

Critical Review on the Energy Retrofitting Trends in Residential Buildings of Arab Mashreq and Maghreb Countries

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Abstract: In the 21st century, global energy security is a critical concern. Buildings contribute to over 40% of the worldwide energy consumption, primarily due to heating and cooling, resulting in a third of greenhouse gas emissions. The residential sector accounts for 25% of global electricity consumption, and in the Arab Mashreq and Maghreb (AMM) countries, the residential sector consumes around 41% of the total electricity. Existing residential buildings constitute a significant portion of the building sector, playing a crucial role in the overall performance of the building sector. To address this issue, it is essential to invest in the energy retrofitting of existing unsustainable residential buildings. This study aims to provide a comprehensive critical review of the literature on residential buildings' energy retrofitting trends in the AMM countries. Using a keyword-based search, 41 relevant studies were identified and critically analysed to identify gaps in the literature, benchmarking against global retrofit studies' trends, including the absence of top-down and bottom-up physical approaches and the limited use of modern tools like BIM. Additionally, there is a significant lack of studies that present measured and verified case studies of implemented energy retrofitting projects. The study concludes with recommendations for future research to bridge the gaps in the literature.



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1. Introduction

In the 21st century, the urgent concern of energy sustainability looms large. The prevailing energy production and consumption methods have led to a disturbing surge in greenhouse gas (GHG) emissions, precipitating severe global climate complications. These emissions have catalysed critical issues, including global warming, which directly threatens human well-being and health [1,2]. Concurrently, the world struggles with the depletion of traditional energy resources, exacerbating the necessity to explore viable and sustainable energy alternatives such as solar and wind power [3]. The International Energy Agency (IEA) highlighted that the transportation and residential sectors are the major contributors to global energy consumption, comprising 35% and 20%, respectively [4].

In this complex scenario, the transportation sector's efforts toward adopting cleaner energy sources—such as electric power—have been carefully studied and evaluated [5,6]. Despite the positive impact of reducing dependence on conventional fuels, a new set of challenges is emerging: increasing demand for electricity within the residential sector, which is primarily due to electric vehicle charging needs, especially in countries that lack charging infrastructure [7]. However, this challenge represents a unique opportunity for the residential sector to contribute significantly to climate change mitigation by enhancing its energy efficiency.

This important improvement opportunity involves two key aspects: first, the creation of new energy-efficient residential buildings, which includes innovative ideas like nearly or net-zero carbon buildings; and second, the modification of existing structures through targeted energy retrofit projects [8]. Existing residential buildings constitute a significant portion of the total building stock and, as such, play a crucial role in the overall performance of the building sector [9]. Therefore, strategically upgrading these existing structures becomes a powerful tool to both combat climate change and enhance energy sustainability.

Central to this endeavour is the concept of retrofitting, involving the comprehensive modification or upgrade of existing systems. For buildings, it signifies the deliberate upgrading of buildings' structures, forms, or systems to meet contemporary requirements or conditions [10]. A sustainable urban retrofit, as championed by the Retrofit 2050 initiative, entails purposeful alterations to enhance energy, water, and waste efficiencies [11]. Narrowing our focus to this paper, the energy retrofitting of existing buildings, specifically residential, constitutes a process of improving the inefficiencies to optimize buildings' energy performance. This transformative process holds the potential for multifaceted benefits in improving the energy consumption of the existing residential buildings [12]. Various types of energy retrofitting, spanning from minor improvements to comprehensive upgrades aiming for nearly zero energy consumption in buildings, represent a spectrum of actions that can impact energy efficiency [13].

This pursuit of energy efficiency and sustainability is not confined to geographical boundaries. Both developed and developing countries grapple with the task of elevating the energy performance of their residential building stocks. However, a discrepancy emerges: developed countries demonstrate greater progress in energy retrofitting, leaving developing countries to navigate a more complex scenario [14,15]. On average, the total energy consumption of the residential sector in developing countries is approximately one and a half times that of the residential sector in developed countries [16]. A confluence of factors, including indeterminate retrofitting strategies, financial infeasibility, and a lack of requisite support, underscores the challenges faced by the latter [14].

With an understanding of the above, developing countries must overcome these barriers and create tailored mechanisms to accelerate progress in retrofitting existing residential buildings. This paper explores the current energy retrofitting trends within the Arab Mashreq and Maghreb (AMM) countries, including Jordan, Egypt, Palestine, Iraq, and Syria for the Mashreq and Morocco, Algeria, Tunisia, and Libya for the Maghreb [17]. These nations, classified as developing economies by the United Nations, not only share geographical and cultural affinities but also face common challenges and aspirations [18]. Notably, electricity consumption in AMM countries' residential sectors accounts for an average of 41% of the total consumption, surpassing the global average of 25%, as illustrated in Section 2. As populations grow and urbanization continues to advance, the demand for energy within residential buildings in AMM countries is projected to rise without intervention. The solution lies in retrofitting, guiding these countries toward sustainable residential sectors.

The objective of this review is to provide a state-of-the-art review of energy retrofitting trends in existing residential buildings across the AMM countries. While the existing literature touches upon energy retrofitting in AMM countries, a holistic synthesis is imperative to address the fragmented and potentially outdated nature of current research. Subsequently, the methodology for conducting a systematic review is outlined, detailing the parameters employed for analysing the existing literature. Following this, we present the resultant papers and undertake a critical analysis of their findings utilizing the defined parameters. Consequently, the paper concludes by identifying gaps that guide future research directions.

2. Background on the Need for the Energy Retrofitting of Residential Buildings in the AMM Countries

This section outlines the background of the AMM countries, stressing the need for energy retrofitting in their existing residential stock. These countries share commonalities in terms of climate, culture, economy, and energy characteristics [17]. Geographically, they fall into two Köppen climate zones: Zone B (Desert, Semi-arid) and Zone C (Mediterranean), as depicted in Figure 1 [19]. Zone B experiences exceptionally high temperatures, requiring significant energy consumption for cooling compared to Zone C. Conversely, Zone C demands substantial energy input for heating during the heating season to maintain indoor comfort within conditioned buildings. As a result, the residential building stock in the AMM countries exhibits diverse heating and cooling demands, necessitating distinct energy efficiency measure (EEM) configurations.

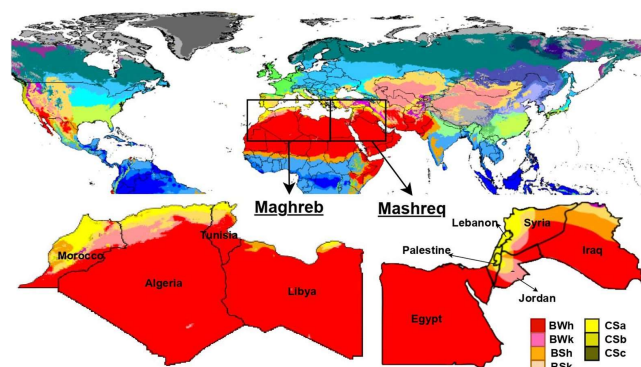


Figure 1. Koppen climate classification of the AMM countries (adapted from [20]).

Over the past decade, energy demand in residential buildings in AMM countries has surged due to three key factors: population growth, urbanization, and resource scarcity. Population growth is a significant driver of increased energy demand. According to World Bank statistics, AMM countries have experienced an average annual population growth rate of 1.6%, nearly one and a half times the world's average [21], as depicted in Figure 2a. Additionally, political instability, particularly civil wars in certain AMM countries during the Arab Spring, resulted in population displacement, immigration, and a refugee influx into neighbouring countries [22]. For instance, Jordan and Lebanon witnessed substantial annual population growth rates of 11.8% and 10%, respectively, in 2014, primarily due to the Syrian crisis, as shown in Figure 2b. This population increase directly contributes to higher energy demand in the residential sector.

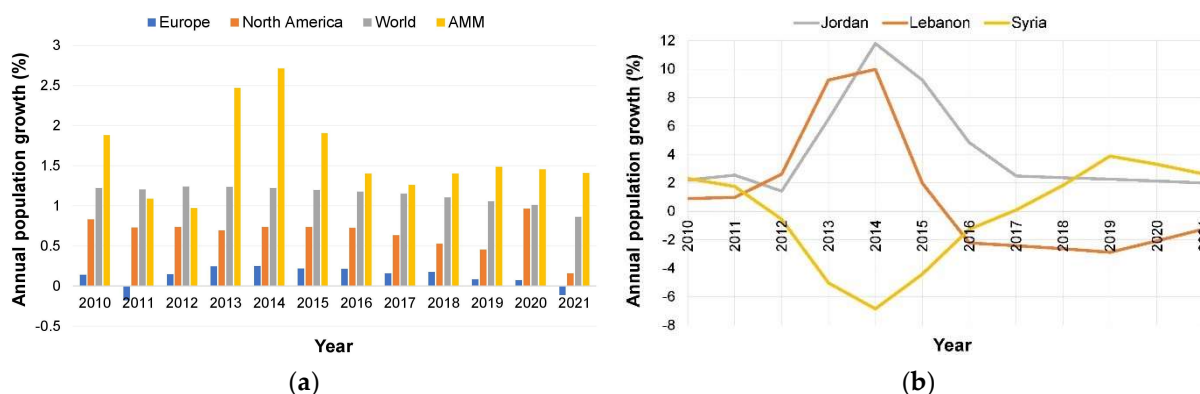


Figure 2. Population growth rate of the AMM countries: (a) comparison between the AMM countries, North America, Europe, and world; and (b) the impact of the Arab Spring in Syria on the population growth rate in Jordan and Lebanon (based on the data provided by [21,23]).

Furthermore, recent research has revealed that urbanization can lead to a rise in energy consumption, particularly in countries categorized as upper-middle and low-middle income [24]. This phenomenon can be attributed to the fact that in middle-income countries, the shift from rural to urban areas necessitates the construction of adequate infrastructure and additional houses to meet residents' needs [25]. The average proportion of the population residing in urban areas in AMM countries has risen from 68% in 2010 to approximately 72% in 2021 [23], with Jordan having the highest rate and Egypt the lowest, at 92% and 43%, respectively. The global average for 2021 stands at 56%. This trend can significantly impact the surge in energy consumption, especially when considering that the majority of AMM countries fall within the low-middle-income category. Additionally, the growth of multifamily housing, a consequence of urbanization, presents challenges in implementing renewable energy systems such as solar panels on rooftops due to limited surface area, posing a challenge for the widespread application of renewable energy systems [26].

In addition to the challenges contributing to the surge in energy demand mentioned earlier, most AMM countries lack abundant natural energy resources, with Iraq and Algeria being exceptions. This scarcity further exacerbates concerns about energy security due to the inability to meet growing energy demands. The economic analysis of Arab countries in Krarti's study [17] highlighted that many AMM governments offer energy subsidies, potentially leading to an increase in energy consumption. This was evident in the recent research of Albatayneh et al. [27], demonstrating how energy subsidies drive up consumption in developing countries, using Jordan as an example. Their findings revealed that subsidized households consume more than twice the amount of energy compared to unsubsidized households, emphasizing the necessity for subsidy reform. Given that most AMM countries are classified as low-middle-income [24], any potential subsidy reform may pose economic challenges for households.

To further elaborate on the current energy consumption of residential buildings, electricity consumption is a key parameter. Over the past decade, the average electricity consumption by the residential sector in AMM countries has significantly exceeded that of developed countries and the global average, as shown in Figure 3. In 2020, it reached 41%, whereas the averages for North America, Europe, and the world were 36%, 28%, and 25% respectively. This suggests a lack of energy efficiency in residential buildings and a dearth of proactive measures for the energy retrofit of the existing residential building stock. Therefore, enhancing the energy efficiency of the residential sector is imperative for the development of the AMM countries.

