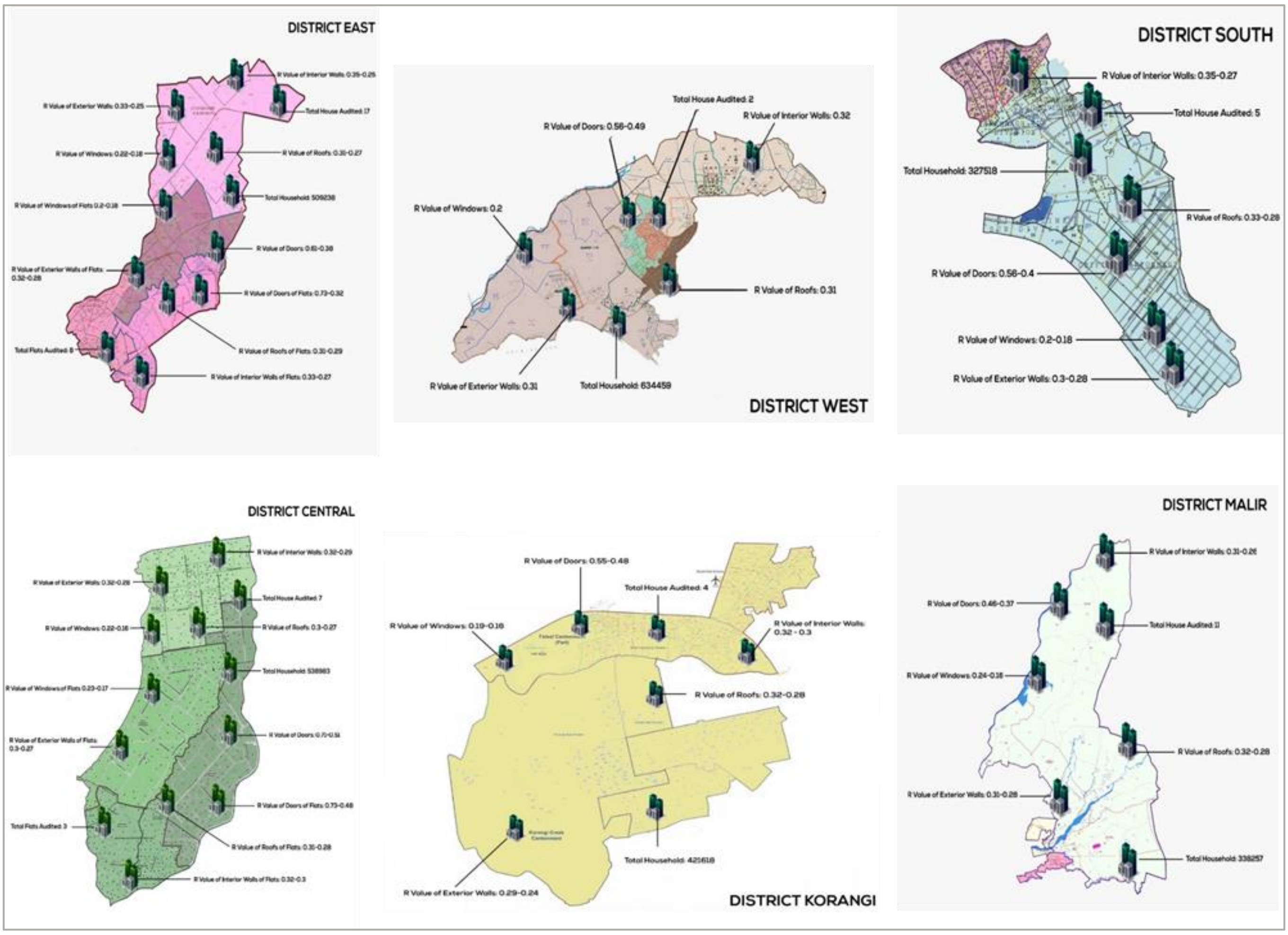


Fig. 4. Mapping Of R-Values For Different Districts Of Karachi

6.4 Energy Profile of Appliances - Pareto Charts

A Pareto Chart is a tool that helps to analyze and prioritize issue resolution. A Pareto chart combines a bar graph and a line graph. Here each bar represents an electrical appliance. The height of the bar (on the y-axis) represents the total wattage of the appliance multiplied by the total operating hour per day. The bars are presented in descending order that can be observed which defects are more frequent at a glance. At the same time, the line represents the cumulative percentage of defects. The cumulative percentage line indicates which defects to prioritize and get the overall improvement.

