

## Review

# A Critical Review of Energy Consumption in Libyan Residential Buildings: Addressing Knowledge Gaps in Design, Materials, Construction Practices, and Occupant Behaviour

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## Abstract

Residential buildings have been responsible for the increasing percentage of final energy consumption in Libya, which is mainly due to the cooling of buildings in hot arid climatic conditions, but there is still a constant discrepancy between the projected and actual energy performance. This review critically synthesises the available literature to find out the knowledge gaps underlying residential energy overconsumption, and it concentrates on the systemic loss of contact between the architectural design intent, material and envelope performance, construction execution, and occupant behaviour throughout the building lifecycle. The literature employed to complete the study is peer-reviewed journals, conference papers, and technical reports concerning Libya and similar hot-arid and Mediterranean settings, which are arranged into four overlapping areas, namely, design practices, materials and construction quality, regulatory enforcement, and occupant energy use patterns. The results show that the cumulative and reinforcing inefficiencies are caused by the lack of adoption of climate-sensitive designs, inattentive view of thermal material properties, ineffective control over the quality of construction, ineffective regulation enforcement, and neglect of the occupant behaviour in performance analysis, which contribute to the increase in cooling loads and expansion of the performance gap. Building a coherent conceptual structure using disjointed evidence, the review offers recommendations that can be applied in practice by architects, engineers, policymakers and housing stakeholders, highlighting the importance of lifecycle-based design methodologies, improved governance and performance energy strategies with behavioural elements in Libyan residential buildings.

**Keywords:** residential buildings; energy consumption; knowledge gap; building design; construction practices; occupant behaviour; Libya

Academic Editor: Chi Yan Tso

Received: 4 June 2026

Revised: 30 June 2026

Accepted: 3 July 2026

Published: 15 July 2026

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## 1. Introduction

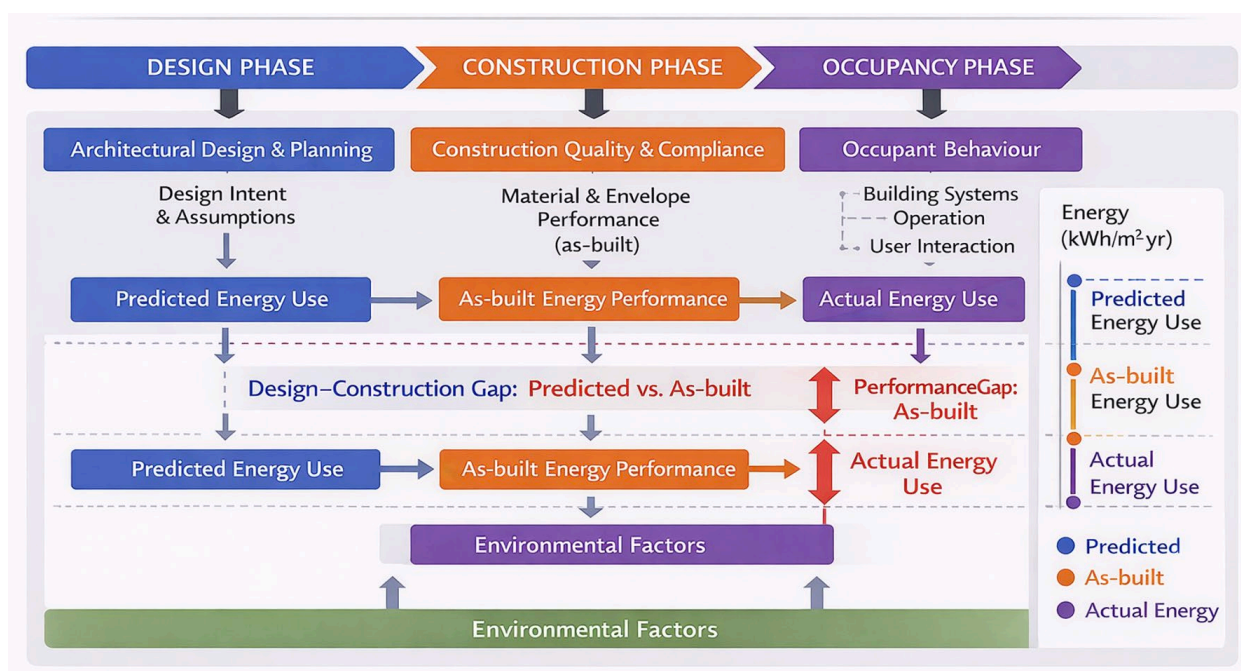
Housing units are one of the most significant fields in energy consumption and climate change mitigation in the world. Globally, the residential industry consumes a significant percentage of final energy demand, mainly through space cooling and heating, as well as the use of appliances, with the forecasts showing a rise in residential energy consumption attributed to urbanisation, population growth and comfort expectations [1–5]. Enhancing the energy efficiency of residential buildings is thus paramount to climate tar-

gets, greenhouse gas emission reduction, and pressure on the national systems of energy, specifically in areas with extreme climatic conditions [6,7].

The consumption patterns of electric energy in hot-arid areas as well as Mediterranean areas demonstrate that there is a high reliance on mechanical cooling, which leads to high peak loads and high electric demand [8–10]. The ambient temperatures and cooling periods in these climates are high, the sun is very hot and the cooling periods are long, making the residential energy consumption very heavy, particularly where passive designs and thermally efficient construction technologies are not effectively utilised [11,12]. Research in similar climatic conditions already shows that buildings constructed in a non-climate-responsive way are also characterised by significantly higher cooling loads and greater variances between the predicted and actual energy performance [13,14].

In the global context, Libya is an especially serious case. National electricity demand is predominantly focused on the residential sector, which is mainly fuelled by the cooling demand and aggravated by the fast growth of housing and lack of regulations to enforce energy efficiency [1,15,16]. Current housing stock is extensively typified by traditional modes of construction, standardised models of designs, and choice of materials, which in many cases is dependent on availability and cost, rather than thermal functionality [16,17]. Consequently, residential energy is steadily on the increase, and it puts a toll on the national energy grid and further complicates the issue of supply reliability [18,19].

There is a growing body of literature implying that these consequences cannot be attributed to climatic severity or energy supply limitations only. Rather, they are indicative of a larger and more systemic gap in expert knowledge throughout the residential building lifecycle, along with architectural design, choice of material, construction operation, regulatory execution and occupant behaviour [3,9,13]. Although these dimensions have been considered separately in the literature, there is still no comprehensive knowledge on how the failure at various points of the chain reacts to create an actual residential energy performance. This interaction is conceptualised in Figure 1, which shows how design intent, material performance, construction quality and occupant behaviour interact to affect residential energy consumption and cause the performance gap, which is observed.



**Figure 1.** Conceptual framework of residential energy performance across the building lifecycle. Note: The figure shows the relationship of four stages of the lifecycle—architectural design, selec-

tion of materials and building envelopes, construction quality, behaviour of occupants, how these are impacted by the enforcement of regulations, how they influence energy consumption and the resultant performance gap in hot and arid regions. Influence is indicated by arrows and coupling effects by overlapping areas in the figure. Empirical and review-based research further suggests that occupant behaviour is a highly critical mediating factor, which usually increases inefficiency inherent at the design and construction phases through intensive air-conditioning utilisation, window operation behaviour, and lack of energy consciousness [3,9].

The real performance gap can be understood by describing interactions, not just by identifying separate factors or constraints. Take poorly designed wall elements along with construction materials of very low thermal resistivity and poor construction practice. A wall made of hollow concrete blocks has an R-value (thermal resistance) of approx. 0.3–0.5 m<sup>2</sup>·K/W. This is already low compared to the generally accepted range of 1.5–2.5 m<sup>2</sup>·K/W for hot-arid climates [20,21].

When a wall has construction defects such as the absence of insulation or the presence of a concrete column, both of which are typical for Libyan houses [22,23], the effective R-value at the thermal bridge might be lower than 0.1 m<sup>2</sup>·K/W. In fact, heat flow through the thermal bridge would be three to five times greater than the standard wall construction would suggest. As a result, the occupants suffer from persistent overheating and would adjust the thermostat in vain to try to remedy the situation. This practice, in turn, leads to a normalisation of air-conditioning use at uncomfortably low settings (18–20 °C) and sustained use [1,15].

The interaction of poor-quality materials, poor-quality construction, and the use of air-conditioning results in an exponential increase in the demand for cooling energy. The same effect is generated when a building is poorly oriented with respect to the sun and, in addition, is constructed without the provision for external shading. If the windows are left closed and no means of shading is used, the heat in the building due to solar gain cannot escape except through the air-conditioning system [9,13].

These complex interactions illustrate why, for example, replacing an old appliance with a new energy-efficient one, or adding insulation to one wall, will not energise the expected energy savings: there will still be other supporting factors that will continue to keep the high energy demand trajectory.

Meanwhile, ineffective enforcement of regulations and informal methods of construction decrease the efficiency of current energy regulations, permitting the design-stage assumptions to be widely different from as-built and in-use conditions [24–26]. Table 1 gives a synthesis of these drivers and their applicability to the Libyan context and summarises the main determinants of residential energy consumption determined in the world literature, and relates them to the observed conditions in Libya.

Recent studies have focused on why an energy performance gap exists in hot-arid regions. Albarssi et al. [27] have provided the most expansive review of residential retrofitting opportunities in Libya and the surrounding Mediterranean regions. They have concluded that building envelope upgrades have the most potential to reduce cooling energy demand; however, the local supply chains for high-performance materials are lacking and a constraint.

According to Alafya and Maka [28], energy performance gaps of 35–55% in residential energy consumption in Libya can be attributed to gaps in the building envelope and cooling (occupant) behaviours. Aoul et al. [22] focused on the construction side and documented the presence of thermal defects in the majority of residential buildings in the UAE (which is contextually similar to their area of study). They noted that the most prevalent defects were thermal bridges and discontinuities in insulation.

The elimination of energy subsidies in oil-rich countries (including Libya) would remove the artificial restraint on energy prices. This would in turn promote energy savings, as noted by the IEA [29] and ElShazly [30]. It is clear from the findings that the gaps in the performance of residential buildings in Libya are the result of a combination of poor design, poor choice of materials, substandard construction, poor governance, and poor behavioural control. This is the framework that this review adopts.