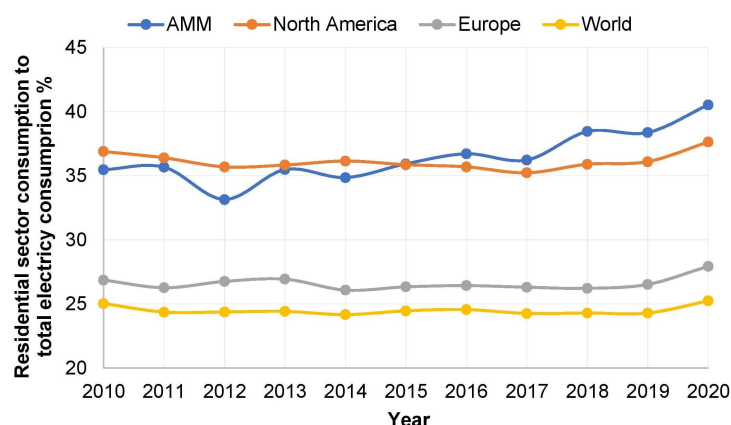


Figure 3. Comparison of the residential sector percentage consumption of the total electricity consumption in AMM countries, developed countries, and the world (based on the data provided by [28]).

Despite the past, governments in AMM countries are now beginning to prioritize energy sustainability. This is evident in the sustainability goals set by these governments, such as Jordan's "Energy Sector Green Growth National Action Plan 2021–2025" [29] and

Egypt's Vision 2030 [30]. Moreover, recent research has reported that through energy retrofitting of existing buildings, the potential reduction in energy consumption can reach up to 80% through the implementation of various EEMs [17]. Additionally, the adoption of deep energy retrofitting strategies, which incorporate renewable energy systems such as photovoltaic systems, holds the potential to transform the building stock in AMM countries into a net-zero energy efficiency model [31,32]. Therefore, to ensure a sustainable energy future, it is imperative for the AMM countries to invest in the energy retrofitting of their existing unsustainable residential building stock.

3. Methodology for the Systematic Review

3.1. Data Collection

To systematically identify relevant studies for this review, a comprehensive keyword-based search was conducted within the SCOPUS and Web of Science (WoS) databases. These databases were chosen for their reliability and ability to yield a wide array of pertinent studies in the area under study. The search strategy involved various combinations of keywords, including “energy, retrofit*, rehab*, renovat*, energy efficiency, energy conservation measures, homes, residential buildings, dwellings” (the “*” is used to include all possible concepts from the world root, such as renovate and renovation). This extensive set of keywords was designed to cast a broad net and capture studies related to energy retrofitting in residential buildings. To ensure the inclusion of high-quality and authentic research work related to the review objective, the following eligibility criteria were applied:

- Type of publication: Only journal articles or books/book chapters indexed in SCOPUS or WoS were included.
- Publication language: Only studies written in English were included.
- Year of publication: Studies published from the year 2000 onwards were considered, enabling the incorporation of the latest trends and developments in the research topic.
- Geographical focus: Studies should have evaluated the energy retrofitting of residential buildings in the AMM countries, employing at least one residential building as a case study.
- Methodology: Studies should have used numerical simulation to assess the energy improvements resulting from the application of at least one EEM.

Regarding the exclusion criteria, this review specifically focuses on energy retrofitting in residential buildings. Consequently, studies primarily concerned with designing new energy-efficient residential buildings or nearly zero energy buildings in the AMM countries were not considered.

The selection process involved three stages:

- Initial screening: Titles and abstracts of retrieved studies were imported into the Mendeley Desktop reference management software. Duplicates were removed, and an initial screening of titles and abstracts was carried out to eliminate studies that did not meet the eligibility and exclusion criteria mentioned above.
- Secondary screening: A secondary screening was conducted, focusing on the methodology and conclusion sections of the remaining studies. This step ensured that only studies directly relevant to the research area were retained.
- In-depth analysis: The final set of studies that passed the secondary screening underwent a comprehensive and in-depth analysis to determine their suitability for inclusion in this review.

3.2. Parameters for the Critical Review

3.2.1. Background

To thoroughly explore and investigate the objectives, outcomes, actions, and decision-making models related to the research on energy retrofitting in existing residential buildings, it is essential to comprehensively define and present all the parameters associated with energy retrofitting within existing studies. The energy retrofitting of existing buildings

involves three main processes: pre-retrofitting, execution, and monitoring and evaluation, as outlined by Ma et al. [8]. Several steps within these processes are demonstrated to properly conduct energy retrofitting, as shown in Figure 4.

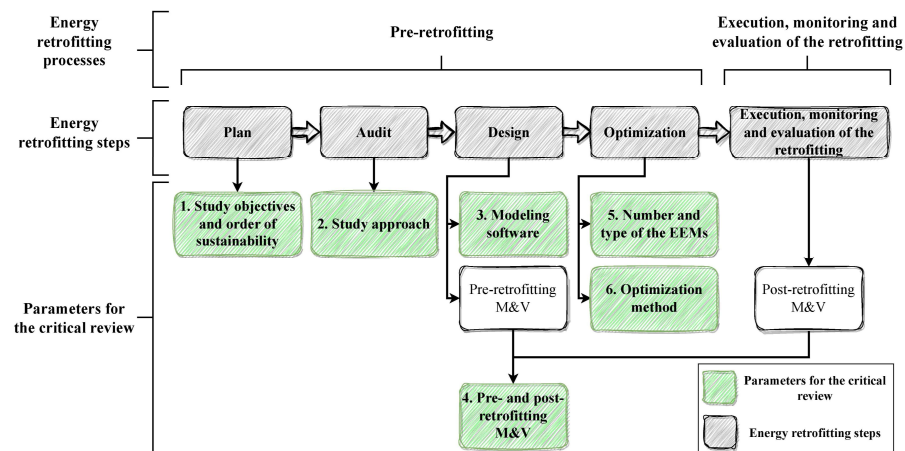


Figure 4. Processes, tasks, and parameters for the energy retrofit of existing residential buildings.

Global review studies have illustrated several parameters falling under the steps of energy retrofitting [33–36]. These parameters can generally be categorized into six main benchmarks, as shown in Table 1. For instance, Ahmed and Asif [36] reviewed the trends in energy retrofitting of residential buildings in the Arabian Gulf countries, considering four key parameters: study approach, pre- and post-retrofitting measurement and verification (M&V), types and quantities of EEMs, and optimization software. In this review, the six parameters identified in Table 1 and illustrated in Figure 4 will be employed to comprehend the current research scope in AMM countries. Further elaboration on each parameter is provided through Sections 3.2.2–3.2.7. These parameters aid in identifying research gaps and shaping future research directions in the AMM countries.

Table 1. Parameters for analysing the energy retrofitting studies in the AMM countries.

Energy Sustainability Criteria and Objectives	Study Approach	Software Used	Pre and Post Retrofit M&V	Type and Number of EEMs	Optimization Method
1st order (objectives)	Top-Down	3D modelling software	Yes (method used)	Single	Scenario analysis
2nd order (objectives)	Bottom-Up (Physical)	Energy simulation engine	No	Multiple	Optimization technique
3rd order (objectives)	Bottom-Up (Statistical)	BIM application			

3.2.2. Energy Sustainability Criteria and Objectives

Setting goals and objectives is an essential initial step in residential energy retrofitting projects, aligning with desired project outcomes. Sustainability, initially introduced by the Brundtland Commission, means meeting present needs without compromising future generations' abilities [37]. Energy retrofitting studies typically fall within the three sustainability criteria: environmental, economic, and social [35]. These three criteria, environmental, economic, and social, are interdependent and sustainability can only exist when addressing all of them [38,39]. Nevertheless, Edum-Fotwe and Price [40] proposed three sustainability orders: addressing each criterion separately (1st order), prioritizing two criteria at the expense of the third (2nd order), and integrating all three criteria (3rd order). Figure 5a depicts the criteria and orders of sustainability.

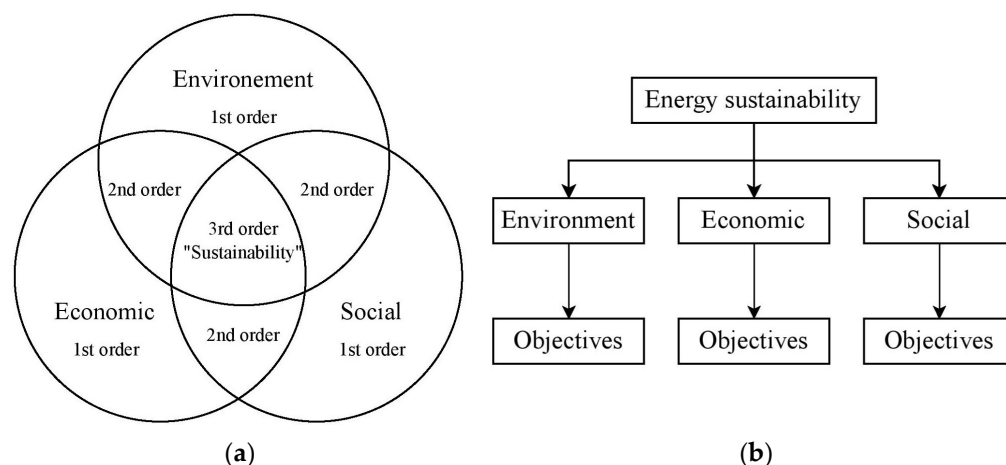


Figure 5. Energy sustainability criteria and objectives: (a) sustainability orders and (b) hierarchy of sustainability criteria and objectives.

Each sustainability criterion encompasses one or more objectives [35]. Objectives related to energy and the environment, such as energy savings and GHG emission reductions, fall under environmental sustainability. Economic sustainability includes goals related to project viability, assessed through methods such as cost-effectiveness and life cycle cost (LCC) analysis. Social sustainability aims to enhance the quality of life by improving thermal comfort and indoor air quality, reducing inequality through the provision of energy-efficient houses, and preserving cultural values. Figure 5b illustrates the hierarchical relationship among criteria and objectives, providing a visual representation of their interconnectedness. The primary goal of energy retrofitting is to enhance building energy efficiency [33–35], resulting in reduced energy consumption and support for environmental objectives, such as the reduction of carbon dioxide (CO₂) emissions. However, current research often tends to focus more on environmental aspects, neglecting the equal importance of the economic and social criteria [41–43].

3.2.3. Study Approach

The energy retrofitting of existing buildings can be approached from two main perspectives: top-down and bottom-up, as illustrated in Figure 6. The top-down approach primarily focuses on the macro-level and can be further divided into two categories: the econometric top-down approach and the technological top-down approach. The former focuses on energy retrofitting policies and their connection to economic and social variables, such as household income and fuel prices, which influence decision-making processes related to retrofitting [44]. For example, Alam et al. [14] proposed top-down strategies to address barriers in retrofitting public buildings by conducting focus groups with Australian government officials. Their findings underscored solutions to the barriers at the government level by highlighting the government's role in overcoming financial, technical, procurement, and social hurdles associated with energy retrofitting in the public sector.

Conversely, the technological top-down approach concentrates on the overarching characteristics of the entire residential building stock. For instance, Galvin [45] assessed Germany's federal government policies and schemes, particularly the Energy Saving Regulations (EnEV), aimed at reducing 80% of CO₂ emissions resulting from home heating energy demand by 2050. Galvin argued that stringent policy measures could impose indirect costs, "anyway costs", on homeowners when implementing EEMs. Furthermore, he emphasized the role of professionals, such as architects, in shaping policies to overcome obstacles in achieving the 80% reduction goal by 2050.

