Energy resilience in buildings for hot tropical climate conditions: A review

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Abstract. Buildings allow satisfying several needs of society, although their construction and use imply significant energy consumption and pollutant emissions. In general, they experience temporary or permanent events that could affect the conditions of well-being, safety, and use of equipment in interior spaces from an energy perspective. It is expected that the building can respond to such events by its design features (passive response) or by its systems (active response), which is studied from the energy resilience approach. However, there is little research on this topic. Therefore, this paper conducts a literature review covering definitions, assessment strategies, and case studies, particularly for the tropical zone, to identify and socialize the most relevant findings to facilitate future research.

Keywords. Energy resilience, buildings, automation, tropical zone.

1. Introduction
According to the International Energy Agency, buildings account for approximately 36% of global energy consumption and 24% of greenhouse gas emissions [1,2]. Within the life cycle of a building, the operation stage represents 80-90% of the total gas emissions corresponding to the functionality of the systems to provide comfort to the occupants [3,4].

Buildings should aim to control the usability conditions of the interior spaces (e.g., temperature, illuminance, and humidity) [5,6]. These comfort conditions are affected by external events that vary the level of comfort over time. Such variations should be mitigated to ensure the comfort of the users and the safeguarding of the facilities [7]. Events can be frequent or occasional, temporary (short or long duration) or permanent, such as failures in the supply of a service, earthquakes, cybernetic attacks, increase in the ambient temperature, etc. Buildings can respond to a lesser or greater degree to such events due to their design characteristics or to integrated control systems for their operation.

Building automation systems (BAS) and building management systems (BMS) are designed to automatically manage, monitor, verify, control, operate, and adjust complex mechanical and electrical building systems [3,8]. The BAS/BMS are oriented to ensure the comfort of users and the safety of people and facilities [7,9]. Therefore, the main variables monitored are micro-climatic conditions in the surrounding area, as well as illuminance, space occupancy, user habits, indoor temperature, air humidity, CO₂ concentration, and energy consumption, among others [6–8,10]. Although these systems involve challenges due to the technological complexity (hardware and software) [7]. The versatility of building management and automation favours the resilience or responsiveness of a building to changes in expected or normal operating conditions [7,11,12]. However, there is still little research on exploiting the capabilities of BAS/BMS to cope with unexpected changes in the operating conditions of buildings [7,13]. These systems have mainly two disturbance paths, one with events in the electrical system and the other with a change in the conditions of the system to be controlled. These two tend to be treated separately [7,14–25]. Particularly, buildings located in tropical zones are affected to a greater extent in their energy consumption by climatic conditions, which are quasi-constant throughout the year [17,25–28].

Section 2 presents the methodology used for the literature review concerning the measurement and analysis of energy resilience associated with buildings. Section 3 characterizes the findings and elaborates on the definition of energy resilience, analyzes the contribution of BAS/BMS, and presents resilience assessment strategies. Finally, Section 4 presents the conclusions of this review.

2. Review Methodology
A. Search
This review is based on a search of papers published in databases such as ELSEVIER, IEEE, SAGE, and Taylor&Francis. The keywords considered in the search criteria are Resilience, Building, Energy, Automation, and Comfort. Some of the search criteria are:
Resilien* AND Building
Resilien* AND Building AND Automation
Resilien* AND Building AND Control
Resilien* AND Building AND Energy
Resilien* AND (Building OR Dwelling)
Resilien* AND (Building OR Dwelling) AND Energy
AND Comfort
B. Classification of results
A characterization of the papers according to the year of publication, journal, and specific topic is carried out initially. Subsequently, the SCOPUS Preview and VOSVIEWR tools are applied. Finally, in the Fig. 1, we proceed to recognize the definitions of resilience applicable to the energy approach in buildings, evaluation strategies, and case studies for the tropical zone.

Fig. 1. Papers selection workflow.

3. Review results
A. Results Characterization
After the search for the relevant terms, the results were restricted to those after the year 2010 and publications in journals, and finally excluding the results that are related to the word "seismic". As expressed in this search equation, (TITLE-ABS-KEY (energy AND resilient*) AND TITLE-ABS-KEY (building) AND NOT TITLE-ABS-KEY (seismic)) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")). With a total of 1,340 documents found. Fig. 2 shows a growing trend of publications since 2010, exceeding 200 since 2019, which shows the validity of this theme.

Fig. 2. Documents published by year.

Fig. 3 shows that the largest number of publications corresponds to the United States, the United Kingdom, China, Italy and Canada; meanwhile, the most recent publications correspond to Egypt, Iran, the Philippines and Hungary.

Fig. 3. Publication density by country

The keyword analysis, shown in Fig. 5, indicates that the most relevant topics in these investigations are climate change, resilience, energy utilization, intelligent buildings, electric power transmission, construction, and heating urban planning, among others.

Fig. 4. Publication density by source.