**Table 1.** Key drivers of residential energy consumption identified in global literature and their relevance to the Libyan residential context.

| Driver Category                       | Key Aspects Identified in Global Literature                                                                                                      | Evidence from Prior Studies                                                                                             | Relevance to Libyan Residential Buildings                                                                                                              |
|---------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| Architectural design                  | Building orientation, form, compactness, shading, and use of passive cooling strategies strongly influence cooling loads and peak demand [27,30] | Climate-responsive design shown to reduce cooling energy significantly in hot-arid and Mediterranean regions [27,31–33] | Predominant use of standardised layouts with limited passive design integration contributes to elevated cooling demand and performance gaps [27,32,33] |
| Materials and envelope performance    | Thermal conductivity, heat capacity, insulation levels, and glazing characteristics affect heat gains and indoor comfort [20,21]                 | Envelope optimisation reduces cooling loads and improves thermal stability [20,21]                                      | Widespread use of conventional wall and roof materials with limited thermal optimisation increases heat gains and cooling energy use [20,21,32]        |
| Construction quality                  | Workmanship quality, detailing, and continuity of insulation influence air leakage and thermal bridges [22,23,34,35]                             | Poor execution widens the gap between designed and actual performance [22,23,35]                                        | Frequent deviations between design intent and as-built conditions reduce envelope effectiveness in practice [22,23]                                    |
| Regulatory frameworks and enforcement | Energy codes and standards are effective only when consistently enforced [29,30]                                                                 | Weak enforcement undermines expected energy savings [29,30]                                                             | Existing regulations are inconsistently applied, particularly in informal and small-scale residential construction [29,32]                             |
| Occupant behaviour                    | Cooling setpoints, air-conditioning usage patterns, window operation, and appliance use strongly affect actual energy consumption [36,37]        | Behavioural factors can outweigh design-stage efficiency gains [28,36,37]                                               | High reliance on air-conditioning, limited energy awareness, and culturally driven usage patterns amplify cooling demand [28,36,37]                    |
| Socio-economic factors                | Income level, household size, lifestyle, and energy pricing influence consumption behaviour [28,30,36]                                           | Socio-economic context shapes energy use intensity [28,30,36]                                                           | Large household sizes and subsidised electricity tariffs reduce incentives for energy-efficient behaviour [28,30]                                      |
| Energy modelling assumptions          | Simplified or generic occupancy and usage assumptions lead to inaccurate predictions [32,34,36]                                                  | Modelled energy use often underestimates real consumption [3,34,36]                                                     | Limited use of performance-based modelling exacerbates discrepancies between predicted and observed energy use [32,34]                                 |
| Lifecycle integration                 | Fragmented consideration of design, construction, and use stages limits holistic performance assessment [34,38]                                  | Integrated lifecycle approaches reduce performance gaps [34,38]                                                         | Lack of coordination across lifecycle stages reinforces cumulative inefficiencies [34,38]                                                              |

Although it is possible to find the individual pieces of evidence, there is still no evidence of a systematic review that can bring together these interrelated pieces of knowledge gaps that are found in the Libyan residential sector. This deficiency in synthesis restricts the capacity of policymakers, designers and housing stakeholders to develop

effective policymaking within the lifecycle-based interventions that target root causes instead of symptoms of energy inefficiency.

This review seeks to fulfill two aims. First, from an analytical standpoint, I will review the existing literature to identify and assemble the existing research on Libya's residential energy use overconsumption in four interrelated areas (or domains) of the lifecycle. These include architectural design and construction, building materials and envelopes, construction and building quality and adherence to regulations, and user behaviour and energy consumption. This will also have a practical aim. From this analysis, I will generate systems-based, contextual, and climate-responsive recommendations for Libyan architects, engineers, and construction and policy stakeholders.

There are three main reasons this review is an important contribution to the existing literature. First, this review will be the first complete lifecycle study of residential energy use in Libya. Other studies are more fragmented and concentrate on individual areas (or domains) of the lifecycle. In addition, this review will examine existing local and regional Libyan research and compare it to the research and findings of other regions of the world, particularly those of comparable climates, and stipulate conditions under which the findings may be applicable. Finally, this review offers a working example and framework of what may be used to develop further research, policies, and professional practice and education in Libya and in other regions and countries of similar hot and arid climates.

## 2. Methodology of the Critical Review

### 2.1. Review Design and Scope

This paper incorporates a form of critical narrative review [39]. This type of review is suitable for a situation where there are many different types of literature related to emerging research and the main objective is related to the integration of concepts. This type of review is more flexible than a systematic review and allows integration of different types of evidence, such as empirical research and advocacy papers, and allows the reviewer to be flexible and interpret evidence to identify patterns and gaps. This is suitable for the situation of Libyan residential energy where there are a limited number of Libyan-specific studies. This type of review allows the inclusion of evidence from other climates and institutional environments.

### 2.2. Literature Search Strategy

Literature was obtained by searching three major databases: Scopus, Web of Science and Google Scholar. The primary search terms were/are: residential energy consumption, building energy performance gap, hot-arid climate buildings, Libya residential buildings, building envelope thermal performance, occupant behaviour energy, construction quality thermal, and Mediterranean climate energy efficiency. Searches were performed in English and covered the period from 2000 to 2025 with emphasis on the period from 2015 to 2025. Relevant papers were located by checking the references of the selected papers (backward and forward citation tracking).

### 2.3. Inclusion and Exclusion Criteria

Studies were included when they: (i) dealt with one or more of the four review dimensions regarding the energy performance of residential buildings; (ii) took place in Libya, North Africa, the Middle East, or other hot-arid and Mediterranean region/like places; and (iii) were published in peer-reviewed journals, conference proceedings, or reputable technical reports. Studies were excluded when they dealt with non-residential buildings only, dealt with climates not comparable to Libya, and/or could not be obtained

in full text. In total, 43 sources were cited in this review, and 30 additional references were added to address the comments of the reviewers.

## 2.4. Organisation of the Review

The literature reviewed will be grouped into four themes corresponding to the different stages of the lifecycle of a residential building: (i) energy modelling and architectural design; (ii) building materials and envelope; (iii) construction quality and enforcement of regulations; (iv) behaviour and patterns of energy use. The coupled and integrated effects of the domains will be analysed and explained (see Figure 2). The model is based on Libyan residential buildings as discussed in Section 3.

Knowledge Gaps in Libyan Residential Buildings: Energy Consumption | PRISMA-adapted Critical Narrative Review

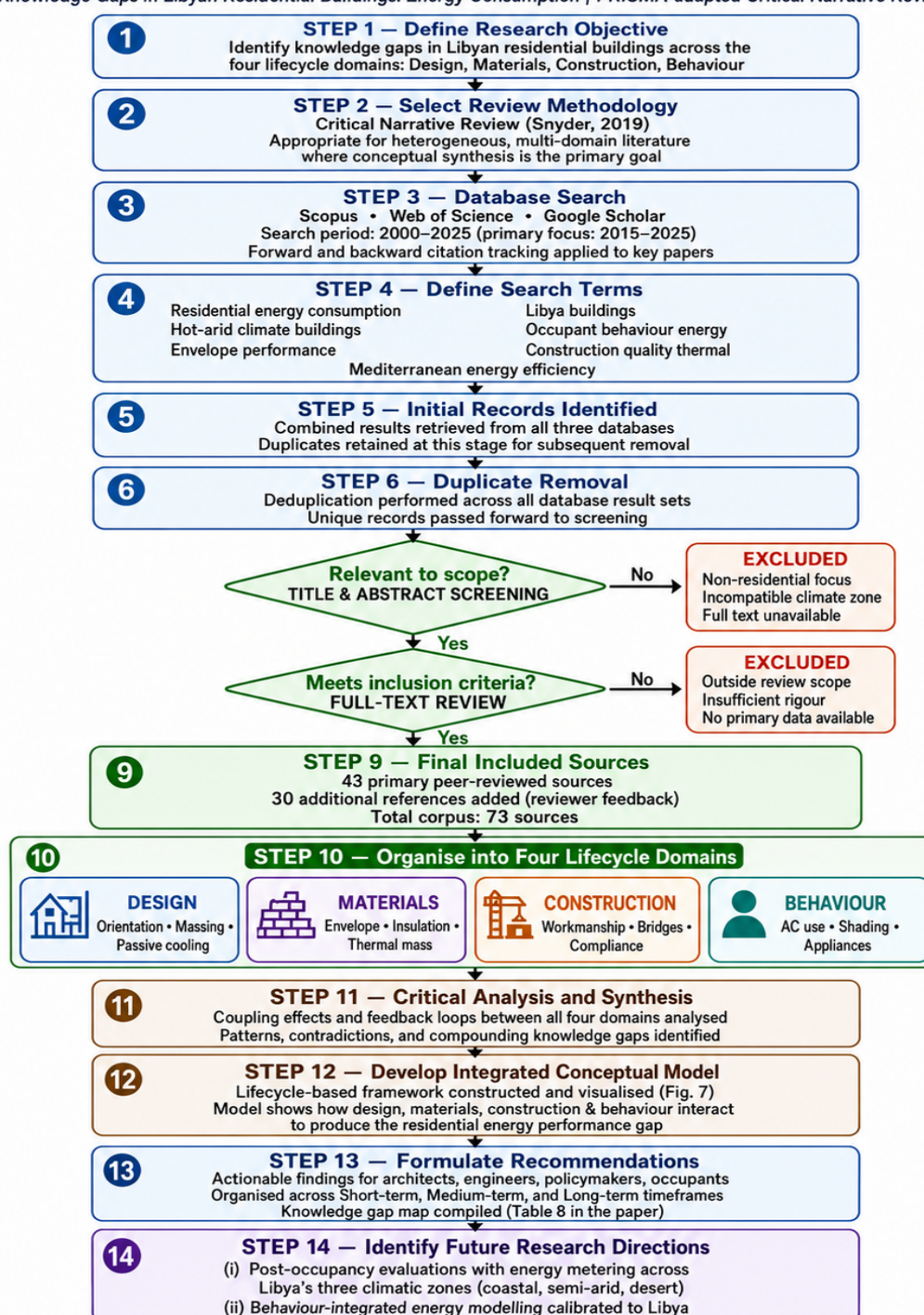


Figure 2. Methodology flow chart of the critical review.

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist in generating figures based on detailed instructions provided by the authors. The tool was used solely for creating graphical illustrations. The authors reviewed and edited all outputs and take full responsibility for the content of this publication.

### 3. Context of Residential Buildings in Libya

#### 3.1. Climatic and Environmental Conditions

**Climatic variation.** Libya includes three separate climatic zones. The coastal zone has hot and dry summer months and milder winter months. There are more extreme temperature changes from day to night in the zone that is further from the coast. The southern zone of Libya has extreme temperature ranges for the day and very low humidity. There are specifics for how these different climatic zones of Libya impact the demand for energy and these specific regional analyses can be found in the previous section.

**Cooling demand.** In all three climatic zones of Libya, the largest demand for electricity comes in the summer months when the majority of the population requires mechanical air-conditioning to remain comfortable. The concentration of electrical demand for cooling on a seasonal basis causes severe problems with the supply of electricity and frequent interruptions to service.