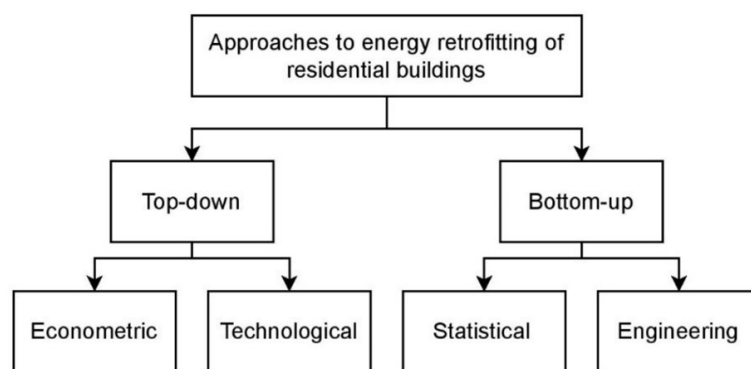


Figure 6. Approach to energy retrofitting of residential buildings.

In contrast, bottom-up approaches can address both the macro and micro levels, and they can be categorized as bottom-up statistical and bottom-up physical approaches [46]. The former primarily deals with macro-level assumptions based on statistical data, such as prototypical residential building characteristics that represent the building stock in a given region. For example, Al-ajmi and Hanby [47] employed a bottom-up statistical approach to explore potential energy consumption reductions in Kuwait’s residential buildings. They applied various measures to a prototypical residential building representing the country’s building stock and found that improving the building envelope could lead to a reduction of up to 19.7% in annual energy consumption.

Studies using a bottom-up physical approach are more focused and involve the retrofitting of specific residential building cases. These studies delve into technical details of building characteristics. An example of the bottom-up physical approach is illustrated in Aldossary et al.’s study [48]. Furthermore, bottom-up studies may involve the monitoring and evaluation of retrofitted buildings to validate energy optimization. For example, Synnefa et al. [49] employed a bottom-up physical approach to examine the impact of various EEMs in a seven-storey residential building in Athens, Greece. They used sensors and data collection technologies to evaluate the building envelope’s performance before and after the implementation of EEMs.

3.2.4. Simulation Software

The construction industry has introduced various emerging dynamic building energy modelling (BEM) software tools that can help measure the improvement in buildings’ energy efficiency and select the most feasible EEMs [50]. BEM is primarily used in the pre-retrofitting phase, requiring data collection of building geometry and energy-related details [8]. BEM employs three methods [51,52]: standalone energy simulation tools (e.g., EnergyPlus), integration with 3D modelling software (e.g., Revit), and all-in-one software (e.g., DesignBuilder). The selection of the BEM software depends on various factors, including the availability of the software, personal preference, and the users’ expertise.

Using BEM offers valuable methods to investigating energy retrofitting; however, there are several drawbacks to using BEM software in the retrofitting of existing buildings. This includes the long timescale of building models from scratch, which necessitates making assumptions about the building geometry and energy-related information [53]. Furthermore, BEM software is primarily suited for the pre-retrofitting phase. Its application in subsequent stages, such as execution and post-retrofitting monitoring and evaluation, demands more extensive data and information management. Therefore, managing retrofitting projects throughout the construction and post-retrofit phases becomes a complex task.

To address these challenges, integrating Building Information Modelling (BIM) with BEM proves instrumental. This integration not only helps overcome the limitations of BEM but also extends its impact by facilitating comprehensive information and data management throughout the entire lifecycle of energy retrofitting projects [54]. The International Organization for Standardization (ISO) defined BIM as the “use of a shared digital repre-

sensation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions” [55]. In energy retrofitting of existing buildings, BIM has increasingly been used to evaluate the energy efficiency. Connecting BEM with BIM can assist in both the planning and design stages by facilitating the acquisition of geometric and energy-related data [51]. Also, the resulting BIM models can help in the whole life cycle of the energy retrofitting by managing information related to the execution, monitoring and evaluating the retrofitting projects.

Consequently, the adoption of BIM in the energy retrofitting of residential buildings became a trending research topic, stressed by several researchers who have introduced frameworks based on BIM to overcome the abovementioned challenges [51,56]. For instance, Sanhudo et al. [51] conducted a comprehensive review of using BIM for existing buildings’ retrofit, outlining four main processes necessary for energy analysis: (1) data acquisition, (2) BIM modelling, (3) interoperability, and (4) energy modelling. They further illustrate the benefits of the integration between BIM and BEM, providing a case study [56]. In the context of the Arab countries, Ahmed and Asif [57] illustrated a BIM-based framework for the energy retrofitting of existing residential buildings in Saudi Arabia. The framework involved exporting the building’s 3D model, designed using Revit software, and importing it into DesignBuilder using the gbXML scheme. However, this framework was limited to interoperability between the BIM authoring software and the BEM software and did not capture the full potential of using BIM [36].

3.2.5. Pre- and Post-Retrofit M&V

The data acquisition during the planning phase of energy retrofitting in existing buildings may involve various assumptions due to limited access to data [8,51]. These assumptions can impact the credibility and viability of energy models. Consequently, pre- and post-retrofitting M&V processes are essential steps to calibrate and validate buildings’ energy models. Typically, the M&V processes follow a bottom-up physical approach [36]. Pre-retrofitting M&V involves the calibration and validation of energy building models, which is usually conducted at the end of the design stage, as depicted in Figure 1.

There are several approaches to conduct the pre-retrofitting M&V, such as performing actual measurements and tests, comparing the energy models with earlier studies, and validation based on the accuracy of the energy simulation software [58]. In the former scenario, measurements can be performed using energy metering sensors or by measuring the energy consumption using the energy utility bills. For example, Aldossary et al. [48] calibrated and validated the energy model by comparing it to the actual electricity consumption collected from energy utility bills.

On the other hand, post-retrofitting M&V is the process of monitoring and validating retrofitted buildings after the implementation of the EEMs [16]. Various protocols exist for the M&V in residential building energy retrofitting, such as the standards and guidelines offered by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Performance Measurement and Verification Protocol (IPMVP) [8]. For example, Alfaris et al. [59] used IPMVP Option C for 12 months of post-retrofit M&V in villas in the United Arab Emirates. They assessed the energy performance of the villas that were retrofitted with various EEMs (e.g., improving the envelope and upgrading systems) and compared energy bills before and after retrofitting, achieving energy savings between 14.4% and 47.6%.

3.2.6. Number and Type of EEMs

According to global review studies [8,35], various types of EEMs enhance existing residential building energy performance. These EEMs broadly fall into three groups: (1) demand side, (2) human factors, and (3) supply side [8]. The demand side aims to reduce building energy demand, with categories including envelope EEMs (e.g., insulation) and load reduction EEMs (e.g., efficient appliances). Human factors involve control measures

like adjusting set point temperatures and considering behaviour and consumption patterns. Lastly, the supply side promotes renewable energy systems such as solar power [60].

Energy retrofitting studies found in the literature propose single or multiple EEMs. In the latter case, some compare the impact of individual EEMs on building performance, while others identify optimal EEM bundles based on specific objectives. For example, Krarti et al. [61] assessed the energy savings from applying six EEMs to residential building in Saudi Arabia. They analysed each EEM individually and combined them into three retrofitting levels based on their costs. The results showed that these EEMs could eliminate 76 million tons of CO₂ emissions, save 100,000 GWh of electricity, and create approximately 2.5 million jobs per year.

3.2.7. Optimization Method

The term optimization can generally be defined as “to make as perfect or effective as possible” (Available at: <https://www.thefreedictionary.com/optimization> [accessed on 30 July 2023]). In the context of the energy retrofitting of buildings, it involves finding the most effective and feasible solutions. In other words, energy retrofit optimization is about identifying the best EEMs to achieve retrofitting goals, such as improving energy consumption and overall energy efficiency [62]. Global energy retrofitting reviews categorize optimization into scenario analysis and optimization techniques [34,35]. Scenario analysis assesses the impact of predefined EEMs (e.g., insulation) to find the best EEMs package that achieves specific objectives, often supported by parametric analysis in BEM software [63].

Scenario analysis can be performed in several ways [34]: It can involve investigating one or multiple EEMs that have predefined values and examine the impact of each EEM individually on buildings’ energy and overall performance. These EEMs are then combined as a proposed package for the energy retrofitting. Bataineh and Alrabee [64] offer an example of this approach. Also, scenario analysis can involve investigating a range of values for each EEM. In this case, the values of each EEM are tested through the parametric analysis and the best value is selected considering the study objective. Then, the selected values of each EEM can be combined to represent the optimum package of EEMs, as presented by Abu Qadourah et al. [65].

However, when dealing with many values and combinations of EEMs, finding the best solution can become challenging, particularly when considering the complex and nonlinear relation that might exist between multiple objectives under different criteria of sustainability [62,66]. Optimization techniques come into play to reduce complexity in such cases [35]. The use of algorithms that dynamically adjust the values of EEMs allows for a faster and more effective search for the optimal solutions that meet the desired objectives, aiding in the discovery of the optimal EEM package.

Furthermore, energy optimization can address either single or multiple objectives. These objectives typically fall under the sustainability criteria [35]. A single-objective optimization problem involves optimizing building performance based on a sole objective, such as enhancing the energy efficiency. On the other hand, multi-objective optimization tackles scenarios with multiple, often conflicting, objectives [66,67]. This complexity arises when improvements in one aspect may result in compromises in another. Unlike single-objective problems, where a singular optimal solution is sought, multi-objective optimization yields a set of solutions that offer trade-offs among the diverse objectives. Within the domain of multi-objective optimization, solutions are categorized as either dominant or non-dominant. A solution is deemed dominant if it outperforms another solution in at least one objective and does not fare worse in any other. Conversely, a non-dominant solution is one that is not surpassed by any other solution in all objectives.

Nguyen et al. [62] outline three optimization phases: pre-processing (defining objectives, selecting EEMs, and choosing algorithms), running and monitoring the optimization algorithms, and post-processing (interpreting results). Following these phases and considering the conflict between objectives and the massive amount of EEMs values can lead to a

brute force approach, which is time-consuming [67]. Hence, researchers tend to integrate and propose various methodologies and decision-making tools that aim to minimize the time needed for searching for the optimal solutions through narrowing the design variable space including the number and values of possible EEMs [66]. In other words, these proposed methodologies and decision-making tools narrow down the searching through the space of EEMs values, often involving constraints and evolutionary multi-objective algorithms [68].

For instance, Krarti and Ihm [67] enhanced a villa's energy performance using pre-defined EEM values and a sequential search optimization method using a combination of the DOE2 simulation engine, BEopt optimization program, and Genetic Algorithm for optimization. They assessed individual EEMs and then combined them to find the best trade-off between energy savings and LCC. This method drastically reduced the computing time compared to brute force optimization. The authors highlighted that the computing time required when considering 8 EEMs with 92,160 possible solutions was 1733 min (around 29 h) compared to 4.6 min using sequential search optimization. Moreover, they found that the optimal packages obtained through the sequential search were found to be significantly close to those obtained from the brute force approach.

3.2.8. Important Remarks

The overview of the global reviews on the energy retrofitting of existing residential buildings illustrated the importance of considering the benchmarked parameters in studies pertaining to the investigation of the energy retrofitting of residential buildings in the AMM countries. Incorporating the three criteria of sustainability informs decision making in the retrofitting of residential buildings [9]. Also, it highlights the benefits of energy efficiency improvements and encouraging household investments in the energy retrofit. Comprehensive studies addressing these criteria are crucial for informed actions, paving the way for effective policies that align with global decarbonization goals in the AMM countries.

Furthermore, to inform actions and decisions regarding energy retrofitting in existing residential buildings, it is essential to conduct studies using both top-down and bottom-up approaches. Such studies play a pivotal role in developing appropriate schemes and policies aimed at achieving the decarbonization transition targets established by the AMM countries. In this regard, developing a comprehensive framework for the energy modelling of existing buildings that integrates BEM with BIM is essential.

In addition, the literature related to residential energy retrofitting in the AMM countries should encompass both pre- and post-retrofit M&V processes. Pre-retrofit M&V facilitates the calibration and validation of energy models, while post-M&V processes validate the outcomes of energy retrofitting in existing residential buildings. This approach not only informs retrofit decisions but also encourages and builds confidence in homeowners to embrace energy retrofitting initiatives.