From Fig. 5, sample house 01, situated in district Central, shows that refrigerators and LED bulbs consumed 56.4% of the energy. Focusing on these two appliances, we can save up to 50% on energy consumption. Sample house 02, which is situated in the district east, shows that Freezer, refrigerators, and Fans consumed 60% of the energy. By focusing on these three appliances, we can save up to 60% on energy consumption. In the Sample, house 03, which is situated in the district south, shows that Air conditions consumed 43.4% of the energy. Focusing only on AC, we can save up to 40% on energy consumption. Sample house 04, which is situated in district Korangi, shows that Freezers, refrigerators, and Fans, consumed 67.78% of the energy. By focusing on these three appliances, we can save up to 60% on energy consumption.

In Sample, house 05, which is situated in district west, shows that the refrigerator consumed 58.9% of the energy. Focusing only on the refrigerator, we can save up to 50% energy consumption.

Sample house 06, which is situated in district Malir, shows that the refrigerator and LED bulbs consumed 55.01% of the energy. Focusing on these two appliances, we can save up to 50% energy consumption, as shown in Fig. 5.

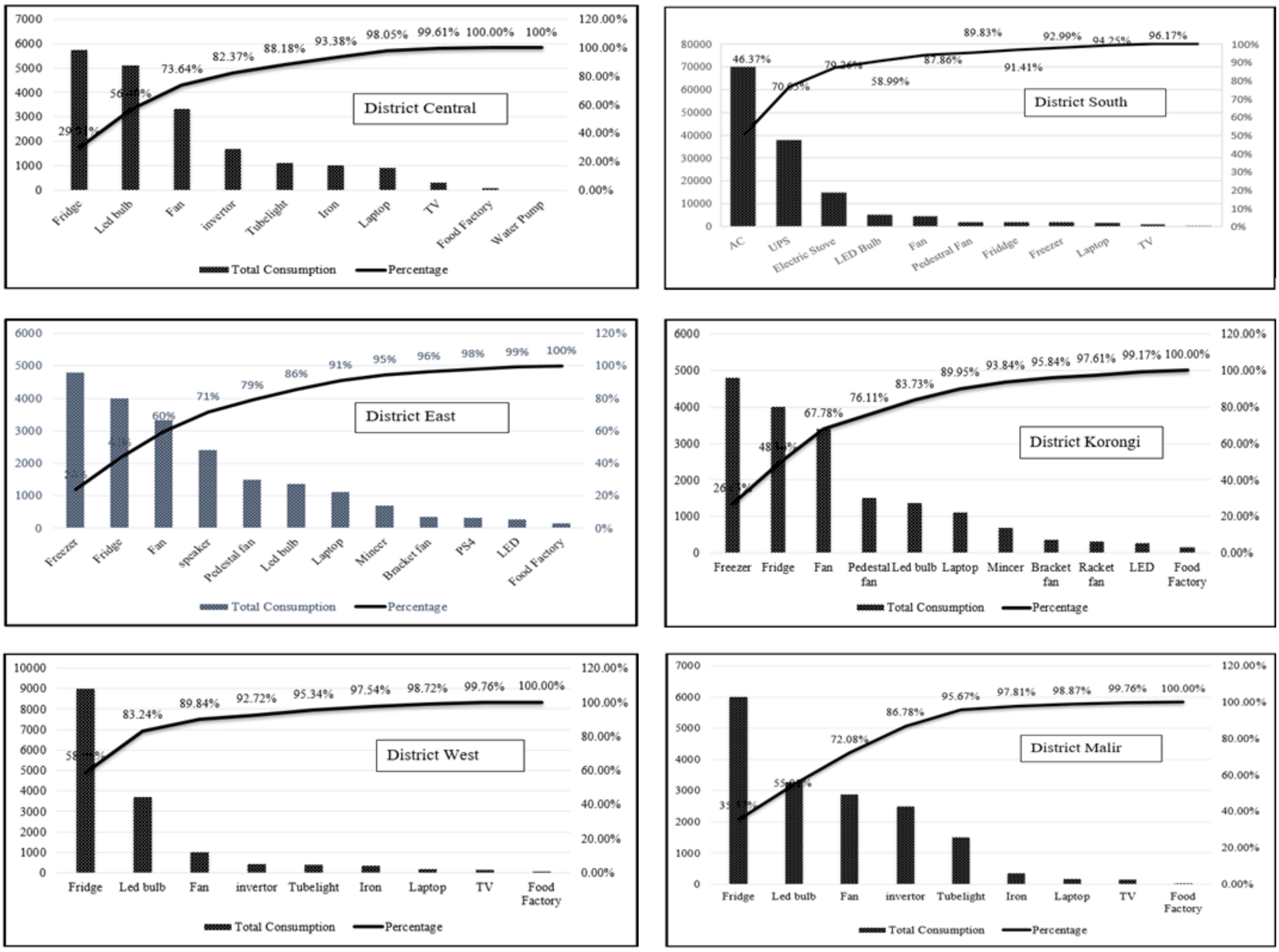


Fig. 5. Pareto Charts For Energy Consumption Of Different Districts Of Karachi

6.5 Type of Construction and Load Infiltrations

6.5.1 Construction material

The data collected about the construction material of houses articulates that about 56.1% of the houses were built of high mass construction with no proper insulation system. In contrast, 33.3% of houses were built of lightweight construction with no proper insulation.