**Climatic drivers of envelope.** In the hot, arid and Mediterranean zone, envelope heat gains are the main way that external heat enters buildings. In Libya, the combination of high external temperatures and very few passive cooling designs means that there is a very real risk of indoor overheating for much of the year.

**Conventional construction.** The combination of high absorptivity finishes, poorly insulated walls, and highly conductive roofs means that the Libyan housing stock suffers the greatest reliance on mechanical cooling systems. These interactive climatic conditions touch directly on the gaps in construction knowledge that are examined in further sections.

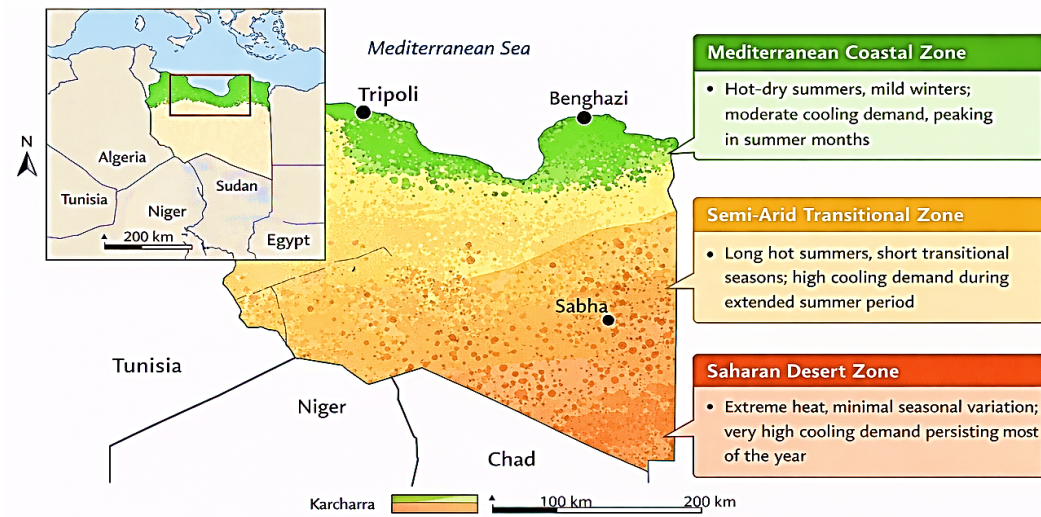
There are significant differences in the energy implications of the three climate zones that require individual attention. The coastal Mediterranean climate (e.g., Tripoli and Benghazi) has hot, moderate summer (27–32 °C) temperatures and high summer humidity. The combination of high humidity and hot summer temperatures limits the passive cooling potential and creates a continuous demand for active mechanical cooling [8,15]. Here, the placement of windows and the design of building orientation are the key elements of design.

In the semi-arid transitional climate (e.g., Misurata and part of Jebel Nafusa), the daytime temperatures can reach over 38 °C, while the night temperatures can fall to the low 20s. These conditions create the potential to use night ventilation and the passive-thermal-mass building system effectively to alleviate discomfort [11,12].

In the Saharan desert climate (e.g., Sebha and Ghadames), the extreme daytime temperatures can reach over 42 °C, and the relative humidity is very low. Here, the reliance on mechanical cooling is essential, and due to the highly absorbent nature of the building materials, the impact of design on energy reduction for cooling is substantial [16,17].

Having these distinctions is important for policymakers. Without regional differences in thermal performance, one energy policy for Libya will most likely fail.

Figure 3 summarises the climatic regions of Libya and the cooling demand trends that are normally associated with the regions.



**Figure 3.** Climatic zones of Libya and residential cooling demand characteristics (Source: Author's own elaboration).

The spatial representation of the key climatic regions of Libya, the Mediterranean coastal, semi-arid transitional, and Saharan desert zones, and the patterns of residential cooling demand related to them, demonstrating the growing level and the length of cooling demand by the north–south direction. On balance, the climatic conditions in Libya create the preconditions of the risks of energy overconsumption in the residential sector, and the use of climate-responsive design and thermally efficient building practices becomes paramount in the reduction of the energy performance gap.

### 3.2. Residential Building Typologies

The Libyan residential environment consists of three prevailing housing types, which are detached single-family houses, multi-storey apartment blocks, and informal or self-built housing units. The most widespread type of detached house is all that is found in the suburban and peri-urban areas, which feature large plot sizes and horizontal growth trends [40,41]. Such buildings are likely to have masonry walls, reinforced-concrete frames and somewhat large, exposed surfaces, which increase the heat gain without appropriate thermal optimisation [16,17]. Lower envelope-to-floor-area ratios in apartment buildings (common to dense urban centres like Tripoli and Benghazi) can lower cooling loads, although they still have to cope with other issues, including insufficient ventilation, limited shading, and poor construction quality [40,41].

Since the 1990s, informal housing has grown tremendously because of the high rate of population growth, economic instability and lack of proper regulation of housing. Such houses are often built with the help of the available low-cost resources, and little attention is paid to the energy-saving recommendations or climatic conditions [24,25]. Informal construction proliferation has helped to introduce large variability in thermal performance in the housing stock, which has strengthened heterogeneity in residential energy consumption patterns.

Traditionally, the Libyan residential design followed the vernacular, climate-adapted architecture in the shape of thick earthen walls, internal courtyards, compact massing and strategic shading to modern reinforced-concrete construction due to post-1970s urbanisation and the state housing programmes in Libya [14,41]. This shift substituted passive techniques with standard architectural patterns that did not fit the local climate very well. Similar happenings have been recorded in other hot-arid and Mediterranean areas, where social-economic changes and modernisation have undermined the traditional norms of

climate-sensitive principles [42,43]. Therefore, the modern day Libyan residential buildings tend to exhibit a lack of thermal protection, insufficient shading and poor envelope performance, which adds to the high cooling-energy demand.

Table 2 provides a systematic review of the key types of residential buildings of Libya, construction dates and associated climatic exposures, which will serve as the foundation of future analysis of the gaps in knowledge about design, material and construction.

**Table 2.** Libyan residential building typologies, dominant construction periods, and climatic exposure.

| Residential Typology                | Dominant Construction Period        | Typical Structural and Envelope Characteristics                                                                                                        | Climatic Exposure                                    | Implications for Cooling Energy Demand                                                                                                                             |
|-------------------------------------|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Detached single-family houses       | 1970s–present                       | Reinforced concrete frames; masonry or hollow concrete block walls; flat concrete roofs; limited insulation; large exposed envelope area [20,21,28,32] | Coastal, semi-arid, and desert regions [28,32]       | High solar and conductive heat gains due to large surface-to-volume ratio and weak thermal protection, resulting in elevated cooling loads [1,16,17,20,21,28,32]   |
| Urban apartment buildings           | 1980s–present                       | Multi-storey concrete structures; shared walls between units; moderate glazing; limited shading; inconsistent ventilation design [29,31,32,44]         | Predominantly coastal and urban centres [28,32]      | Reduced envelope exposure compared to detached houses but compromised by poor ventilation and shading, leading to moderate-to-high cooling demand [29,31,40,41,44] |
| Informal/self-built housing         | 1990s–present                       | Non-standard construction; variable material quality; minimal compliance with design or energy guidelines; limited insulation [22,29,32]               | Semi-arid and desert regions [28,32]                 | Highly variable thermal performance; frequent overheating and excessive reliance on mechanical cooling [22,24–26,29,32]                                            |
| Traditional courtyard-based housing | Pre-1970s (limited remaining stock) | Thick masonry or earthen walls; compact massing; internal courtyards; passive shading and ventilation features [31,45,46]                              | Mainly desert and historic urban areas [31,32,45,46] | Lower cooling demand due to passive climate-responsive design, though often compromised by later modifications [31,41,43,45,46]                                    |
| Public or mass housing schemes      | 1970s–1990s                         | Standardised design templates; repetitive layouts; concrete construction; limited climatic adaptation [29,31,32]                                       | Coastal and semi-arid regions [28,32]                | Uniform designs insufficiently adapted to local climate, resulting in higher-than-expected cooling energy use [17,20,29,31,32,40]                                  |

## 4. Knowledge Gaps in Building Design

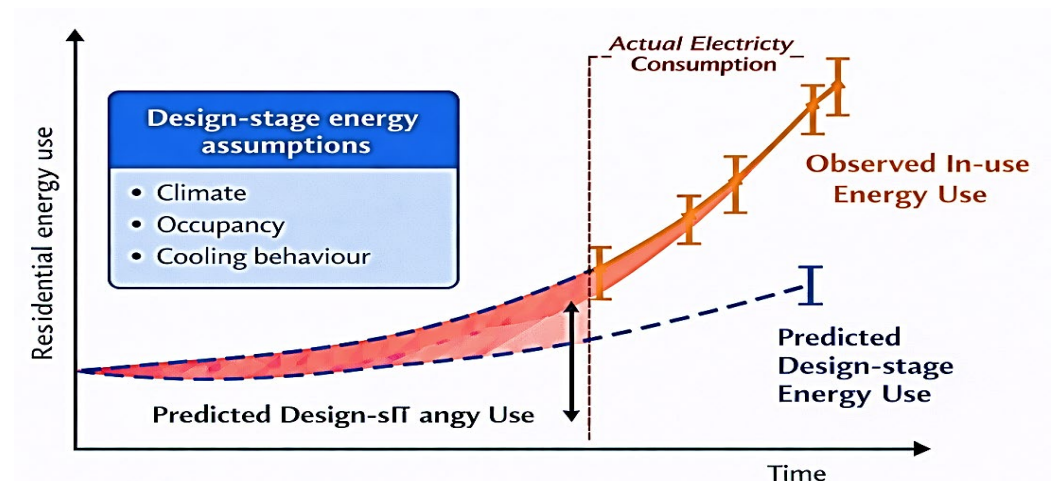
### 4.1. Architectural Design Practices

The architectural design has a central role in establishing residential energy performance, especially in hot-arid and Mediterranean climates in which the cooling demand is the leading annual energy consumption. International studies have shown that the orientation of the building, spatial planning and massing can have a strong impact on the level of solar exposure, heat gain, and thermal comfort in the building [2,11,12,47,48]. Compact massing, maximum orientation, controlled glazing ratios and effective shading approaches in climate-responsive residential designs could significantly decrease cooling loads and peak electricity demand [9,10].