It is noteworthy that the selection of EEMs depends on the building's location, taking into account the unique climate, building types, and local EEM markets. Energy retrofitting studies in the AMM countries should analyse implementable EEMs and present the most feasible ones based on sustainability criteria and objectives. Thus, incorporating optimization methods aids in developing effective approaches to identify the most suitable or optimum EEM packages for improving the energy performance and overall sustainability of the existing residential building stock.

4. Results

The initial search yielded 23,565 documents. Following the application of inclusion and exclusion criteria through Boolean options in SCOPUS and WoS, and the subsequent removal of duplicates, the search results were refined to 774 articles. The initial screening identified 328 articles, and after the second screening, 152 articles remained. The final screening process yielded 41 relevant studies in the AMM countries, with 32 studies found in Mashreq countries and 9 in Maghreb countries, as shown in Figure 7. In the

Mashreq countries, there were 18 studies in Jordan [64,65,69–84], 9 in Egypt [85–94], 2 in Palestine [95,96], 2 in Iraq [97,98], 1 in Lebanon [99], and no study was presented for Syria. In the Maghreb countries, there were 5 studies in Algeria [100–104], 3 in Morocco [105–107], 1 in Tunisia [67], and no study was presented for Libya. Table 2 presents a record of all the studies found, including the year of publication, author names, and article titles, indicating the most prominent researchers in this topic within the region.

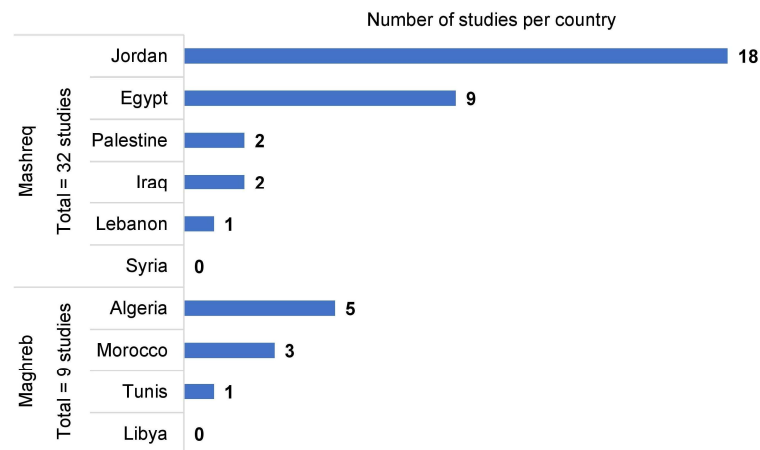


Figure 7. The geographical distribution of the studies in the AMM countries.

Table 2. Resulting studies.

Ref.	Year	Authors	Title
[69]	2011	Jaber, Samar, Ajib, Salman	“Optimum, technical and energy efficiency design of residential building in Mediterranean region”
[64]	2018	Bataineh, Khaled, Alrabee, Ayham	“Improving the energy efficiency of the residential buildings in Jordan”
[70]	2020	Albatayneh, Aiman, Assaf, Mohammad, Jaradat, Mustafa, Alterman, Dariusz	“The effectiveness of infiltration against roof insulation aimed at low income housing retrofits for different climate zones in Jordan”
[71]	2021	Albatayneh, Aiman	“Optimisation of building envelope parameters in a semi-arid and warm Mediterranean climate zone”
[72]	2021	Albatayneh, Aiman	“Optimising the parameters of a building envelope in the east Mediterranean Saharan, cool climate Zone”
[73]	2021	Albatayneh, Aiman, Tayara, Tarek, Mohammad, Jaradat, Al-Omary, Murad, Hindiyeh, Muna, Alterman, Dariusz, Ishbeytah, Manal	“Optimum Building Design Variables in a Warm Saharan Mediterranean Climate Zone”
[74]	2021	Albatayneh, Aiman, Atieh, Haya, Jaradat, Mustafa, Al-Omary, Murad, Zaquot, Maha, Juaidi, Adel, Abdallah, Ramez, Manzano-Agugliaro, Francisco	“The impact of modern artificial lighting on the optimum window-to-wall ratio of residential buildings in Jordan”
[75]	2021	Albatayneh, Aiman, Juaidi, Adel, Abdallah, Ramez, Manzano-Agugliaro, Francisco	“Influence of the advancement in the led lighting technologies on the optimum windows-to-wall ratio of Jordanians residential buildings”
[76]	2021	Muhaidat, Jihan, Albatayneh, Aiman, Assaf, Mohammed, Juaidi, Adel, Abdallah, Ramez, Manzano-Agugliaro, Francisco	“The significance of occupants’ interaction with their environment on reducing cooling loads and dermatological distresses in east Mediterranean climates”

Table 2. Cont.

Ref.	Year	Authors	Title
[65]	2022	Abu Qadourah, Jenan, Al-Falahat, Ala'a, Alrwashdeh, Saad, Nytsch-Geusen, Christoph	"Improving the energy performance of the typical multi-family buildings in Amman, Jordan"
[77]	2022	Albdour, Mohammad, Shalby, Mohammad, Salah, Ahmad, Alhomaidat, Fadi	"Evaluating and enhancing the energy efficiency of representative residential buildings by applying national and international standards using BIM"
[78]	2022	Bataineh, Khaled, Alrabee, Ayham	"A cost effective approach to design of energy efficient residential buildings"
[79]	2022	Bataineh, Khaled, Alrabee, Ayham	"Design optimization of energy efficient residential buildings in Mediterranean region"
[80]	2022	Albatayneh, Aiman, Albadaine, Renad, Juaidi, Adel, Abdallah, Ramez, Montoya, Maria, Manzano-Agugliaro, Francisco	"Rooftop photovoltaic system as a shading device for uninsulated buildings"
[81]	2022	Albatayneh, Aiman, Albadaine, Renad, Juaidi, Adel, Abdallah, Ramez, Zabalo, Alberto, Manzano-Agugliaro, Francisco	"Enhancing the energy efficiency of buildings by shading with PV panels in semi-arid climate zone"
[82]	2022	Albatayneh, Aiman, Assaf, Mohammed, Albadaine, Renad, Juaidi, Adel, Abdallah, Ramez, Zabalo, Alberto, Manzano-Agugliaro, Francisco	"Reducing the operating energy of buildings in arid climates through an adaptive approach"
[83]	2023	Nouh Ma'bdeh, Shouib, Ghani, Yasmeen Abdull, Obeidat, Laith, Alosan, Mohammed	"Affordability assessment of passive retrofitting measures for residential buildings using life cycle assessment"
[84]	2023	Nouh Ma'bdeh, Shouib, Fawwaz Alrebei, Odi, Obeidat, Laith, Al-Radaideh, Tamer, Kaouri, Katerina, Amhamed, Abdulkarem	"Quantifying energy reduction and thermal comfort for a residential building ventilated with a window-windcatcher: A case study"
[85]	2015	Dabaieh, Marwa, Elbably, Ahmed	"Ventilated Trombe wall as a passive solar heating and cooling retrofitting approach; a low-tech design for off-grid settlements in semi-arid climates"
[86]	2019	Dabaieha, Marwa, Maguidb, Dalya, El-Mahdyb, Deena, Wanasc, Omar,	"An urban living lab monitoring and post occupancy evaluation for a Trombe wall proof of concept"
[87]	2021	Abdelrady, Ahmed, Abdelhafez, Mohamed Hssan Hassan, Ragab, Ayman	"Use of insulation based on nanomaterials to improve energy efficiency of residential buildings in a hot desert climate"
[88]	2022	Kazem, Medhat, Ezzeldin, Sherif, Tolba, Osama	"Life-cycle cost analysis for façade retrofit measures of residential buildings in Cairo"
[89]	2020	Sameh, Sherin, Kamel, Basil	"Promoting green retrofitting to enhance energy efficiency of residential buildings in Egypt"
[90]	2018	Wahba, Sherine, Kamel, Basil, Nassar, Khaled, Abdelsalam, Ahmed,	"Effectiveness of green roofs and green walls on energy consumption and indoor comfort in arid climates"
[91]	2020	Ahmad, Rehab, El-Sayed, Zeyadm Taha, Dina, Fath, Hassan, Mahmoud, Hatem	"An approach to achieve thermal comfort and save energy in heritage buildings using different operating patterns"
[92]	2021	Ibrahim, Hanan, Khan, Ahmed, Mahar, Waqas Ahmed, Attia, Shady, Serag, Yehya	"Assessment of passive retrofitting scenarios in heritage residential buildings in hot, dry climates"
[93]	2023	Elsheikh, Asser, Motawa, Ibrahim, Diab, Esraa	"Multi-objective genetic algorithm optimization model for energy efficiency of residential building envelope under different climatic conditions in Egypt"

Table 2. Cont.

Ref.	Year	Authors	Title
[94]	2022	Haj Hussein, Muhannad, Monna, Sameh, Abdallah, Ramez, Juaidi, Adel, Albatayneh, Aiman	"Improving the thermal performance of building envelopes: An approach to enhancing the building energy efficiency code"
[95]	2021	Monna, Sameh, Juaidi, Adel, Abdallah, Ramez, Albatayneh, Aiman, Dutournie, Patrick, Jeguirim, Mejd	"Towards sustainable energy retrofitting, a simulation for potential energy use reduction in residential buildings in Palestine"
[96]	2021	Khudhaire Huda Yaseen, Naji, Hafeth Ibrahim	"Using building information modeling to retrofit abandoned construction projects in Iraq to achieve low-energy"
[97]	2018	Radha, Chro Ali Hama	"Traditional houses energy optimization using passive strategies"
[98]	2022	Sassine, Emilio, Dgheim, Joseph, Cherif, Yassine, Antczak, Emmanuel	"Low-energy building envelope design in Lebanese climate context: the case study of traditional Lebanese detached house"
[99]	2017	Derradji, Lotfi, Imessad, Khaled, Amara, Mohamed, Boudali Errebai, Farid	"A study on residential energy requirement and the effect of the glazing on the optimum insulation thickness"
[100]	2018	Djebbar, Khadidja, Salem, Souria, Mokhtari, Abderrahmane	"A multi-objective optimization approach of housing in Algeria. A step towards sustainability"
[101]	2021	Hamdani, Maamar, Bekkouche, Sidi Mohammad, Al-Saadi, Saleh, Cherier, Mohamed Kamal, Djefal, Rachid, Zaiani, Mohamed	"Judicious method of integrating phase change materials into a building envelope under Saharan climate"
[102]	2022	Kadri, Meryem, Bouchair, Ammar, Laafer, Abdelkader	"The contribution of double skin roof coupled with thermo reflective paint to improve thermal and energy performance for the 'Mozabit' houses: Case of Beni Isguen's Ksar in southern Algeria"
[103]	2020	Kerfah, Ilyas, El Hassar, Sidi Mohamed, Rouleau, Jean, Gosselin, Louis, Larabi, Abdelkader	"Analysis of strategies to reduce thermal discomfort and natural gas consumption during heating season in Algerian residential dwellings"
[104]	2018	Sghiouri, Haitham, Mezrab, Ahmed, Karkri, Mustapha, Naji, Hassane	"Shading devices optimization to enhance thermal comfort and energy performance of a residential building in Morocco"
[105]	2018	Drissi Lamrhari, El-Hadi, Benhamou, Brahim	"Thermal behavior and energy saving analysis of a flat with different energy efficiency measures in six climates"
[106]	2017	Sobhy, Issam, Brakez, Abderrahim, Benhamou, Brahim	"Analysis for thermal behavior and energy savings of a semi-detached house with different insulation strategies in a hot semi-arid climate"
[67]	2012	Ihm, Pyeongchan, Krarti, Moncef	"Design optimization of energy efficient residential buildings in Tunisia"

Furthermore, an analysis of the publication dates of the studies reveals that approximately 72% of the studies have been published in the past five years, while the remaining were published in the seven years prior to that, as shown in Figure 8. Notably, the years 2021 and 2022 witnessed the highest number of studies, with twelve published in each year. This pattern suggests that energy retrofitting is currently a prominent research area in the region, though the field is still emerging and maturing. This is attributed to the increasing importance of energy retrofitting in residential buildings, as explained in the earlier section.