6.5.2 Building service ventilation

Natural ventilation is a process of fresh air entering the building via doors, windows, or another opening. In contrast, mechanical ventilation is the air that is drawn into the building (typically fans). For almost 90% of the houses, VAV-single duct ventilation was the source of ventilation.

7. Energy Efficiency Improvement Opportunities and Measures

To form the improvement opportunities for any particular house, first, the results of the conducted fifty-eight houses were viewed. The general trend of responses was carefully observed before any improvement measures were developed. The three steps-based methodology was used to determine the improvement opportunities for energy-efficient housing: (1) Analysis of Responses. (2) Determination of deficiency in houses. (3) Suggestions for improvement.

After the deficiencies were noted by conducting audits of houses and thorough interviews of the respondents, some improvement measures and recommendations were suggested for each house. Table 3 summarizes several improvement measures that can be useful for improving the energy efficiency of the residential units.

8. Conformance of Improvement Measures Through Thermal Imaging

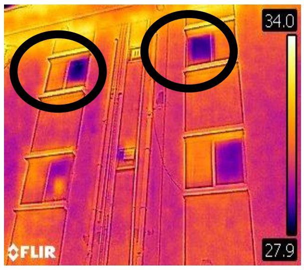
Thermal imaging cameras convert thermal energy (heat) into visible light. This energy was detected by the infrared camera and displayed as images. These are the snapshots from a thermal imaging camera for obtaining the surface temperature of a building. The purple color shows the area with low temperature, and the yellow shade shows relatively high heat absorbance.

For thermal imaging of building facades, as it is visible that the surface heat absorption is very high, the use of heat-resistant paint can help decrease the heat absorption of the surface. Hence, the recommendation is to use heat-resistant paints that can reflect solar heat, as shown in Fig. 6(a). In this Fig. 6(b), the difference in relative surface temperature confirms that the U-value of the single-glazed window is high, so renovating the window frame can help to increase the R-value of the surface; therefore; it is recommended that windows from single glazing to double-glazing will show half the conduction of heat. Where the window frame is in poor condition should be scheduled for renovation. In Fig. 6(c), the high surface temperature of the wall indicates a poor insulation system in the wall, so the internal void and space of the walls must be filled so that infiltration cannot occur. In Fig. 6(d), the high surface heat absorption of the door material indicates that doors should be maintained or replaced, so a badly deteriorated door should be replaced with a new one with energy-efficient insulation and maintenance-free framing materials.

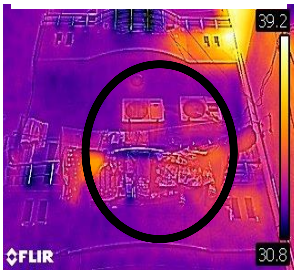
9. Conclusions and Recommendations

The study gathered essential information regarding the building envelope of different houses in Karachi, present in six different districts of Karachi. After getting the information, data were analyzed statistically to present the data in graphical form. R-values for each district have been evaluated, and mapping of R-values for Walls, windows, doors, and roofs has also been done. It is concluded that the R-values of doors for each district are relatively high as compared to other elements, which generally lie close to each other, while the R-values of windows were found to be low in each district. Another opportunity highlighted during the audit was related to 'Windows with cracking.' It was suggested to provide windows of single to double glazing to reduce R-values along with periodical maintenance of the window's frame. It was confirmed by the thermal imaging of the structures that windows with single to double glazing will result in lesser R-values. The possible deficiencies in energy efficiency, improvement opportunities, and improvement measures have also been suggested.

(A) Thermal Imaging Of Building Facade



(B) Thermal Imaging Of Windows



(c) Thermal imaging of Balcony Area

(D) Thermal Imaging Of Door

Fig. 6. Thermal Imaging

Future studies should expand the sample size by including more houses from different districts of Karachi to enhance the reliability and generalizability of the findings. A larger and more diverse dataset would also help in developing a comprehensive database that architects and builders can utilize when designing future homes, considering the current energy efficiency standards.

Additionally, future research should explore and validate energy improvement measures using various advanced techniques beyond thermal imaging. This will increase confidence in the recommended solutions and ensure they are effective across different building types and conditions. Further studies should also investigate the long-term impact of implementing these measures, particularly for elements like windows with single to double glazing, to better understand their effectiveness in reducing R-values and improving overall energy efficiency.