The practices of residential architecture design, however, in the Libyan setting, are mostly standardised and not adapted to climatic conditions. Isolated buildings and apartments often lack consideration of the direction they face in the sun or the direction of the moving wind, and the space planning lacks any thought to thermal performance [17,40]. Exposures, the number of shading appliances, and the depth of the buildings are often small, and this exposes them to direct exposure to solar gains over the prolonged seasons of summer [16,41]. Such design features are in sharp contrast with the traditional Libyan and regional vernacular housing forms, which traditionally used compact form, used courtyards, thick walls, and shaded circulation spaces to establish a moderate indoor environment [41,42].

Use of passive design measures such as natural ventilation, thermal mass optimisation, external shading, and cooling by way of the courtyard is also significantly minimal in modern Libyan housing. Despite a well-known effectiveness of such strategies in hot-arid environments [11,12,49], their implementation in the modern residential design is rather occasional and not based on a systematic approach, but rather, on the individual experience of the designers. This lack of connection indicates a larger gap in knowledge, where the principles of climate responsiveness are recognised theoretically and not reflected in general housing design.

Consequently, architectural design choices undertaken during the early phases of the project tend to commit high cooling demand paths, which, despite technological interventions made later, cannot be reduced entirely. This is an immediate factor toward the discrepancy between projected and actual energy performance as conceptually shown in Figure 4, which demonstrates the overall effect of design-stage assumptions on residential energy use in practice.



**Figure 4.** Design-stage energy assumptions versus observed residential energy use (Source: Author's own elaboration).

In theory, the conceptual model of the difference between the energy performance at the design phase, determined under simplified assumptions about climate, occupancy and cooling behaviour and the increased amounts of electricity consumed during building operation, demonstrates the subsequent residential energy performance discrepancy under hot-arid conditions.

#### 4.2. Energy Modelling and Design Assumptions

In addition to physical form, there is a huge gap in knowledge of energy modelling practices, which govern the residential design decisions. It is demonstrated in the international literature that the performance-based design methods, based on the dynamic sim-

ulation tools and climate-specific occupancy models, can vastly enhance the realism of energy predictions, as well as assist in informative design optimisation [9,10,50,51]. Nevertheless, this has not been exploited in the residential property market in Libya.

The design processes in Libya are often based on generic design templates and rule-of-thumb assumptions, not making use of specific energy modelling, which is balanced with local climatic and behavioural conditions [1,17]. Occupancy schedules, cooling set-points, appliance use, and ventilation behaviour are simplified assumptions, which are frequently made, even though it has been firmly established that such parameters differ considerably across socio-economic and cultural contexts [3,9,52]. Therefore, the estimated energy performance will not give the true electricity consumption, especially during peak periods in the summer season.

The lack of a strong performance-based design culture is further enhanced by the minimal regulations on energy simulation and post-design verification. Compared to jurisdictions in which energy performance modelling has been adopted in the process of approval, in Libyan residential projects, a systematic energy assessment is rarely done before construction [24]. Such an institutional gap gives the design assumptions the opportunity to not be tested, further supporting differences between simulated and operational performance.

Table 3 compiles these problems by comparing climate-responsive design strategies, which are highly suggested in the literature, with practises commonly applied in Libyan housing. The comparison highlights the manner in which inadequacies in knowledge of design and practices of modelling can be converted into scrutinising cooling needs and their enduring energy wastage.

**Table 3.** Comparison of climate-responsive design strategies versus commonly applied practices in Libyan housing.

| Design Dimension         | Climate-Responsive Strategies (Literature)                                         | Common Practices in Libyan Housing                         | Energy Performance Implications                          |
|--------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------|----------------------------------------------------------|
| Building orientation     | Optimised orientation to minimise solar gains and capture prevailing winds [31,46] | Orientation driven by plot geometry or aesthetics [28,32]  | Increased solar heat gains and cooling demand [31,46]    |
| Spatial layout & massing | Compact forms, reduced envelope exposure, internal courtyards [31,45,46]           | Dispersed layouts with large, exposed façades [28,32]      | Higher conductive and radiative heat transfer [31,45,46] |
| Shading strategies       | External shading devices, overhangs, and recessed openings [31,33,53]              | Limited or decorative shading elements [28,32,33]          | Elevated indoor temperatures during summer [31,33]       |
| Natural ventilation      | Cross-ventilation and airflow-oriented layouts [31,44]                             | Inadequate ventilation planning [28,32,44]                 | Increased reliance on mechanical cooling [31,44]         |
| Energy modelling         | Dynamic, climate-specific performance simulation [32,34,36]                        | Rule-of-thumb assumptions and generic templates [32,34,36] | Underestimation of actual energy consumption [32,34,36]  |

### Synthesis

Overall, knowledge gaps in architectural design practices and energy modelling form a critical foundation for the residential energy performance gap in Libya. Decisions made at the design stage—often without adequate climatic consideration or performance verification—create structural inefficiencies that persist throughout the building lifecycle. Addressing these gaps requires not only improved technical capacity but also institutional shifts toward performance-based design and climate-responsive architectural education.

## 5. Knowledge Gaps in Building Materials

### 5.1. Material Selection Practices

The need for a choice of building materials is one of the critical elements of residential building energy performance, and this is much more pronounced in hot and arid and Mediterranean climates. There is a huge documented bibliography regarding the influence of thermal conductivity, specific heat, hygric, and solar absorptivity of building materials upon indoor temperatures and cooling load [2,11,12]. However, the Libyan building materials choice and selection process is actually conventional and mostly depends upon cost.

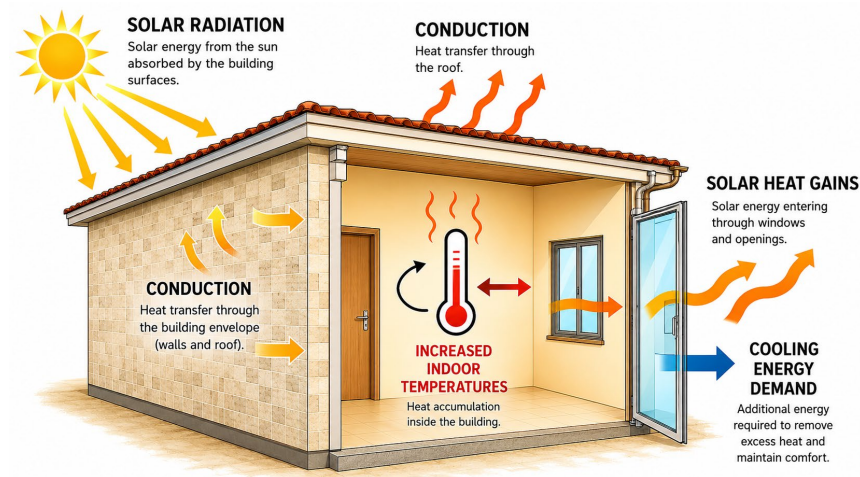
For a substantial part of Libya's housing stock, reinforced concrete frames, along with hollow concrete blocks, cement plaster finishes, and uncovered flat roofs, are typical for the region [16,17]. These are common elements that are locally available and also thermally stable, but at the same time have high thermal conductivity and low thermal resistance, suggesting that they do not perform well during extreme temperatures during the summer season [1,24]. Empirical work carried out in Libyan cities like Sebha and Benghazi shows that wall and roof constructions with conventional wall and roof constructions of conventional materials are responsible for high indoor heat gain relative to thermally optimised wall and roof constructions [11,16].

A further knowledge gap is presented by the lack of awareness pertaining to hygro-thermal performance, such as the interrelation of heat and moisture transfer in envelope components. For example, in hot arid climates, the selection of incompatible materials may increase discomfort by disturbing thermal preferences and accelerating component degradation, yet this is never factored into decision-making strategies for building design and construction [12]. As such, the effectiveness of architectural strategies may be hampered by improper selection of materials, which in turn may encourage the use of machine cooling systems.

### 5.2. Thermal Performance of Envelope Components

The thermal performance of residential envelopes in Libya is mainly influenced by the thermal properties of the building envelope components, such as walls, roofs, and glazing materials. All these aspects together influence the envelope cooling-load requirements. Research and studies on buildings reveal that roofs are the most considerable aspect influencing heat gains due to solar irradiation and poor roof insulation, while walls and glazed areas come next [2,16]. Libyan buildings' flat concrete rooftops are normally flat, without any reflective materials or roof insulation. Thus, they allow solar irradiation to be reflected inside the rooms, increasing the room temperatures to high values even by evening time.

Walls made of hollow concrete or cement blocks have low thermal resistance, especially if there is no shading and if surface properties have high solar absorptivity [11,17]. Glazed facades composed mostly of single-glazed materials with aluminium frames also contribute to heat gain, especially if they have high window-to-wall ratios and poor shading [13,54]. The overall contribution from envelope elements can be observed in Figure 5, which schematically represents major transport mechanisms for heat gain for a typical Libyan residential building.



**Figure 5.** The main heat transfer routes in typical residential building envelopes in Libya.

- Red arrows: Solar radiation. Areas where direct solar radiation impacts roofs and walls.
- Orange arrows: Conductive heat transfer. Transfer of heat through solid building elements consisting of walls, roof slabs, and columns.
- Yellow arrows: Radiant heat exchange. Long-wave radiation transfer between a heated surface and the air and interior surfaces.
- Blue arrows: Convective heat transfer. Movement of heat through air carried by gaps and/or openings in the building envelope and/or through air carried by convection.

Elements shown in grayscale—Locations of thermal bridges. Uninsulated structural elements that bypass the thermal resistance of the building envelope.

Note: The interplay of these pathways depends on the thermal conductivity of the materials, the absorptivity of the surfaces, and the construction quality. The diagram shows the particular weakness of flat, uninsulated concrete roofs (predominantly solar and conductive pathways) and single-glazed aluminium framed windows (predominantly solar and radiant pathways) in the typical Libyan residential situation. The practice of incorporating insulation also lacks consistency. Furthermore, where present, the insulation may not be optimally placed and compatible, making its effectiveness limited [16,55,56]. The lack of a holistic approach to envelope design contributes to a number of cumulative thermal inefficiencies, which means that any gain in one part of the envelope is compensated for by inefficiencies in another. This situation contributes to high levels of cooling loads and the difference between expectation and realisation.

Table 4 presents summaries of commonly used materials in residential constructions in Libya, along with their thermal parameters, whereas Table 5 presents comparisons involving these materials with thermally efficient ones obtained from studies in other countries. What these tables demonstrate is how much of a role knowledge gaps pertaining to materials play in residential energy efficiency.