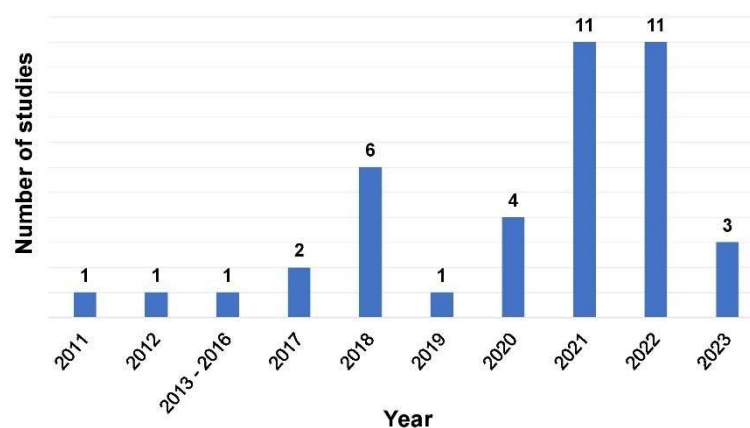


Figure 8. Number of studies per year in AMM countries.

Among AMM countries, Jordan excels with 18 energy retrofit studies, driven by neighbouring instability, population growth, and rising residential energy demand, as discussed in Section 2 of this paper. For instance, Jaber and Ajib [69] examined the impact of enhancing the envelope systems of a typical residential building in Jordan. They employed a bottom-up statistical approach to develop the energy model and conducted a scenario analysis to assess the potential energy savings considering the LCC. They found that potential energy savings of up to 25.31% can be achieved, resulting in an additional cost of 23.5% and LCC of 11.7%.

Furthermore, Bataineh and Alrabee [64,78] employed a comprehensive bottom-up statistical approach to analyse several predefined values of EEMs to improve the energy efficiency of residential buildings in Jordan. The EEMs included envelope insulation, window glazing, adjusting temperature settings, improving lighting systems, and improving the Heating, Ventilation, and Air Conditioning (HVAC) system efficiency. In [64], they developed prototype models for three common building types in the CSa climatic zone: villa, single-family house, and multistorey building. They conducted scenario analysis to investigate the potential environmental, economic, and social benefits from applying each EEM separately. Then, they categorized the EEMs into three levels based on the cost of implementation. The results indicated that implementing the third level of retrofitting, which encompassed all the EEMs, could lead to energy savings of 34.8%, 50.9%, and 47% for single-storey houses, apartment buildings, and two-storey villas, respectively. The corresponding payback periods were estimated at 18.58, 9.4, and 13.9 years. Moreover, the implementation of these measures could result in a reduction in CO₂ emissions by up to 46% and can create approximately 80,769 job opportunities for the local community.

In another research study [78], Bataineh and Alrabee conducted a scenario analysis using a similar categorization of EEMs as in their previous study [64], but this time for a two-storey residential building in three different climatic zones in Jordan: CSa, BWk, and BWh. Subsequently, they performed multi-objective optimization using a sequential search optimization method, considering energy savings and LCC as objectives and a range of values for each of the EEMs. The LCC calculations considered the project's lifespan, discount rate, and inflation rate. The results indicated that using the optimal combination of EEMs led to energy savings of 50%, 50%, and 52% with LCC reductions of 39%, 48.6%, and 48% for the CSa, BWk, and BWh zones, respectively.

Moreover, studies [71–73] examined the potential energy savings from optimizing the building envelope of a single-family house located in three different climatic zones in Jordan: BSh, BWk, and BWh, respectively. These studies investigated various EEMs including adding insulation to the building envelope, modifying the cooling and heating set point temperatures, improving thermal mass through internal walls (partitions), modifying the window-to-wall ratio (WWR), installing internal and external shading devices, and improving the natural ventilation rate. The researchers utilized bottom-up statistical

approach and a multi-objective optimization analysis was performed using the Genetic Algorithm to identify the optimal value for each EEM considering reducing the heating and cooling loads as objectives. The results indicated a potential of more than 90% reduction in heating and cooling loads using the optimal values of the considered EEMs in the three different climatic zones.

In Egypt, nine studies have examined the energy retrofitting of existing residential buildings. For instance, Dabaieh and Elbably [85] aimed to assess the energy performance and economic feasibility of implementing an integrated Trombe wall, which is enhanced with features such as grey paint instead of black paint, 15 cm reversible natural wool insulation, and two 3 mm thick roll-up wool curtains, compared to a traditional Trombe wall. The study employed a bottom-up physical approach to develop an energy model of the building. Three scenarios were considered for parametric analysis: (1) the base case building, (2) the application of a traditional Trombe wall, and (3) the application of an integrated Trombe wall. The results revealed significant improvements in energy efficiency. The integrated Trombe wall reduced heating and cooling loads by 94% and 73%, respectively, leading to a substantial reduction in CO₂ emissions by 144,267 kg. Also, when no systems were used, the discomfort hours during winter and summer were reduced by 2414 and 1072 h, respectively.

Moreover, Dabaieh et al. [86] conducted a one-year post-retrofitting M&V after applying the Trombe wall to one room of the selected case study building. They installed sensors to measure temperature and relative humidity over one year in the retrofitted room and in another room without Trombe walls. Also, the monitoring campaign included a semi-structured questionnaire administered to the building users to evaluate the thermal comfort improvement in the retrofitted room and the willingness to adopt the integrated Trombe walls. The results demonstrated a reduction in thermal discomfort hours in the retrofitted room by 425 h (24.4%) during summer and 15 (0.75%) hours during winter, compared with the non-retrofitted room. This indicated a significant difference between the simulation and the measurements.

Furthermore, Abdelrady et al. [87] investigated the potential energy savings achievable by improving the envelope system of a multifamily residential building located in the BWh climatic zone in Egypt. They also assessed the economic viability of applying EEMs using the simple payback period method. The EEMs included the addition of nanomaterials as insulation to the external walls and the enhancement of window glazing. A bottom-up physical approach was employed for designing the energy model. A scenario analysis was conducted, starting with analysing each EEM separately, followed by different combinations. The results indicated annual energy savings of 23% for wall insulation, 26% for window glazing improvements, and 47.6% when both walls and windows were insulated. Moreover, the result revealed a payback period of 17 years for the implemented measures.

Two studies were conducted on the energy retrofitting of residential buildings in Palestine. Monna et al. [95] investigated the potential energy savings achieved by implementing various EEMs to the residential building stock across three climatic zones: CSa, BSh, and BWh. The retrofitting plans were divided into three levels based on the cost of EEMs. They conducted scenario analyses using the three levels of retrofitting plans. Results indicated that energy consumption could be reduced by up to 24%, 57%, and 80% using level one, two, and three, respectively.

Furthermore, Haj Hussein et al. [94] examined the potential energy savings resulting from the implementation of four different energy codes to the residential sector in the CSa, BSh, and BWh climatic zones in Palestine: the Jordanian building energy code, Palestinian building energy code, green building guidelines, and the ASHRAE code for building envelopes. The focus was primarily on improving the U-value of the building envelope. A bottom-up statistical approach was utilized to develop the energy model for two prototypical multifamily buildings. The study revealed that the current energy performance of the residential building stock, without energy codes or under the existing Palestinian building energy code, fell significantly short of buildings complying with international building

energy codes. Additionally, the use of thermal insulation to enhance the U-value of the building envelope was found to reduce heating energy demand by 43% to 83%, depending on the climatic zone.

In Iraq, Khudhaire and Naji [96] examined the potential energy savings resulting from implementing three EEMs in an abandoned multifamily building in the BSh climatic zone. The EEMs included enhancements to the lighting and HVAC systems and improvements to the window glazing. The authors employed a bottom-up statistical approach to develop the energy model. Parametric analysis was conducted separately for each EEM, followed by an investigation of the cumulative energy savings resulting from the EEMs combined. The findings revealed a 24% reduction in energy consumption upon implementing the EEMs.

Additionally, Radha [97] assessed the energy-saving benefits of employing six EEMs in the CSa climatic zone in Iraq. These EEMs included installing thermal insulation to the building envelope, enhancing window glazing, reducing WWR, minimizing infiltration rates, installing window wind catchers, and implementing external shading. The researcher employed a bottom-up statistical approach to develop the energy model. Scenario analyses were conducted using the proposed EEMs. Initially, the researcher evaluated the potential savings from each EEM and subsequently combined the most effective EEMs. The findings indicated that by implementing the best combination of EEMs, a potential energy saving of 34% could be achieved with only a 1% improvement in thermal comfort hours.

In Lebanon, Sassine et al. [98] examined the potential energy savings resulting from applying various EEMs to the existing houses across the CSa, CSb, Dsa, and DSb climatic zones. These EEMs included enhancing the building envelope using insulation materials and improving the solar absorptance of the surface, modifying the WWR, and improving airtightness. They utilized a bottom-up statistical approach to develop the energy model of prototypical two-storey house. Additionally, they conducted experimental tests on the walls to measure heat transfer, which was used to validate the energy model. Initially, they conducted a parametric analysis considering different values for each EEM separately. Subsequently, they utilized GenOpt software and a genetic algorithm, with the single objective of reducing energy consumption, to determine the optimal combination of measures that would maximize energy savings. Their findings indicate that by implementing the optimal combination, energy savings of up to 80% can be achieved depending on the climatic condition.

In Algeria, Derradji et al. [99] investigated the optimum insulation thickness for improving the energy performance and thermal comfort of the residential buildings across the CSa climatic zone. The methodology consisted of three stages. First, they conducted in situ measurements of the temperature and RH for an insulated single-storey residential building. Then, they built the energy model on TRNSYS which was calibrated and validated based on the in situ measurements. Following that, they removed the insulation materials from the walls to represent the prototypical residential buildings in Algeria. Both models, with and without insulation, were simulated. The result indicated that the addition of 9 cm thick insulation materials saved 70% of energy and reduced the impact of the outdoor temperature on the indoor temperature during summer and winter, which enhances occupants' thermal comfort.

Additionally, the authors investigated the optimum insulation thickness. A numerical method for optimization was performed. This method depended on various factors, including the cost and the U-value of the insulation material, the type of window glazing, WWR, cost of energy (considering three types of energy resources for heating, electricity, natural gas, and butane gas, and electricity for cooling), yearly heating and cooling transmission loads, the efficiency of the heating system and cooling equipment, and the lifetime of the building and the present worth factor. Three levels of window glazing and WWR were considered, by changing the insulation materials' thickness from 0 to 10 cm with 1 cm increments. They found that the optimal insulation thickness ranged between 1 and 2.5 cm for cooling and 1 and 7 cm for heating, with energy savings of up to USD 12.7/m².

Moreover, Hamdani et al. [101] explored the potential energy savings and improvement in thermal comfort by incorporating phase change material (PCM) into the building envelope in the BWh climatic zone in Algeria. They utilized a bottom-up statistical approach to develop a 3D model of the building using SketchUp, which was subsequently imported into TRNSYS for energy simulation. They conducted a parametric analysis to investigate the potential energy savings and thermal comfort enhancement from applying PCM to the building envelope. The results indicated that the application of fixed PCM panels to the whole envelope system (roofs and external walls) can achieve up to a 36.4% reduction in the annual energy consumption, along with a significant enhancement in thermal comfort during the summer season. Furthermore, they highlighted that judiciously integrating PCM (removable PCM panels) based on orientation and seasonal variations could yield additional energy savings of 14.34%.