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Table 3

Audit-based energy efficiency improvement opportunities

S. No.	Area of concern	Deficiencies	Improvement Opportunity (% of Houses/ Housing Units)	Improvement Measures
1	Lighting	Low power density due to old tube lights.	61.4	Routine cleaning maintenance of light fixtures, changing a fluorescent tubes to LED tubes, and more energy saving.
2		Complex and ineffective lighting controls.	31.6	Installing occupant sensors to control lights
3	Cooling (fans/ACs)	Houses have old fans running 24/7 without being effective.	56.1	Change the motor of the fan if it is too old, Adjust the height of fans according to the operating height.
4		Excessive running of the air conditioning	67	Routinely replace or clean its filters. Minimize air leakage by fitting the room. Asphalt Roofing. Place AC outer unit in a shady spot to reduce energy consumption.
5	Windows	Cracked windows, warped or rotten wood frames	85.7	Renovation of window frames.
6		High heat infiltrations and conduction values in windows	57	Change windows glass from single glazing to double glazing to reduce the conduction of heat.
7	Doors	Cracked doors, warped or rotten wood frames	72	A badly deteriorated door should be replaced with a new one with energy-efficient insulation and maintenance-free framing materials.
8		Poor quality doors having fewer R values	49.1	
9	Roofs	Leaked Roofs	70	Seal all leaks and cracks in the roof.
10		Roofing materials having high heat infiltrations and conduction	65	Use asphalt paste and paint which can reflect solar heat.
11	Walls	Non-insulated walls	55.4	Internal voids and the space of walls should be filled to avoid infiltration.
12	Orientation	Rooms are directly heated by the sun and have to use AC throughout the day	65.5	Use heat-resistant paints that can reflect solar heat.
13		Inefficient use of daylight	35.7	Attach low-cost solutions or change the orientation of windows.

11. Reference

[1] IEA, “Renewables 2021 – Analysis”, IEA, Dec. 2021. https://www.iea.org/reports/renewables-2021

[2] UNSTATS, “The Sustainable Development Goals Report 2021”, Department of Economic and Social Affairs, United Nations, 2021 https://unstats.un.org/sdgs/report/2021

[3] World Bank Group, “World Bank Climate Change Knowledge Portal”, Accessed: Sep. 30, 2024. [Online]. Available: https://climateknowledgeportal.worldbank.org/country/pakistan/climate-data-historical

[4] V. Butala and P. Novak, “Energy consumption and potential energy savings in old school buildings”, Energy and Buildings, vol. 29, no. 3, pp. 241–246, Jan. 1999, doi: https://doi.org/10.1016/s0378-7788(98)00062-0.

[5] European Commission. The European green building program energy audit guidelines. 2005.

[6] F. Ascione, F. de Rossi, and G. P. Vanoli, “Energy retrofit of historical buildings: theoretical and experimental investigations for the modelling of reliable performance scenarios”, Energy and Buildings, vol. 43, no. 8, pp. 1925–1936, Aug. 2011, doi: https://doi.org/10.1016/j.enbuild.2011.03.040.

[7] “Energy Heritage A guide to improving energy efficiency in traditional and historic homes.” Accessed: Sep. 30, 2024. [Online]. Available: https://www.fuelpovertylibrary.info/sites/default/files/EAGA41%20%282008%29%20GUIDANCE%20Energy%20Heritage%20-%20A%20guide%20to%20improving%20energy%20efficiency%20in%20traditional%20and%20historic%20buildings.pdf

[8] BCP Energy Provisions 2011 “Building Code of Pakistan Energy Provisions”, Pakistan Engineering Council (PEC) 2011. https://www.pec.org.pk/wp-content/uploads/2023/11/BCP-Energy-Provisions-2011.pdf

[9] ISO 52000-1:2017, “Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures”, International Organization for Standardization (ISO), Geneva, Switzerland, 2017, https://www.iso.org/standard/65601.html.

[10] ISO 6946:2017, “Building Components and Building Elements. Thermal Resistance and Thermal Transmittance. Calculation Methods”, International Organization for Standardization (ISO), Geneva, Switzerland, 2017. https://www.iso.org/standard/65708.html

[11] ISO 10456:2007 “Building materials and products -Hygrothermal Properties-Tabulated design values and procedures for determining declared and designed thermal values”, International Organization for Standardization (ISO), Geneva, Switzerland, 2007 https://www.iso.org/standard/40966.html

[12] Pakistan Bureau of Statistics -PBS, “Housing Units by Number of Rooms and Type”, Accessed: May 2021. [Online]. Available https://www.pbs.gov.pk/node/107