**Table 4.** Common residential construction materials in Libya and their thermal characteristics.

| Envelope Component | Commonly Used Material                                | Typical Thermal Characteristics                           | Implications for Cooling Demand                       |
|--------------------|-------------------------------------------------------|-----------------------------------------------------------|-------------------------------------------------------|
| External walls     | Hollow concrete blocks with cement plaster [20,21,36] | High thermal conductivity, low thermal resistance [20,21] | Increased conductive heat gains during summer [20,21] |
| Roofs              | Reinforced concrete slab [21,31,32]                   | High solar absorptance, minimal insulation [21,31]        | Major contributor to indoor overheating [19, 24]      |

|            |                                                   |                                          |                                     |
|------------|---------------------------------------------------|------------------------------------------|-------------------------------------|
| Glazing    | Single-pane glass with aluminum frames [31,32,37] | High solar heat gain coefficient [31,37] | Elevated solar heat ingress [31,37] |
| Finishes   | Dark cement or ceramic surfaces [31]              | High surface absorptivity [31]           | Increased radiant heat gains [31]   |
| Insulation | Limited or absent [21,32]                         | Inadequate thermal buffering [21,33]     | Prolonged cooling operation [21,33] |

**Table 5.** Comparison between locally used materials and thermally efficient alternatives reported in the literature.

| Envelope Element    | Common Libyan Practice | Thermally Efficient Alternatives                         | Reported Performance Benefits                               |
|---------------------|------------------------|----------------------------------------------------------|-------------------------------------------------------------|
| Wall systems        | Hollow concrete blocks | Insulated masonry, composite walls, EPS-enhanced systems | Reduced cooling loads and improved indoor stability [12,16] |
| Roof assemblies     | Bare concrete slabs    | Insulated roofs, reflective coatings, green roofs        | Lower peak indoor temperatures [7,44]                       |
| Glazing             | Single glazing         | Double glazing, low-emissivity glass                     | Reduced solar heat gain [13,54,57]                          |
| Surface finishes    | Dark external finishes | Light-coloured or reflective coatings                    | Lower surface temperatures [2]                              |
| Insulation approach | Ad-hoc or absent       | Integrated envelope insulation strategies                | Improved energy performance consistency [12]                |

### Synthesis

In conclusion, it is evident that the knowledge gap concerning materials as well as envelope performance is a big measure of residential energy inefficiency in Libya. The continuous reliance on materials that are not thermally suitable, coupled with a lack of understanding of heat transfer, means that a high trajectory in terms of cooling demand is inevitable for residential buildings. Therefore, a move from the current materials to better ones ought to involve a shift in terms of integrated envelope design.

## 6. Knowledge Gaps in Construction and Execution

### 6.1. Construction Quality and Workmanship

A very important but neglected factor in the residential energy performance in buildings is construction quality. Even with proper design and material specifications in buildings, deviations in the design and actual constructed buildings can affect the performance of buildings to a great extent. Studies in different parts of the world have indicated that discrepancies in design and actual construction practices contribute significantly to the energy performance gap in buildings [2,9,12]. In hot and arid regions, heat transfer in buildings needs to be kept as low as possible in order to keep the demand for cooling low in buildings.

In the Libyan residential sector, building practices are said to be associated with a lack of quality control, site management, and workmanship standards, particularly in small-scale and self-built buildings [24–26]. Empirical studies suggest that residential defects often include a lack of seal between the junction of the roof and wall; depleted insulation levels (when installed); and inaccurate fitting of windows and doors [16,41]. These defects allow thermal bridges, contributing to convective and conductive heat gains that destabilise indoor thermal conditions and extend the operation of cooling systems.

The issue of thermal bridging is especially important in reinforced concrete building systems, commonly employed in Libya. The structural building elements bypass the envelope's thermal resistance, thereby allowing heat to directly enter interior spaces [11,12]. In addition, any leakages in building envelope enclosures owing to unsatisfactory sealing

around openings cause uncontrolled infiltration of air; consequently, hot air enters the systems, thereby increasing the latent and sensible heat loads [13,54]. The implications of all these building defects can be visualised in Figure 6 below, which illustrates how building defects at the construction stage increase the gap between design-stage performance expectations and actual operation performance.



**Figure 6.** Construction-stage performance gap in residential buildings (Source: Author’s own elaboration).

Conceptual schematics of the disconnect between intended design specifications and actual construction elements emphasise the contributions of workmanship defects, thermal bridges, air leakage, and material substitutions to increased heat gain and concomitant cooling loads. Accordingly, it is evident from the literature that construction-related knowledge gaps not only create counterproductive effects for potential efficiencies that could have been achieved at the building design stage but also render buildings inefficient over a long period, as remediation is typically an expensive process, especially for residential buildings [12,58].

## 6.2. Regulatory and Enforcement Challenges

Beyond technical workmanship, institutional and regulation-related factors remain very significant in influencing the quality of construction outcomes. Although building regulations and energy-related regulation exist in theory, in Libya, building regulations and energy-related regulation sometimes differ in terms of implementation in residential buildings [1,24]. Sometimes little attention is paid to thermal performance and energy efficiency requirements in the permit process in the country.

This problem is compounded by the high occurrence of informal building techniques. There is a high incidence of residential buildings constructed without formal regulatory control. This is attributed to housing demands, economic factors, and limited regulatory enforcement capabilities. Consequently, in these buildings, no consideration is given to the buildings’ energy performance; instead, these decisions are largely influenced by short-term costs.

Previous comparative research carried out in other hot arid and Mediterranean regions indicated that inadequate enforcement of regulation is strongly correlated to comparatively greater residential energy consumption, together with performance gaps [13,14]. This is further aggravated for Libyan conditions, given the lack of professional training in efficient construction techniques and the lack of verification of building performance post-construction [24]. Even when present, conscious design guidelines for buildings are unable to ensure corresponding energy savings at the operation level.

Table 6 provides a summary of common defects encountered in the construction of residential buildings, as well as an overview of their associated effects as documented. It is important to note how defects at the construction stage have a way of bolstering systemic flaws from design and materials.

**Table 6.** Typical construction defects affecting thermal performance and their energy implications.

| Construction Defect      | Description                                                                 | Thermal Implication                        | Impact on Cooling Energy Demand              |
|--------------------------|-----------------------------------------------------------------------------|--------------------------------------------|----------------------------------------------|
| Discontinuous insulation | Insulation omitted or interrupted at joints and structural elements [22,23] | Increased conductive heat transfer [22,23] | Higher peak and annual cooling loads [22,23] |

|                                    |                                                           |                                               |                                               |
|------------------------------------|-----------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Thermal bridges                    | Uninsulated beams, columns, and slab edges [22,23,35]     | Direct heat flow into interior spaces [23,35] | Elevated indoor temperatures [22,23,35]       |
| Poor window installation           | Gaps around frames and low-quality sealing [22,31]        | Air leakage and solar heat gains [22,31,37]   | Increased cooling system runtime [22,31]      |
| Roof detailing defects             | Inadequate insulation or reflective treatment [21,22,37]  | Excessive solar heat absorption [21,22,37]    | Night-time overheating persistence [21,22,37] |
| Construction material substitution | Use of lower-performance materials than specified [20,22] | Reduced envelope thermal resistance [20–22]   | Long-term energy inefficiency [20,22]         |

### Synthesis

Lack of knowledge in residential building quality and regulatory enforcement represents a major bottleneck in increasing residential building efficiency in Libya. There have been many occurrences where building design objectives were not achieved at the implementation stage. There are inefficient practices in residential building designs. Better regulatory mechanisms are required to address these challenges. Without these mechanisms, increasing residential building efficiency using building design and materials cannot lead to the intended results.

## 7. Occupant Behaviour and Energy Consumption

### 7.1. Occupancy Patterns in Libyan Homes

Occupant behaviour is generally accepted to be one of the most significant influencers upon residential energy consumption and may often overwhelm any potential influence from architectural design or material properties [3,9]. Occupancy behaviour in Libya exhibits a range of influences on residential stock from a combination of socio-cultural, adaptation behaviours to climatic conditions, and demographic factors. This often leads to patterns of occupancy based upon larger household group structures—aided by occupancy patterns by nature during the day, where temperatures during the peak summer period limit outdoor activity [8,16].

Irregular daily occupancy patterns are also characteristic of building occupancy. For example, indoor environment usage is more pronounced during the day due to work and school demands and mid-day sleep by many cultures. Such occupancy habits translate to consistent cooling requirements since building interiors need to be mechanically conditioned to maintain desired comfort zones for long periods of time [1,15]. Moreover, habits related to lifestyle and socio-cultural values, such as closed doors and windows due to the need for privacy and electrical cooling devices, contribute to high cooling usage intensity.

### 7.2. Behavioural Drivers of Energy Use

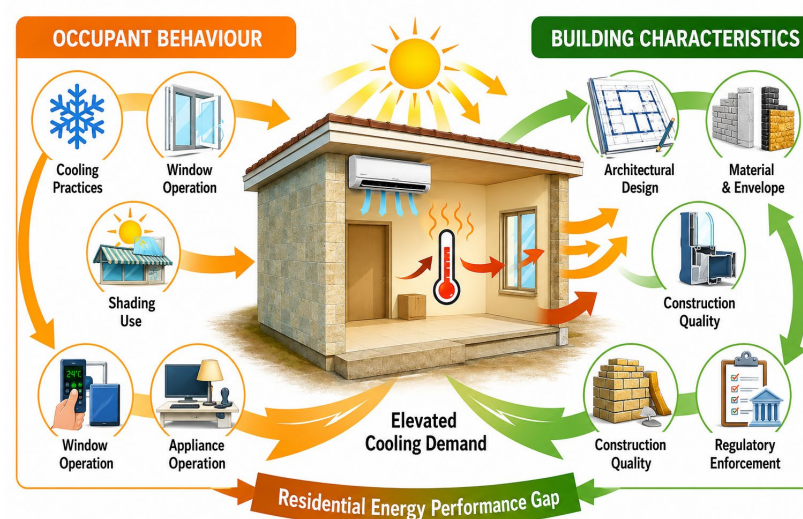
Cooling practices have been identified as the single biggest driving force behind electric energy consumption in Libyan domestic buildings. Many studies have identified that electric energy use in Libyan HVAC systems heavily relies on users' dependency on air-conditioning systems running for long periods during extended summer holiday seasons, with minimal thermostat temperatures set at very low levels [1,15,19]. The typical nature of end-user habits and their tendencies to use cooling systems in unoccupied areas of buildings, minimal use of temperature setback strategies, and poor ventilation during night-time hours all contribute to increasing cooling demands.

The operation of windows and shades is another influential factor. In hot-arid climatic conditions, the effective use of “night ventilation” is strongly capable of reducing energy consumption. However, residents may choose to keep windows closed for reasons of privacy, avoidance of dust accumulation, and security issues [8,13,59,60]. The use of external shades is ineffective and irregular, resulting in a failure to reduce solar radiation

and heating loads during peak sun hours. Electrical appliances like television, refrigerators, and lighting equipment increase internal loads and add to space cooling loads, considering the climatic conditions and weather [52].