Sghiouri et al. [104] conducted research on enhancing thermal comfort and reducing energy consumption through the implementation of external overhang shadings on windows in three climatic zones in Morocco: BSh, BSk, and CSa. Using the bottom-up statistical approach, they created the energy model of a prototypical two-storey multifamily building. Through single-objective optimization and using the Non-dominated Sorting Genetic Algorithm II (NSGA-II), they determined the optimal length for the external shading, considering thermal discomfort hours as the objective of the optimization. JEPlus was used to conduct the optimization, connecting the results of the TRNSYS simulation with the NSGA-II algorithm that changed the length of the overhang shading. To reduce the time of optimization, the authors used a 3 cm increment in the length of the overhang and the number of generations was set to a maximum of 150. The study concluded that the optimal length of the overhang depends on factors such as window orientation and climatic zones. The results demonstrated a reduction in discomfort hours ranging from 104 to 138 h, depending on the climatic zone. Additionally, the cooling energy demand decreased by up to 4.8%, while the heating energy load increased by up to 2%.

In addition, in their study, Sobhy et al. [106] investigated the energy savings from improving the envelope system of a two-storey house located in the BSh climatic zone in Morocco. They investigated the application of the following EEMs: wall insulation using a cavity wall (air gap) and roof insulation using either 4 cm XPS or a hollow core slab with a 5 cm gap. The bottom-up physical approach was employed, and the energy model was developed using TRNSYS software. Scenario analyses were performed through the application of the EEMs both separately and combined. The results indicated that the implementation of the 4 cm XPS roof insulation reduced heating and cooling loads by 10% and 30% respectively. Additionally, the 5 cm cavity wall insulation, which exists in the real building, resulted in energy consumption reductions of 13% for heating and 5% for cooling compared with the reference building. The combination of these two insulation measures achieved energy reductions of 26% for heating and 40% for cooling. Furthermore, the 5 cm gap in the slab contributed to heating and cooling load reductions of 19% and 31% respectively.

Krarti and Ihm [67], from Tunisia, conducted a study that aimed to enhance the energy performance of the residential building stock across four climatic zones: CSa, BSh, BWk, and BWh. They investigated the optimal values and combinations of various EEMs including building orientation, wall insulation, roof insulation, WWR, window glazing, lighting, infiltration rate, cooling set point temperature, and the efficiency of appliances such as refrigerators, boilers, and air conditioning. To develop the energy model of a prototypical villa, they utilized a bottom-up statistical approach with the DOE2 simulation engine. The researchers conducted multi-objective optimization using the sequential search optimization method, as described in detail in Section 3.2.7, and considering two objectives: energy savings and LCC. The LCC calculation factored in the initial costs of implementing the EEMs, energy costs, annual discounted rate, and the expected lifespan of the measures. The findings revealed that the optimal package of EEMs for each climatic zone resulted in approximately 60% energy savings and 33,000 LCC. Furthermore, the

researchers explored the impact of changing the annual discount rate and highlighted that higher annual discount rates led to the selection of different optimum EEM packages, potentially resulting in lower energy savings and LCC.

In both Syria and Libya, no studies were identified. In Libya, a limited number of studies were found, focusing on energy retrofitting, including a case study of an office building [107] and improvement in the HVAC systems in residential buildings [108]. Nevertheless, these studies were excluded based on the inclusion and exclusion criteria outlined in the methodology section. Despite these findings, it is important to acknowledge that the overall research landscape in Libya remains limited.

5. Discussion

A considerable number of studies in the literature have focused on the energy retrofitting of residential buildings in the AMM countries. These studies consistently highlight the potential for substantial energy consumption reductions through the application of retrofitting measures. A more in-depth analysis of these studies reveals several gaps that must be addressed to develop comprehensive actions and decision-making models for the energy retrofitting of existing homes and to advance the practice of energy retrofitting in the AMM countries. This section aims to critically analyse the studies based on the six parameters presented in Section 3.2.

5.1. Energy Sustainability Criteria and Objectives

The sustainability criteria, order, and objectives in the 41 studies are listed in Table 3. Notably, 47.6% and 36.6% of these studies focus on the 1st and 2nd orders of sustainability, while only 17.1% explore the 3rd order. This highlights a significant gap in 3rd order energy sustainability research. Figure 9 illustrates the distribution of sustainability orders in AMM countries' energy retrofitting studies.

Table 3. Energy sustainability criteria and objectives.

Ref.	Order of Sustainability	Environment	Economic	Social
[69]	2nd order	Energy saving	LCC	No
[64]	3rd order	Energy saving CO ₂ emission reduction	Payback period	Job creation
[70]	1st order	Energy saving	No	No
[71]	1st order	Energy saving	No	No
[72]	1st order	Energy saving	No	No
[73]	1st order	Energy saving	No	No
[74]	1st order	Energy saving	No	No
[75]	1st order	Energy saving	No	No
[76]	1st order	Energy saving	No	No
[65]	1st order	Energy saving	No	No
[77]	1st order	Energy saving	No	No
[78]	3rd order	Energy saving	Payback period and LCC	Job creation
[79]	2nd order	Energy saving	LCC	No
[80]	1st order	Energy saving	No	No
[81]	1st order	Energy saving	No	No
[82]	1st order	Energy saving	No	No
[83]	2nd order	Energy saving Life Cycle CO ₂ emission reduction	LCC	No

Table 3. Cont.

Ref.	Order of Sustainability	Environment	Economic	Social
[84]	3rd order	Energy saving	Cost reduction of cooling load	Thermal discomfort hours
[85]	3rd order	Energy saving CO ₂ emissions reduction	Payback period LCC	Thermal comfort
[86]	1st order	No	No	Thermal comfort
[87]	2nd order	Energy saving	Simple payback period	No
[88]	2nd order	Energy saving	LCC	No
[89]	1st order	Energy saving	No	No
[90]	2nd order	Energy saving CO ₂ emissions reduction	No	Thermal comfort
[91]	2nd order	Energy saving	No	Thermal comfort and heritage identity
[92]	2nd order	Energy saving	No	Thermal comfort and heritage identity
[93]	3rd order	Energy saving	LCC	Thermal comfort
[94]	1st order	Energy saving	No	No
[95]	1st order	Energy saving	No	No
[96]	1st order	Energy saving	No	No
[97]	2nd order	Energy saving	No	Thermal comfort
[98]	1st order	Energy saving	No	No
[99]	3rd order	Energy saving	Cost of energy saving	Thermal comfort
[100]	3rd order	Energy saving	Payback period	Thermal comfort
[101]	2nd order	Energy saving	No	Thermal comfort
[102]	2nd order	Energy saving	No	Thermal comfort
[103]	2nd order	Energy saving	No	Thermal comfort
[104]	2nd order	Energy saving	No	Thermal comfort
[105]	2nd order	Energy saving	No	Thermal comfort
[106]	1st order	Energy saving	No	No
[67]	2nd order	Energy saving	LCC	No

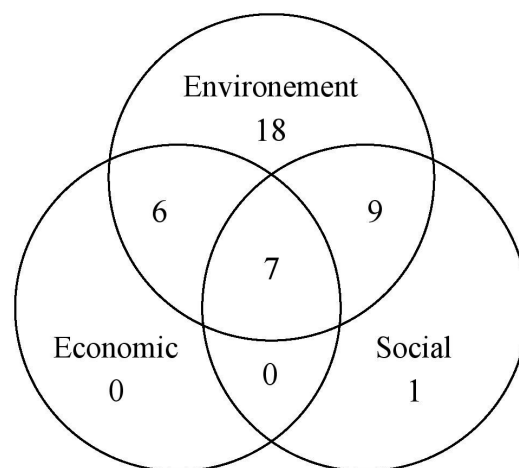


Figure 9. Orders of sustainability of the selected studies.

In the energy-related environmental criteria, energy savings are the primary objective in all studies except [86]. This aligns with previous reviews emphasizing energy-related goals like reducing consumption [33–35]. It suggests significant potential for energy consumption reduction in AMM residential buildings. However, only four studies address reducing CO₂ emissions from retrofitting. While saving energy lowers GHG emissions, researchers should also consider emission reduction, especially with fossil fuels. Focusing on CO₂ reduction can encourage local governments to invest in decarbonization.

Economic criteria were examined in 13 studies, primarily focusing on the payback period, followed by LCC and cost-effectiveness. The economic assessment of residential retrofitting is well established in the region but is lacking in some countries like Palestine, Iraq, Lebanon, and Morocco. However, calculating costs based on international rates limits accuracy. Conducting country-level market studies would provide more realistic figures, promoting household investment.

Seventeen studies explored the social dimension, with most emphasizing thermal comfort. Few investigated job creation and historical building identity. There is a scarcity of thermal comfort studies in Arab Mashreq countries compared to Arab Maghreb countries. Prior reviews also noted the need for more social research, including visual, lighting, and acoustic comforts resulting from residential energy retrofitting [35].

5.2. Study Approach

In the 41 studies conducted in AMM countries (Table 4), 78% employ the bottom-up statistical approach, while none use the top-down approach, a significant finding. Top-down approaches, recommended by government bodies, assess energy retrofitting's holistic impact, including the environmental, economic, and social aspects [14]. The lack of studies utilizing the top-down approach in the AMM countries can be attributed to two potential scenarios. Firstly, such studies might exist but have not been published in scientific domains. It is possible that government agencies and researchers have conducted assessments utilizing the top-down approach but chose not to share the findings publicly. Secondly, it is more likely that no research utilizing the top-down approach has been conducted at all. This could be due to the requirement of significant expertise, access to confidential data, and resources, which may be lacking in the AMM countries.

Another reason for the absence of top-down studies could be the lack of established energy retrofitting schemes for residential buildings across AMM countries, despite their growing focus on energy sustainability. Addressing this research gap is essential, requiring comprehensive, top-down studies in each AMM country to understand barriers and develop effective strategies.

On the other hand, the bottom-up statistical approach is prevalent, with prototypical models representing building stocks. However, the bottom-up physical approach is underutilized (22% of studies), indicating a literature gap in detailed energy retrofitting aspects. Embracing the bottom-up physical approach can provide valuable experimental data on indoor comfort, air quality, and greenhouse gas emissions. This approach offers a more realistic assessment of energy retrofitting's impacts, motivating homeowners to invest. The data collected through the bottom-up physical approach can play a crucial role in monitoring and evaluating energy retrofitting work both before and after the retrofitting process. This monitoring capability enhances the overall effectiveness of retrofit projects and contributes to the continuous improvement in existing frameworks. Conducting more studies based on executed retrofit projects will address this gap besides validating the existing proven frameworks.

Table 4. Study approach.

Ref.	Case Study Model Type	Approach	Framework Presented
[69]	Prototypical	Bottom-up statistical	No
[64]	Prototypical	Bottom-up statistical	No
[70]	Prototypical	Bottom-up statistical	No
[71]	Prototypical	Bottom-up statistical	No
[72]	Prototypical	Bottom-up statistical	No
[73]	Prototypical	Bottom-up statistical	No
[74]	Prototypical	Bottom-up statistical	No
[75]	Prototypical	Bottom-up statistical	No
[76]	Prototypical	Bottom-up statistical	No
[65]	Prototypical	Bottom-up statistical	Yes
[77]	Specific	Bottom-up physical	Yes
[78]	Prototypical	Bottom-up statistical	No
[79]	Prototypical	Bottom-up statistical	Yes
[80]	Prototypical	Bottom-up statistical	Yes
[81]	Prototypical	Bottom-up statistical	No
[82]	Prototypical	Bottom-up statistical	No
[83]	Prototypical	Bottom-up statistical	No
[84]	Prototypical	Bottom-up statistical	No
[85]	Specific	Bottom-up physical	No
[86]	Specific	Bottom-up physical	Yes
[87]	Specific	Bottom-up physical	Yes
[88]	Prototypical	Bottom-up statistical	No
[89]	Prototypical	Bottom-up statistical	No
[90]	Prototypical	Bottom-up statistical	No
[91]	Prototypical	Bottom-up statistical	No
[92]	Specific	Bottom-up physical	Yes
[93]	Prototypical	Bottom-up statistical	Yes
[94]	Prototypical	Bottom-up statistical	Yes
[95]	Prototypical	Bottom-up statistical	No
[96]	Prototypical	Bottom-up statistical	Yes
[97]	Prototypical	Bottom-up statistical	Yes
[98]	Prototypical	Bottom-up statistical	Yes
[99]	Specific	Bottom-up physical	No
[100]	Prototypical	Bottom-up statistical	No
[101]	Prototypical	Bottom-up statistical	No
[102]	Specific	Bottom-up physical	Yes
[103]	Specific	Bottom-up physical	No
[104]	Prototypical	Bottom-up statistical	Yes
[105]	Prototypical	Bottom-up statistical	No
[106]	Specific	Bottom-up physical	No
[67]	Prototypical	Bottom-up statistical	Yes

Moreover, the analysis revealed a predominant focus on individual building levels, with commonly used case study model types being either prototypical buildings or specific individual buildings. This underscores the oversight of interactions between buildings and the environment. The adoption of an urban-scale retrofit approach has demonstrated the potential to increase the renovation rate by over 3% [109]. However, implementing an urban level retrofit poses challenges, as it necessitates the collection and analysis of substantial amounts of data [110]. Shifting the focus from the individual building level to an urban level in the AMM countries is imperative for the sustainable development of residential building stocks.

5.3. Software Used

Table 5 outlines the use of 3D modelling software, energy simulation tools, and BIM applications across the 41 studies. Also, Figure 10a,b show the percentages of 3D modelling software and energy simulation tools' usage, respectively. The majority of the studies, 56.1%, employed the all-in-one BEM approach primarily utilizing DesignBuilder software (53.7%) and IDA ICE software (2.4%). An integration between 3D modelling software and energy analysis software appeared in 17.1% of the studies, with 9.8% using Revit and 7.3% utilizing Sketchup software. The remaining studies, 24.4%, employed the standalone approach without mentioning the method used to build the 3D models. Notably, DesignBuilder and EnergyPlus are the most recognized BEM software and simulation tools due to their user-friendly interface and capabilities, making them suitable for the AMM region's energy retrofitting initiatives.

Table 5. Software used in the selected studies.

Ref.	3D Model Creation Software	Energy Analysis Software	BIM Use
[69]	Not mentioned	TRNSYS	No
[64]	DesignBuilder	EnergyPlus	No
[70]	DesignBuilder	EnergyPlus	No
[71]	DesignBuilder	EnergyPlus	No
[72]	DesignBuilder	EnergyPlus	No
[73]	DesignBuilder	EnergyPlus	No
[74]	DesignBuilder	EnergyPlus	No
[75]	DesignBuilder	EnergyPlus	No
[76]	DesignBuilder	EnergyPlus	No
[65]	Sketchup	IDA ICE	No
[77]	Revit 2020	EnergyPlus	Yes (limited)
[78]	DesignBuilder	EnergyPlus	No
[79]	DesignBuilder	EnergyPlus	No
[80]	Revit 2020	IES-VE	No
[81]	Revit 2020	IES-VE	Yes (limited)
[82]	DesignBuilder	EnergyPlus	No
[83]	Not mentioned	IES-VE	No
[84]	DesignBuilder	EnergyPlus	No
[85]	DesignBuilder	EnergyPlus	No
[86]	None	None	No
[87]	DesignBuilder	EnergyPlus	No
[88]	DesignBuilder	EnergyPlus	No

Table 5. Cont.

Ref.	3D Model Creation Software	Energy Analysis Software	BIM Use
[89]	Not mentioned	Hourly Analysis Program (HAP)	No
[90]	DesignBuilder	EnergyPlus	No
[91]	DesignBuilder	EnergyPlus	No
[92]	DesignBuilder	EnergyPlus	No
[93]	DesignBuilder	EnergyPlus	No
[94]	DesignBuilder	EnergyPlus	No
[95]	DesignBuilder	EnergyPlus	No
[96]	Revit 2020	EnergyPlus	Yes (limited)
[97]	IDA ICE	IDA ICE	No
[98]	Not mentioned	TRNSYS	No
[99]	Not mentioned	TRNSYS	No
[100]	DesignBuilder	EnergyPlus	No
[101]	Sketchup	TRNSYS	No
[102]	Not mentioned	TRNSYS	No
[103]	Not mentioned	TRNSYS	No
[104]	Sketchup	TRNSYS	No
[105]	Not mentioned	TRNSYS	No
[106]	Not mentioned	TRNSYS	No
[67]	Not mentioned	DOE-2.2	No

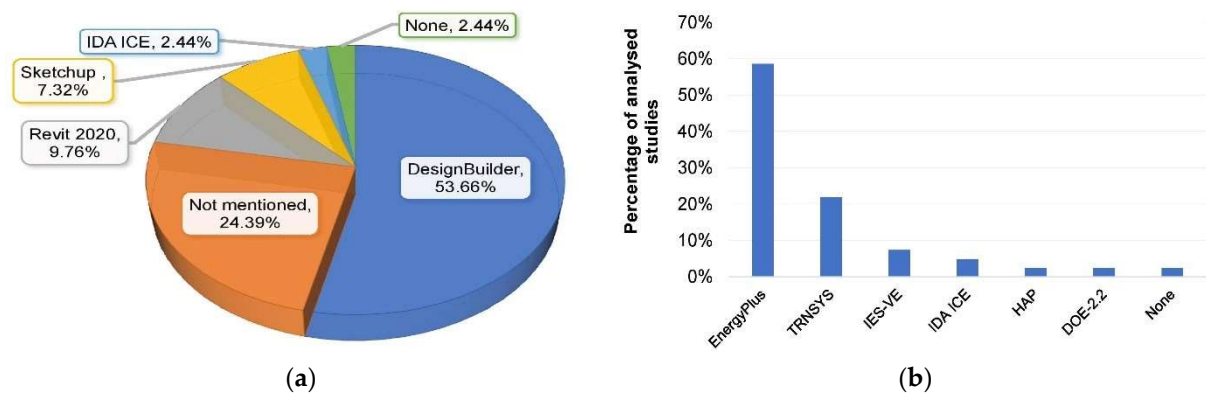


Figure 10. Software utilized in studies: (a) percentage of the use of 3D model creation software and (b) percentage of the use of energy simulation engines.

Three studies in AMM countries explicitly incorporated BIM for retrofitting existing buildings. However, the usage of BIM was limited to the interoperability between 3D models in BIM authoring tools and energy analysis software. This signifies a notable absence of a BIM-based framework capturing advantages beyond software interoperability, as discussed in Section 3.2.4. This identified gap underscores the need for future research efforts to develop and implement successful BIM-based frameworks through case studies. A thorough exploration of BIM's role in retrofitting within the studied region is deemed crucial to address this gap comprehensively.

5.4. Pre- and Post-Retrofitting M&V

Table 6 displays the use of pre- and post-retrofit M&V in the 41 studies. Notably, significant numbers of studies, representing 64%, relied on uncalibrated energy models. Of the few conducting pre-retrofit M&V, nine models were calibrated using sensors measuring temperature and humidity, three models were calibrated using energy bills, one used both sensors and bills for calibration, and one relied on laboratory tests for the calibration. Moreover, ASHRAE Guideline 14 was the major protocol used for the calibration of the energy models. For studies that utilized in situ measurements, it was noted that most measurements spanned a short period, with a maximum of two weeks. Nonetheless, some studies calibrated the models based on data collected in previous studies, which might not accurately represent the energy models. This highlights a lack of experimental data and realism in results.

Remarkably, only one study presented post-retrofit M&V, underscoring a severe gap in the literature. The absence of post-retrofit M&V leaves energy retrofitting unvalidated, linked to the scarcity of bottom-up physical approaches in AMM countries. Closing this gap is crucial for complete regional decision making and more effective retrofit schemes. Proven post-retrofit results can motivate homeowners and stakeholders to invest in sustainable retrofits.

Table 6. Pre-and post-retrofit M&V in the analysed studies.

Ref.	Model Calibration	Post-Retrofitting M&V	Monitoring Method
[69]	No	No	No
[64]	No	No	No
[70]	No	No	No
[71]	No	No	No
[72]	No	No	No
[73]	No	No	No
[74]	No	No	No
[75]	No	No	No
[76]	No	No	No
[65]	No	No	No
[77]	Yes (sensors, survey, energy bills)	No	No
[78]	Yes (sensors)	No	No
[79]	Yes (sensors)	No	No
[80]	No	No	No
[81]	No	No	No
[82]	No	No	No
[83]	No	No	No
[84]	Yes (sensors)	No	No
[85]	Yes (sensors)	No	No
[86]	No	Yes	Sensors and post-occupancy evaluation
[87]	Yes (energy bills)	No	No
[88]	Yes (energy bills based on Attia's study)	No	No
[89]	No	No	No
[90]	Yes (energy bills) default apartment	No	No
[91]	No	No	No

Table 6. *Cont.*

Ref.	Model Calibration	Post-Retrofitting M&V	Monitoring Method
[92]	Yes (sensors)	No	No
[93]	No	No	No
[94]	No	No	No
[95]	No	No	No
[96]	No	No	No
[97]	No	No	No
[98]	Yes (experimental laboratory test)	No	No
[99]	Yes (sensors)	No	No
[100]	No	No	No
[101]	No	No	No
[102]	Yes (sensors)	No	No
[103]	Yes (sensors)	No	No
[104]	No	No	No
[105]	No	No	No
[106]	Yes (sensors)	No	No
[67]	No	No	No

5.5. Number, Type, and Values of EEMs

Most studies in AMM countries have explored various EEMs for retrofitting residential buildings (Table 7). The results indicated fifteen practical EEMs: (1) proper envelope insulation, (2) window glazing replacement, (3) window shading for daylight control, (4) WWR adjustment, (5) airtightness improvement, (6) efficient lighting, (7) enhanced night natural ventilation, (8) cooling/heating set point adjustment, (9) efficient HVAC systems, (10) HVAC schedule control, (11) efficient appliances (e.g., refrigerators, boilers), (12) lighter wall finishing colours, (13) increased thermal mass (e.g., internal wall thickness), (14) cool and green roofs, (15) window catchers.

Table 7. Number and type of EEMs.

Ref.	EEMs Used
[69]	WWR, external shading device, and envelope insulation.
[64]	Increasing cooling set point temperature, decreasing heating set point temperature, using efficient lighting system, adding envelope insulation, installing shading device, improving glazing type, and using efficient HVAC system.
[70]	Adding envelope insulation and reducing air infiltration.
[71]	Cooling set point temperature, heating set point temperature, envelope insulation, thermal mass, glazing type, WWR, infiltration rate, shading device, window's shading, and natural ventilation rate.
[72]	Cooling set point temperature, heating set point temperature, envelope insulation, thermal mass, glazing type, WWR, infiltration rate, shading device, window's shading, and natural ventilation rate.
[73]	Cooling set point temperature, heating set point temperature, envelope insulation, thermal mass, glazing type, WWR, infiltration rate, shading device, window's shading, and natural ventilation rate.
[74]	WWR.
[75]	WWR and lighting system.

Table 7. Cont.