Energy literacy and socio-economic parameters are the influencers that mould such behaviour. It has been pointed out that energy literacy is low, a reason for less understanding of efficient cooling practices. Moreover, there is a perception that electricity is a very cheap or subsidised commodity given by the government, which in turn diminishes the incentive to conserve it [24,41,61]. In lower-income households, the appliances used are older and less efficient, thereby increasing not only energy consumption but internal heat gains as well [32,52,62]. Such behavioural habits interact with building characteristics like envelope performance and ventilation design to produce significant variability in actual residential energy demand relative to design expectations.

The cumulative effect of these behavioural drivers is summarised in Figure 7, which conceptualises how occupant practices interact with building design, material performance, and climatic conditions to determine operational energy consumption.



**Figure 7.** Interaction between occupant behaviour and residential energy performance (Source: Author's own elaboration).

Conceptual model showing the relationships between occupant behaviour, such as cooling practices, window operation, shading device control, and appliance usage, and building-related factors, representing the role of behavioural patterns in moderating the impacts of building design, materials used, and construction techniques on residential energy consumption in hot-arid environments.

To organise the behavioural determinants in a more systematised form, Table 7 summarises the major occupant behaviour variables affecting residential energy use in hot arid regions with specific emphasis on their relevance in the context of Libya.

**Table 7.** Summary of occupant behaviour variables influencing residential energy use in hot-arid contexts.

| Behavioural Variable         | Observed Patterns in Libya                    | Energy Performance Implication                                  | Supporting Literature |
|------------------------------|-----------------------------------------------|-----------------------------------------------------------------|-----------------------|
| Household size and schedules | Large households; extended day-time occupancy | Sustained cooling demand; higher internal heat gains            | [1,8,16]              |
| Air-conditioning use         | Continuous AC operation; low set-points       | Significant increase in peak and annual electricity consumption | [9,15,19]             |

|                           |                                                          |                                                     |         |
|---------------------------|----------------------------------------------------------|-----------------------------------------------------|---------|
| Window operation          | Windows kept closed for privacy/security                 | Reduced natural ventilation; higher reliance on AC  | [9,13]  |
| Shading behaviour         | Inconsistent use of shutters/blinds                      | Increased solar heat gain through glazing           | [13,54] |
| Appliance use             | Older and less efficient appliances; high internal loads | Elevated cooling demand and electricity consumption | [52]    |
| Energy awareness          | Limited knowledge of efficient practices                 | Inefficient operation of cooling and appliances     | [24,41] |
| Socio-economic influences | Cost-driven choices; low-efficiency appliances           | Persistent high operational energy intensity        | [52]    |

### Synthesis

Overall, occupant behaviour is considered an integral behaviour for the residential energy performance gap in Libya, which exacerbates the problem of any design and construction-related inefficiencies. For example, behaviours that are influenced by various social and cultural attributes, climatic responses, and insufficient energy literacy also contribute to considerable cooling energy consumption. Hence, an integrated approach can be considered for dealing with the behaviour of occupants, by undertaking design solutions, energy information for occupants, socio-economic measures, and information measures, respectively.

## 8. Thermal Comfort Parameters in Libyan Residential Buildings

### 8.1. Thermal Comfort Principles, Parameters, and Energy Considerations

“Thermal Comfort” describes a person’s thermal satisfaction and is a major factor influencing the demand for cooling in residential buildings. There is a two-way relationship between thermal comfort and energy use. If a building does not adequately achieve thermal comfort through passive means, the occupants will rely on intensive use of mechanical cooling. On the other hand, energy-saving strategies that enhance the building envelope can allow thermal comfort at elevated indoor temperatures and reduce the demand for cooling [11,12].

### 8.2. Existing Standards and Comfort Models

The two dominant models for thermal comfort are ASHRAE 55 [63] and ISO 7730 [64,65]. ASHRAE 55 for sedentary, lightly clothed individuals, defines the thermal comfort range as being operative temperatures of 23 to 26 °C at 50% relative humidity. The adaptive comfort model of ASHRAE 55 which is more applicable to residential buildings, permits operative temperatures of 28 to 30 °C in naturally ventilated buildings when the outdoor mean temperatures are elevated [66]. This is very relevant to Libya, where cross-ventilation and night-time cooling are viable options [13,67,68].

### 8.3. Analysing Comfort Levels in Libyan Homes

Existing data from Libyan homes indicates that in summer, indoor, unconditioned, coastal Libyan city homes can reach uncomfortably high temperatures of 32–38 degrees, with 38–45 degree temperatures commonplace in Libyan desert homes (and well above the universally accepted levels of indoor comfort) [16,17]. In contrast, the use of air conditioning in Libyan homes has resulted in thermostat settings of 18–22 degrees (uncomfortably cold levels by international standards and requiring constant high levels of air conditioning in order to combat the effects of the ‘over-cooling’), which is indicative of the high levels of thermal resistance of the building, the occupants’ degree of acclimatisation, the cultural need for coolness, and the low cost of electricity [3,52].

#### *8.4. Impact of Design and Policy*

The use of design features, which result in the passive control of indoor temperatures to levels in the range of 26–28 degrees in coastal Libya, has the capability of reducing the need for active air conditioning for the majority of the year in coastal Libya. When considering, for example, the traditional Libyan courtyard architectural design, the passive use of shading and orienting of the building can result in the desired levels of comfort [41,45]. Without appropriate changes in the design to control indoor comfort levels and therefore mitigate ‘over-cooling’, energy efficiency programs aimed at equipment efficiency will only result in negligible benefits.

#### *8.5. Humidity and Perceived Comfort*

On the coast, summer months bring 60–80% relative humidity. Combined with high temperatures, this is perceived as even greater heat, further reducing the effectiveness of natural ventilation. The PET index shows that conditions that are marginally acceptable at 30 °C and 30% RH become clearly unacceptable at the same temperature and 70% RH [12]. Humid coastal regions of Libya, therefore, necessitate temperature reduction and humidity removal. In the inland desert, a very low (less than 20%) RH means that some relief is possible from the use of evaporative cooling. However, this is largely absent from the housing design of Libya and has implications in terms of energy use and comfort.

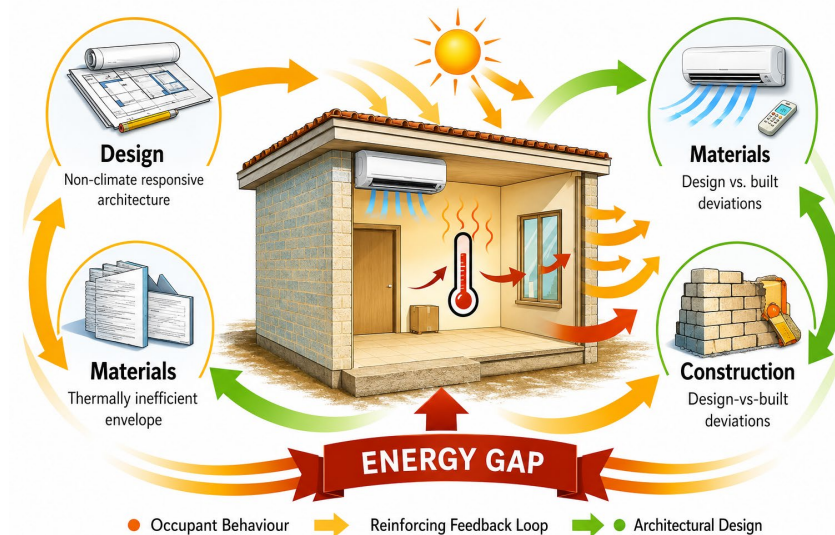
### **9. Integrated Analysis: The Residential Energy Performance Gap**

#### *9.1. Interactions Across the Building Lifecycle*

The existing residential energy performance gap in Libya is not due to isolated factors, as these are mutually influential and cumulative in their interactions, which embrace the dimensions of architecture, building materials, construction, and occupant behaviour. Though each of these aspects has been studied in isolation by previous researchers, the overall effect has not been broadly analysed as a whole, and the subject is still approached in a fragmented manner under the umbrella of policies and technology developments.

At the design stage, non-climate-responsive orientation, massing, and layout are critical for determining baseline conditions with high solar exposure and limited possibilities for natural cooling [2,11]. The challenges are further complicated at the material stage by non-thermally efficient building envelope assemblies that can potentially promote conductive and radiative heat gain [16,24]. At the construction phase, design-as-built differences, thermal bridging, and air infiltration issues adversely impact envelope thermal efficiency, thus negating any attempted efficiency measures isolated to earlier stages of the construction process [12]. The impact of occupant use is a prominent amplifier of existing inefficiencies across the building envelope, with high levels of air-conditioning use, non-existent natural ventilation use, and non-uniform shading practices [3,9].

These interactions do not act in isolation but rather in a mutually supporting role that creates feedback loops, ensuring that buildings establish trajectories of excessive energy demand. This can be seen in the case whereby building envelope inadequacies cause discomfort to building occupants who then use cooling systems more extensively to cover up inadequacies in building designs and constructions [3,52]. This ultimately normalises energy use, contributing to the differential between expected and actual performance to energy demand in buildings. The concept of these interactions in the lifecycle of buildings is described in Figure 8, which depicts the knowledge gaps in the lifecycle that influence building energy demand.



**Figure 8.** Integrated model of knowledge gaps and residential energy performance (Source: Author's own elaboration).

Integrated conceptual model showing the relationship between knowledge gaps in architectural design, building material and envelope selection, construction quality and legislative control, and resident behaviour to build up their influence on cooling demand and the residential energy performance gap in hot arid climates.

### 9.2. Implications for Energy Consumption

The clear disparity experienced between predicted energy use and existing energy use in Libya can be described by various contributing aspects. Initially, predicted energy use before building completion is normally associated with a number of assumptions, which, when fulfilled, lead to general undershooting in relation to energy demand [9,10]. Secondly, errors experienced at this stage, especially pertaining to defects, result in reduced thermal resistances, increasing energy demand beyond expectations [11,12,16]. Lastly, aspects related to building occupancy have proved to exhibit marked variability, particularly when such scenarios persist for longer periods, as observed across Libya, where such comfort needs may have cultural implications [3,52].

Information on Libya is sparse but will allow for the estimation of some order-of-magnitude values. Non-climate responsive buildings demand significantly (40% to 60%) more cooling energy compared to environmentally responsive buildings that employ effective orientation, shading, and insulation, as reported in studies of other similar hot-arid regions of North Africa and the Middle East [11,12].

Conventional, uninsulated hollow concrete block walls ( $U$ -value  $\sim 2.0$ – $2.5$   $\text{W/m}^2\text{K}$ ) allow the passage of heat to/from the environment four to five times greater than the insulated case ( $U$ -value  $\sim 0.4$ – $0.6$   $\text{W/m}^2\text{K}$ ). The effect of this in summer is a proportional increase in cooling loads [20,21]. Uninsulated flat concrete roofs in desert regions can, under midday sun, attain a roof surface temperature of  $75^\circ\text{C}$ , while, with an insulated roof, surface temperatures may be  $45^\circ\text{C}$  and internal ceiling temperatures may be  $35^\circ\text{C}$  [16].

Regarding occupant behaviour, the research shows that in climates similar to Libya, an increase of the thermostat setting by  $4^\circ\text{C}$  (i.e., from  $20^\circ\text{C}$  to  $24^\circ\text{C}$ ) can cause an annual decrease in cooling energy use of between 15% and 25% [3,9]. It is important to note that a lack of post-occupancy evaluation in Libya is the greatest constraint to estimating cooling energy use. However, it demonstrates an opportunity to address the areas of energy use over the magnitude that this review has highlighted.

Constraints related to Libya itself will highlight the discrepancy in these findings even further. For Libya generally, climatic severity in terms of high temperature and intense solar irradiance will determine that buildings will be sensitive to even small levels of design and construction inefficiency in building design and construction [3,11]. Socio-economic factors related to subsidised electric tariffs and poor implementation of energy regulations will reduce the incentives for energy efficiency in Libya generally [1,24]. Furthermore, the prevalence of informal construction will reduce the applicability of design standards and verification schemes, allowing inefficient practices to prevail in the residential sector in Libya in general [24,25].

Together, these elements provide a rationale for why improvements focused incrementally upon individual elements, such as upgrading appliances or other components, such as envelope components, involve incremental levels of success but do not provide the desired results for the reduction of energy consumption generally in the residential space. The evidence cited indicates that comprehensive approaches based upon the concept of life cycles would provide the necessary elements to address the residential energy performance gap issue in Libya properly.

### Synthesis

Such an integrated analysis serves as a reminder that the energy performance gap in residential property in Libya is a fundamentally systemic issue, driven by a complex interplay of knowledge gaps, rather than a linear problem of technical failures. Figure 8 chooses to bring together the interplay in a unified conceptual model, with a focus towards rethinking energy efficiency as a holistic lifecycle issue, which is discussed further in the following section as a recommendation path.

## 10. Discussion

This review has brought together evidence that reveals that the residential energy performance gap in Libya is created by a series of interacting gaps in design, materials, and occupants rather than being the result of some isolated technical error. The experience found in Libya shows consistency as well as variation in comparison to similar hot arid and Mediterranean climates.

### 10.1. Energy Use in Libyan Houses

An understanding of the size and pattern of energy use in Libyan houses is necessary to begin to identify and discuss the existing knowledge gaps and ramifications. The Libyan residential sector is estimated to consume 50–60% of the country's total electricity use, which is significantly higher than the global residential sector consumption average of about 27%. This is indicative of the predominance of electricity use in the residential sector for space cooling, combined with the underdeveloped state of the industrial and commercial sectors in Libya [1,15,18]. It has been estimated that the annual residential electricity consumption per capita in Libya is between 4000 and 5000 KWh. This is also high in comparison with countries at a similar income level, which is again partially due to subsidized electricity [30].

Electricity consumption in Libya exhibits a high degree of seasonality. The peak electricity demand in July and August can be two to three times the winter monthly average demand, with residential air conditioning estimated to be responsible for between 60 and 75% of demand during peak hours [1,19]. This seasonal demand creates a number of problems for the electricity supply, and the frequent interruptions to supply create a negative cycle where unreliability of supply encourages households to install larger air conditioning units, which drives an even larger demand during peak hours.

Imperfect metered data at the household level and survey-based estimates indicate that an average detached house in a coastal city consumes between 18,000 and 30,000 kWh yearly, with approximately 60–70% of annual consumption attributed to space cooling. The substantial coastal residential energy consumption poses challenges to the environment and energy security, and significantly affects the future costs of energy infrastructure and household financial burdens.

### *10.2. Comparison with Evidence from Similar Climatic Regions*

Research from Mediterranean and hot-arid regions shows that an envelope design that is well detailed and integrates climate responsiveness can lower cooling loads. However, the application of those studies to Libya needs one to be realistic about the differences in structures and the extent to which findings can be generalised.

In Gulf Cooperation Council (GCC) countries, like the UAE and KSA, where the climate is similar to Libya, there has been a gradual tightening of building energy codes within a decade, backed by institutions, accredited inspectors, and a developed market for high-performance insulation and glazing systems [29,69,70]. None of these supportive structures exist in Libya. Because of this, a retrofit in Tripoli may deliver a lot less than the 30% cooling energy reduction that would be expected in Abu Dhabi, given that the same materials may not be available locally, there would be no inspection, and a contractor may choose to use a lower-quality product [24,25].

In Mediterranean countries like Tunisia and Morocco, donor agencies have developed building energy efficiency programs that include the training of contractors and subsidisation of materials. Given Libya's isolation from the aforementioned support and with the disrupted post-2011 supply chains, even when materials that have been specified to be energy efficient are provided, the supply remains unreliable [1,16,71,72].

Looking at Jordan and Egypt shows something valuable. All three countries have created energy codes for similar climates. Like Libya, both have cases of informal construction, and like Libya, both have low construction enforcement. Energy codes alone will not close the gap, alongside the codes, Jordan, Egypt and Libya all need workforce training, materials codes, and construction inspections.

### *10.3. Comparative Study of Reported Energy Performance Results*

The sources consulted for this study show a variety of energy performance results for residential buildings in hot-arid and Mediterranean regions [6,73,74]. Regarding cooling energy demand, research studies from similar North African and Middle Eastern regions show annual cooling energy intensities for non-optimised residential buildings in the 80–160 kWh/m<sup>2</sup>/year range. In contrast, the range is 30–55 kWh/m<sup>2</sup>/year for buildings with passive design and better building envelope assemblies. This indicates potential reductions of 50–70% from design and construction efforts. Alafya and Maka reported that a case study building in Libya used 35–55% more energy than the predicted energy consumption in the building simulation, thus placing Libya in the upper performance gap range for the region.

Regarding the energy performance of building envelopes, Alfarawi et al. reported that the deployment of external insulation in Libyan cohorts reduces wall heat gain by 60–70% when compared to the conventional practice of using hollow block construction. Alghnain et al. report that in Libya, the payback period for roof insulation is between 4 and 7 years at subsidised electricity prices and drops to 2–3 years at market prices. This shows the impact of energy price subsidies on the economic justification for investment in energy efficiency.

Regarding occupant behaviour, Mohamed et al. [4] indicate that the Libyan households in their study used air-conditioning for around 10 to 14 h a day during summer,

with the thermostat at settings below 22 °C. This is a higher level of cooling than is usually found in comparable studies in Tunisia or in Jordan. These comparisons support the premise that the energy challenge posed by residential behaviour in Libya has specific and severe characteristics, especially in the quality of construction, the enforcement of regulations, and cooling behaviour. These severe characteristics require specific contextual solutions, rather than general ones.

#### 10.4. Why Libya Experiences a Compounded and Persistent Knowledge Gap

Three structural factors amplify the gap in Libya:

1. Institutional and enforcement weakness. Energy performance standards are common, but enforcing these standards, as well as post-construction verification, is weak in Libya. This means that design specifications can be bypassed at execution time [24,25].
2. Fragmented professional capacity and supply chains: a lack of coordination between designers, material suppliers, and contractors, as well as a lack of incentives for coordination, low overall awareness of hygrothermal behaviour, and the limited availability of high-performance products, make the likelihood of design translated to in-service performance low [12,16].
3. Behavioural and economic factors: The costs of electricity when subsidised or low, in large households, along with cultural patterns, all contribute to the large demand due to people normalising large AC usages that mask the real technical issues and discourage people from addressing the issue themselves [3,52].

These factors interact (see Figure 8), and enhancements that target one particular layer (e.g., promoting one insulation material) may actually be limited by weaknesses in others (e.g., installation, use, or illicit substitution), which explains the limited results found in regional studies that examined relevant changes across several sectors [11,16].

#### 10.5. Practical Implications

For architects and designers

- Adopt lifecycle thinking. Design decisions should be informed by considerations of construction feasibility along with anticipated occupancy behaviours and should not be considered as technical optimisations in isolation. Consider compact massing, orientation, shading, and courtyards where appropriate; document simple and robust detailing that is forgiving of poor workmanship (See Table 3 and Figure 4).
- Embed passive strategies early. Prioritise passive cooling and low-tech interventions (shading, reflective roofs, night ventilation) that are low-cost and resilient to execution variability [11,12].

For engineers and contractors

- Details for constructability and continuity. Insulation continuity, airtightness detailing and thermal-bridge minimisation to be clearly shown in drawings and site-checked—minor execution mistakes result in outsized energy penalties in hot climates.
- Quality assurance and training. Introduce mandatory commissioning checks for envelope continuity and basic airtightness testing where possible; provide vocational training focused on thermal detailing.

For policymakers and regulators

- Boon is to link approvals to performance evidence. From here, a corresponding move from prescriptive checklists to simple performance verification (e.g., basic envelope u-values, spot checks of installation, or post-occupancy metering pilots). Even low-frequency enforcement and random inspections influence market behaviour.

- Incentivise whole building outcomes. Using subsidies or incentives linked to actual building outcomes (not just product purchasing) should help create a market that channels actors and discourages material substitution and compliance minimisation [24,25].

For residential occupants

- Behavioural engagement. Priority in education campaigns should be given to behavioural methods that are applicable to cooling, such as setpoint management, zone conditioning, strategic shading, and night ventilation. In addition, education should be provided on how these are affected by the building's features in relation to cost savings [3,52].
- User-centred design input. Encourage participatory design or simple occupant profiling during project development to ensure that modelled schedules and setpoints reflect likely in-use behaviour.

#### 10.6. Toward Coordinated Interventions

The reviewed literature suggests that integrated lifecycle interventions combining climate-aware design, material upgrades, construction quality assurance, regulatory checks, and occupant engagement represent the only realistic pathway to narrowing the performance gap at scale. Pilot programs bundling these elements, for example, a cluster of dwellings with verifiable envelope upgrades, trained builders, post-occupancy monitoring, and briefing, are proposed to provide the robust evidence required to design scalable policy instruments and market mechanisms for Libya's housing sector.

## 11. Recommendations and Future Directions

Building on the integrated evidence reviewed in Sections 3–7, this section translates identified knowledge gaps into actionable recommendations across design, construction, governance and user engagement, while outlining priority research directions needed to close the residential energy performance gap in Libya. Recommendations are structured here to reflect lifecycle interdependencies and to emphasise interventions that are robust under hot-arid conditions and prevailing institutional constraints.