Ref.	EEMs Used
[76]	Shading devices schedule, night-time natural ventilation.
[65]	Envelope insulation, glazing type, external shading devices, natural ventilation, and efficient lighting system.
[77]	Improving envelope system, using efficient HVAC system, using efficient water heating system, using efficient lighting system, improving the airtightness, and modifying WWR.
[78]	Increasing cooling set point temperature, decreasing heating set point temperature, using efficient lighting system, adding envelope insulation, installing shading device, improving glazing type, using efficient HVAC system, and using efficient boilers.
[79]	Increasing cooling set point temperature, decreasing heating set point temperature, using efficient lighting system, adding envelope insulation, installing shading device, improving glazing type, using efficient HVAC system, and using efficient boilers.
[80]	Installation of PV panels as rooftop shading device.
[81]	Installation of PV panels as rooftop shading device.
[82]	Control the HVAC system based on adaptive thermal comfort model.
[83]	Adding envelope insulation, improving window type, improving glazing systems and internal shading, adding external shading, improving the infiltration rate, and improving the solar reflection of the envelope.
[84]	Installing window wind catcher.
[85]	Integrated Trombe wall.
[86]	Integrated Trombe wall.
[87]	Adding nanomaterial insulation to external walls and windows.
[88]	Adding insulation to external walls, changing the WWR, improving the glazing, and installing external shading.
[89]	Adding wall insulation, replacing single glazing with double glazing, improving lighting system, and installing external shading.
[90]	Installing green layers to walls and roofs.
[91]	Improving the natural ventilation and controlling the HVAC set point temperature.
[92]	Improving the natural ventilation rate, improving window glazing, applying high reflective paint, and adding insulation to the building envelope.
[93]	Adding insulation to the building envelope, WWR, orientation, set point temperature, and controlling HVAC schedule.
[94]	Adding insulation to the building envelope and enhancing window system.
[95]	Increasing cooling set point temperature, decreasing heating set point temperature, reducing infiltration rate, adding insulation to the building envelope, improving glazing, improving lighting system, installing external shading, improving the natural ventilation, improving the HVAC system schedule, and improving the efficiency of the solar water heating system.
[96]	Improving the lighting system, installing efficient HVAC system, and improving window glazing.
[97]	Adding insulation to building envelope, improving glazing, reducing infiltration rate, reducing the WWR, installing wind catchers, and installing external shading.
[98]	Adding envelope insulation, modifying WWR, improving the airtightness, and improving the solar absorption of the envelope.
[99]	Adding envelope insulation for walls.
[100]	Adding insulation to the building envelope, thermal mass, enhancing window glazing, improving airtightness, and installing external shading
[101]	Installing integrated PCM panels as an insulation to the building envelope.
[102]	Adding insulation to the roofs and using highly reflective paint.

Table 7. Cont.

Ref.	EEMs Used
[103]	Installing an efficient heating system, adding an insulation layer to external walls, improving window glazing, and improving airtightness.
[104]	External shading.
[105]	Adding insulation to the building envelop, improving the glazing, applying a reflective paint colour to the envelope, and controlling the HVAC schedule.
[106]	Adding insulation to the building envelope.
[67]	Adding envelope insulation, increasing WWR, improving glazing, improving the lighting system, reducing the infiltration rate, increasing the cooling set point temperature, improving appliances, and improving the HVAC system.

Figure 11 reveals that the most implemented EEMs are better insulation and window shading for daylight control, appearing in 73% and 59% of studies, respectively. This aligns with previous reviews emphasizing the benefit of these EEMs [34–36] and some expert opinions on EEM choices for hot arid climates [111]. However, it is important to note that there is some inconsistency in selecting appropriate values for certain EEMs. For instance, researchers in the AMM countries have made different recommendations regarding glazing types. Generally, researchers reference previous studies or building codes/standards, but some codes were outdated, possibly affecting the effectiveness of EEM values. Thus, specifying the values for each of the EEMs becomes challenging, even though all the values presented in each study result in significant energy savings in residential buildings.

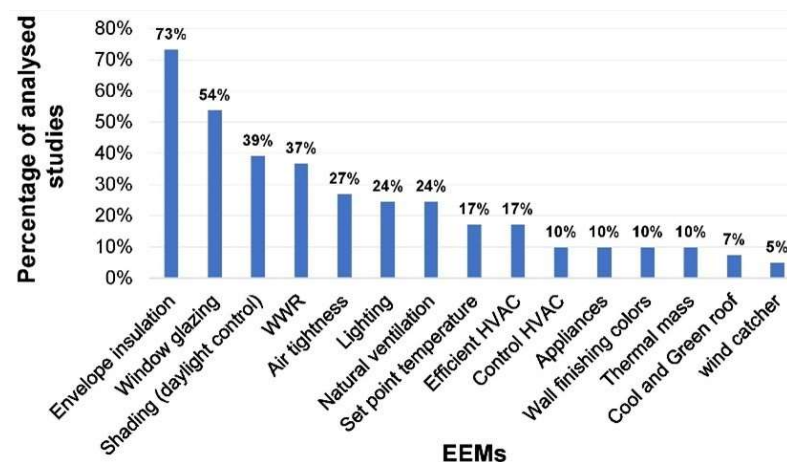


Figure 11. Percentage of the use of measures in analysed studies.

5.6. Optimization Methods

Table 8 displays the optimization methods in the 41 AMM country studies. It is evident that the scenario analysis method for optimization is well established across the AMM countries adopted by 78% of the analysed studies. However, only 22% of studies (nine in total) employed genetic algorithms for optimization. Among these, two focused on single objectives, while seven used multi-objective optimizations. This indicates that there is a lack of studies that utilize the optimization technique as a method of analysis. Most studies centred on environmental and economic criteria with only one study optimizing three objectives, including social criteria like thermal comfort. Expanding objectives to encompass all three sustainability criteria can identify solutions balancing trade-offs, advancing sustainable housing.

Table 8. Optimization method.

Ref.	Method	Optimization Algorithm (Software)	Optimization Objectives
[69]	Scenario analysis	N/A	Not applicable (N/A)
[64]	Scenario analysis	N/A	N/A
[70]	Scenario analysis	N/A	N/A
[71]	Optimization technique	Genetic Algorithm (embedded to DesignBuilder)	Heating vs. cooling energy savings
[72]	Optimization technique	Genetic Algorithm (embedded to DesignBuilder)	Heating vs. cooling energy savings
[73]	Optimization technique	Genetic Algorithm (embedded to DesignBuilder)	Heating vs. cooling energy savings
[74]	Scenario analysis	N/A	N/A
[75]	Scenario analysis	N/A	N/A
[76]	Scenario analysis	N/A	N/A
[65]	Scenario analysis	N/A	N/A
[77]	Scenario analysis	N/A	N/A
[78]	Optimization technique	Genetic Algorithm (BEopt)	Energy savings vs. LCC
[79]	Optimization technique	Genetic Algorithm (BEopt)	Energy savings vs. LCC
[80]	Scenario analysis	N/A	N/A
[81]	Scenario analysis	N/A	N/A
[82]	Scenario analysis	N/A	N/A
[83]	Scenario analysis	N/A	N/A
[84]	Scenario analysis	N/A	N/A
[85]	Scenario analysis	N/A	N/A
[86]	N/A	N/A	N/A
[87]	Scenario analysis	N/A	N/A
[88]	Scenario analysis	N/A	N/A
[89]	Scenario analysis	N/A	N/A
[90]	Scenario analysis	N/A	N/A
[91]	Scenario analysis	N/A	N/A
[92]	Scenario analysis	N/A	N/A
[93]	Optimization technique	NSGA-II (JEPPlus)	Energy consumption vs. LCC vs. discomfort thermal hours
[94]	Scenario analysis	N/A	N/A
[95]	Scenario analysis	N/A	N/A
[96]	Scenario analysis	N/A	N/A
[97]	Scenario analysis	N/A	N/A
[98]	Optimization technique	Genetic Algorithm (GenOpt)	Energy need
[99]	Scenario analysis	N/A	N/A
[100]	Scenario analysis	N/A	N/A
[101]	Scenario analysis	N/A	N/A

Table 8. *Cont.*

Ref.	Method	Optimization Algorithm (Software)	Optimization Objectives
[102]	Scenario analysis	N/A	N/A
[103]	Scenario analysis	N/A	N/A
[104]	Optimization technique	NSGA-II (JEPPlus)	Single objective (thermal discomfort hours)
[105]	Scenario analysis	N/A	N/A
[106]	Scenario analysis	N/A	N/A
[67]	Optimization technique	Genetic Algorithm (BEopt)	LCC vs. energy savings

6. Conclusions

In this study, a comprehensive review of the existing research on energy retrofitting in residential buildings within the AMM countries was conducted. Employing keyword-based searches, 41 pertinent studies that investigated the application of various EEMs for residential energy retrofitting were identified. These studies were predominantly located in the Mashreq region, with 32 studies, including 18 in Jordan, 9 in Egypt, 2 in Palestine, 2 in Iraq, and 1 in Lebanon. In contrast, nine studies were situated in the Maghreb countries, with five in Algeria, three in Morocco, and one in Tunisia. A closer examination of publication dates revealed that nearly 72% of these studies were published within the last five years, underscoring the growing research interest and activity in the field of energy retrofitting in the region.

The collected studies underwent a critical analysis, benchmarked against six key parameters: (1) energy sustainability criteria (environmental, economic, and social) and objectives, (2) approach of the study, (3) software used, (4) pre- and post-retrofit M&V, (5) number and type of EEMs, and (6) optimization methods. The reviewed studies collectively demonstrated substantial potential for environmental, economic, and social improvements through residential building energy retrofitting in the AMM countries. However, the analysis revealed a deficiency in studies considering all three sustainability criteria and the trade-offs between them. For instance, the studies in Jordan lack an investigation into the thermal comfort objective, which is necessary to maintain, in addition to energy savings and economic feasibility. This underscores the need for future studies to adopt a more holistic approach. Such a comprehensive perspective will provide a better understanding of the impact of energy retrofitting.

Moreover, it was found that the majority of studies employed a bottom-up statistical approach using prototypical models to simulate energy efficiency, with a notable absence of studies employing top-down approaches and a lack of studies that utilize bottom-up physical approaches. Therefore, it is imperative to conduct additional top-down and bottom-up physical studies to enrich the decision-making model for residential building energy retrofitting in the region.

Furthermore, the necessity for studies involving actual retrofit projects with M&V results in calibrated and validated energy models which provide more realistic results that validate theoretical findings was emphasized. Only one study reported post-retrofit M&V for the AMM countries. Moving beyond prototype building case studies and simulations, collecting data from the in situ measurements of retrofitted buildings monitored for at least 12 months for the calibration and validation of energy models and prioritizing practical retrofitted projects with post-retrofit M&V protocols is essential in future research.

Additionally, the studies collectively revealed established categories of EEMs for the region, but inconsistencies in the specific values attributed to each EEM were found. Consequently, further investigation is required to determine the optimal values of these EEMs, underscoring the need for more research utilizing optimization techniques. Also, none of the reviewed studies presented a BIM-based framework, an emerging area crucial for energy retrofitting.

Furthermore, future research can include investigating end-users' viewpoints on residential energy retrofitting in AMM countries, understanding their interests, barriers, and motivations. Conducting such exploratory research can guide efforts to promote energy-efficient practices in the residential sector. Additionally, considering urban-level retrofitting by shifting from individual building-level studies to urban-level investigations is crucial. Analysing interactions between multiple buildings and their impact on energy retrofitting outcomes in AMM countries is essential.

In conclusion, addressing these observed gaps and conducting further research to cover these gaps will be instrumental in promoting energy retrofitting in residential buildings within the AMM countries, ultimately contributing to energy sustainability in the region.

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Nomenclature

GHG	Greenhouse Gas
IEA	International Energy Agency
AMM	Arab Mashreq and Maghreb
EEMs	Energy Efficiency Measures
WoS	Web of Science
M&V	Measurement and Verification
LCC	Life Cycle Cost
CO ₂	Carbon Dioxide
BEM	Building Energy Modelling
BIM	Building Information Modelling
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
IPMVP	International Performance Measurement and Verification Protocol
HVAC	Heating, Ventilation, and Air Conditioning
WWR	Window-to-Wall Ratio
PCM	Phase Change Material
NSGA II	Non-dominated Sorting Genetic Algorithm

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