#### *Design and Professional Capacity Building*

Education in climate-responsive design should be incorporated in the curriculum of architectural and engineering disciplines with a strong emphasis on continuing professional education. Buildable and vernacular-inspired strategies to reduce cooling demand with quantification in hot arid and Mediterranean climates should be given emphasis. These should encompass crucial areas such as building orientation, massing, shading, ventilation, and envelope optimisation with a clear emphasis on demand reduction [2,11,12].

## 12. Prioritisation of Actions to Be Taken for Short, Medium and Long-Term Solutions

Some actions take longer planning and are not always urgent. Building on previous analyses, the following prioritisation aims to assist policy makers and practitioners in concentrating their efforts where the impacts of limited available resources would be the greatest.

**Short-Term (0–2 years) Quick wins' using existing capability:** The greatest opportunity for impact at the lowest cost is achieved by implementing basic envelope spot check procedures within the permitting process. These checks will require visible proof that continuous insulation, along with window and door seals, has been provided. No new regu-

lations will be necessary to close the construction quality gap, one of the most significant contributors to the performance gap, since current building regulations will be enforced. At the same time, a national campaign aimed at changing occupant cooling behaviour to a more energy efficient cooling practice would provide a significant decrease in demand at virtually no cost. This campaign would aim to bring about a higher thermostat set point (18–20 °C to 24–26 °C), and to encourage the use of zoned cooling, or even the practice of cooling only those rooms which are currently occupied, instead of whole-house cooling.

**Medium-Term (2–5 years) Systemic Capacity Building:** The primary focus for this time period should be on integrating climate-adapted design into the educational practices of the profession, as well as the project permitting practices. Specifically, this would entail (i) the inclusion of Passive Design and performance-based design in the architecture curriculum and CEPD, respectively, (ii) the development of a Libya-specific energy compliance tool at the basic level with climate-controlled files for the three main zones of Libya, and (iii) the development of a national database of thermal performance materials to assist in the selection of materials to promote the use of insulated and reflective materials in the construction of buildings.

**Long-term (5–10 years) Structural Reform and Evidence Base:** The most robust enhancements entail changes to institutional frameworks. This encompasses: (i) the implementation of an obligatory program for the monitoring of public housing post-occupancy; (ii) an overhaul of the electricity tariff structure to send price signals that promote the adoption of efficient behaviours [30]; and (iii) the establishment of a formal process of energy code revision with regional differentiation and a compliance verification process associated with building permits.

In parallel, the development and application of performance-based design tools is also important. This includes the application of dynamic energy simulations using local climate files and realistic occupant behaviour schedules that could improve prediction accuracy [9,10]. The application of these design tools, however, requires the development of accessible compliance mechanisms, such as the application of template simulations and assumed disclosure, and the production of professional information notes applicable to Libya's housing characteristics [1,16].

### *12.1. Material and Construction Improvements*

Therefore, policies and market instruments that encourage thermally efficient material and system solutions, such as well-insulated walls, roofs that are either reflective or insulated, glazed areas, and continuous insulation approaches that have been demonstrated to minimise the demand for cooling in similar climates [11,12,16], are the solutions that the supply chains will offer under such circumstances.

However, another very important aspect would be strengthening quality control and enforcement. For example, the minimum assessment of envelope integrity, proper placement of insulation, and proper window settings can provide significant savings with regard to costs [12]. There remains scope to evolve these regulatory instruments from input-oriented inspection to outcome-oriented verification, which could include spot checks, use of photographic evidence of building installations, or informal constructions [24–26].

### *12.2. Occupant Awareness and Behavioural Change*

To achieve a sustained reduction in residential energy consumption, the interventions of energy literacy must focus on the process of translating techniques into day-to-day residential life. Programs must focus on behavioural actions such as the temperature used for cooling, zone conditioning, strategic ways of shading, and night ventilation that have been found to impact energy demand within hot climate buildings [3,52].

Moreover, the promotion of user-centric residential designs should be promoted. Doing so will help in the better integration of these expected occupancy influences in the design stage, leading to better matching between modelled performance and real performance, rather than depending on compensatory inferences such as extensive air-conditioning usage [9,13]. Simple profiling can be added to the design brief without increasing complexity.

### 12.3. Future Research Directions

From the above considerations, two research priorities can be identified: First, as a means of filling the performance gaps, a great need for the conduct of post-occupancy evaluations of Libyan dwellings exists [3,9]. Such post-occupancy evaluation programmes must include the process of energy metering in addition to the survey of the behavioural determinants among the occupants.

Second, the development of behaviour-integrated residential energy modelling should be enhanced. Models that incorporate the explicit representation of occupancy schedules, cooling behaviours, and window/shading behaviours have superior predictive accuracy, especially under hot arid conditions [9]. In addition, the development of a simplified behaviour library that is context-specific for Libyan housing types will be useful.

Table 8 presents overall summary of the knowledge gap, observed consequences and recommendation. This table gives the overview of the whole study.

**Table 8.** Summary of identified knowledge gaps, consequences, and recommended interventions.

| Lifecycle Domain | Key Knowledge Gap                                           | Observed Consequence                                  | Recommended Intervention                                                |
|------------------|-------------------------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Design           | Limited climate-responsive practice; simplified assumptions | High solar gains; underpredicted cooling demand       | Education in passive design; performance-based simulations [2,9,11]     |
| Materials        | Predominance of thermally inefficient assemblies            | Elevated conductive and radiative heat gains          | Promote insulated/reflective systems; local supply alignment [11,12,16] |
| Construction     | Design-as-built deviations; weak workmanship                | Thermal bridges, air leakage; widened performance gap | Basic envelope QA; outcome-oriented checks [12]                         |
| Regulation       | Inconsistent enforcement; informal construction             | Persistence of inefficient practices                  | Incremental verification; targeted incentives [24–26]                   |
| Occupants        | Low energy literacy; intensive cooling practices            | Sustained peak and annual demand                      | Behavioural programmes; user-centred design [3,52]                      |
| Evidence base    | Limited POE and behaviour-aware modelling                   | Poor feedback to policy and practice                  | POE campaigns; behaviour-integrated models [3,9]                        |

### Synthesis

These recommendations, collectively, reinforce the premise that to address the energy performance gap in Libya's residential sector, a holistic, lifecycle-based approach to the problem is necessary. While incremental progress is possible through education, materials, and quality assurance, significant progress will require an alignment of design intent, construction quality, regulatory activities, occupant behaviour, informed by the results of post-occupancy monitoring and context-specific modelling.

## 13. Conclusions

This review has synthesised a broad and disparate research base to highlight that the ongoing nature of residential energy overconsumption in Libya is the result of the inter-relationship between knowledge gaps in the entire building lifecycle, and not merely the fault of individual technical problems. The research analysis in the paper has helped to

illustrate the role of non-climate-responsive building design, thermally undesirable building materials, construction problems and lax regulatory control, as well as high levels of occupant cooling practices and the way they all combine to increase the gap between prediction and actual performance.

This review has addressed the four identified knowledge domains in relation to the research objectives outlined in the introduction. First, with reference to architectural design practices, the review found that in modern Libyan housing, climate-responsive orientation, massing, and passive cooling techniques are systematically absent. From a structural standpoint, high solar exposure is the default. Because of this, we found that interventions are limited in the extent to which they can recover from this default structural condition (Section 3).

Second, with reference to materials and envelope performance, the review describes the thermal characteristics of the most prevalent building materials in Libya. We also identified the mechanisms for increased cooling loads and assessed these materials against more thermally efficient materials (Section 4). Third, with reference to construction quality and the enforcement of regulations, the review describes the construction of the residential building stock in Libya, which is characterised by the presence of thermal bridges, discontinuous insulation and excessive air leakage. We explained the presence of these construction faults as a result of limited enforcement of building regulations and informal construction (Section 5).

Fourth, with reference to occupant behaviour, we described the inefficiencies of the building systems in combination with the socio-economic and cultural factors that have been articulated (Section 6). The four contributions described above have combined to form a coherent research base that previously described, across numerous uncoordinated pieces of research, a Libyan residential sector lifecycle model.

By building on the results of the Libya study and similar hot arid/mild Mediterranean zones, the review offers a conceptual understanding of residential building lifecycle-based energy performance, which goes beyond traditional explanations that centre on design or technology. The explained integrated model, which utilises tables, helps readers understand their performance, how the results of early stage decisions have often been compromised in implementation, and why focused improvements using traditional building materials, appliances, or human interaction have, in general, failed to deliver significant system improvements. In this sense, the review contributes to the body of research in residence building energy efficiency in Libya.

The results thus emphasise the point that if significant savings in domestic sector energy use are to be achieved, these must be part of a larger strategy that enlists the support and coordination of many different actors and factors, from the climatically responsive design and materially efficient use of buildings to the regulation and conduct of users themselves. Indeed, the integrated approach, which incorporates both ‘performance-based’ design, basic ‘execution verification,’ and ‘post-occupancy feedback,’ strikes a sensible balance for the climatic conditions in Libya and points to the potential importance of such an approach in other similarly climatically challenged areas of the world.

This review has some limitations which should be acknowledged to maintain academic integrity. First, Libya-specific empirical studies are almost nonexistent. There are few peer-reviewed papers that published metered energy consumption data or conducted post-occupancy evaluations of Libyan residential buildings. Therefore, this review has mostly relied on North African and Middle Eastern studies. It should be noted that the transferability of these studies is subject to the same institutions and industries, as explained in Section 7.

Second, this review is mainly about the formal residential buildings. Therefore, the informal settlements and the newly emerging residential multi-family high-rise buildings

in the urban areas of Libya are not included. Third, because there is no national data of residential energy consumption in Libya, the performance gaps described in this review are based on data from other regions, and Libyan data is not used.

These limitations indicate the most important future research activities, such as, carrying out post-occupancy evaluations in each of the three climate regions in Libya; generating Libyan-specific behaviour profiles to be used for building energy simulation; and developing a residential energy consumption monitoring framework in Libya to support initiatives for evidence-based research.

**Author Contributions:** Conceptualization, A.A.; methodology, A.A.; investigation, A.A.; resources, A.A.; writing—original draft preparation, A.A.; writing—review and editing, A.A.; visualization, L.K.; supervision, N.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** No new data were created or analyzed in this study. Data sharing is not applicable to this article.

**Acknowledgments:** During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist in generating figures based on detailed instructions provided by the authors. The tool was used solely for creating graphical illustrations. The authors reviewed and edited all outputs and take full responsibility for the content of this publication.

**Conflicts of Interest:** The authors declare no conflict of interest.

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