B. Definitions
Resilience is a concept coming from biology, which has been taken to characterize certain behaviors of physical systems with respect to actions that may disturb the correct operation of the system; however, the relationship between resilience, energy, comfort, and buildings is the subject of study [12,22,29].

This concept is commonly used as a measure of stability, sustainability, and vulnerability. Stability of a system is to effectively combat the development of adaptive means to shocks, disruptions, disruptive events, and changing conditions without losing the prior relationships governing the system components [30,31]. The four characteristic components of resilience are robustness, redundancy, resourcefulness, and speed [32–34].

Fig. 5. Keyword density
C. Stages
In general, five stages can be identified: pre-disruptive event, post-disruptive event, stable with degraded performance, restorative process, and normal system performance. Fig. 6 relates these stages in time.

![Fig. 6. resilience trapeze.](image)

Various authors propose a resilience analysis scheme, which have similarities as evidenced in Table 1 in the five stages. The discrepancies between these proposals consist mainly of: (i) time of appearance of the incident or event different from the start time of performance degradation [30], (ii) moment of identification of the threat by the system [30,35,36], (iii) final level of performance different from the level existing before the disturbance [30,35], (iv) recovery of supply consequences; iii) reduction of response times to restore, prevention of supply interruption; ii) mitigation of disasters, such as loss of supply, and recover quickly and efficiently . To do this, adaptation measures are applied to mitigate the loss and quickly learn from previous events.

<table>
<thead>
<tr>
<th>Features</th>
<th>Stage</th>
<th>Time of appearance of the incident or event</th>
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<tbody>
<tr>
<td>Pre-event prediction and preparation through planning, which may include the location and estimation of the severity of the event.</td>
<td>I</td>
<td>Anticipation and preparation [37]</td>
</tr>
<tr>
<td>The system seeks to absorb the initial impact and avoid an unwanted effect. The greater the robustness and redundancy, the less the affection will be.</td>
<td>II</td>
<td>Disturbance progress [38]</td>
</tr>
<tr>
<td>The system reaches a stable but degraded operation, whose duration will last until there is a response from it.</td>
<td>III</td>
<td>Degraded state [38]</td>
</tr>
<tr>
<td>The restorative actions tend to return the normal operating conditions of the system.</td>
<td>IV</td>
<td>Restorative state [38]</td>
</tr>
<tr>
<td>Post-event and restoration of performance to a resilient or balanced state.</td>
<td>V</td>
<td>End operation mode Adaptation [30]</td>
</tr>
</tbody>
</table>

D. Energy Resilience
Energy resilience is a recent concept, in the stage of self-definition without consensus on the appropriate measurement framework [37], which allows studying the ability of a system to predict, prevent and resist all possible disasters, such as loss of supply, and recover quickly and efficiently . To do this, adaptation measures are applied to mitigate the loss and quickly learn from previous events [29,39,40].

The operation of energy systems must be focused on: i) prevention of supply interruption; ii) mitigation of consequences; iii) reduction of response times to restore, and iv) recovery of supply [41]. This includes measurement based on quantification of the frequency and duration of customer disconnections due to disruptive events and also the number of customers disconnected [42] or the level of degradation received by customers of the energy supply per event [43].

By studying the reliability of a power system in various disaster environments, it can be established that resilience in power systems can be studied at two levels: component level and system level. The first level mainly covers cyber-physical components of the system. The system level is more studied and covers the interactions between its components. [44].

E. Resilience in buildings
Champagne y Aktas [45] define the resilience of a building, in the ability to withstand severe weather and natural disasters, along with the ability to recover in a timely and efficient manner if it suffers damage to the built environment, as well as the ability to recover critical infrastructure already control systems as these have a direct impact on the health, safety and communities of the building [34].

In the same page, Joe Clarke [18] establishes guidelines to determine the resilience of a building; establish objectives by type of construction; impose specific disturbances; evaluate specific performance metrics [18]. This approach, based on scenarios, supported by mitigation, vulnerability and anticipation, considers the different threats separately and tries to find partial solutions. [46].

On the other hand, Levite and Rakow point out by defining the energy resilience of a building as the relative capacity of an urban institution to carry out its mission during a shock to the energy system [47]. In the same sense, Osma et al. [7] define this concept as the ability to respond to changing scenarios, which maintains the internal operating conditions during the useful life.

F. Resilience in control systems
Control systems can be classified into three operational hierarchies [48–52]: Low, direct interaction with physical systems; media, monitoring controller aggregation; and high, monitor and coordinate supply and demand.

Conventionally, a resilient control system (RCS) is considered to be a computer and cybersecurity [50–52] along with robust control, tolerant to faults and fluctuations, thanks to its design, parameters or system operating under a given range of disturbances [53], this perspective is broadened by contemplating unexpected extreme and rare events [36,54].

It is desirable that an RCS maintains awareness of state, performance, and functionality - cybersecurity, physical, functional, and energy security, economic efficiency, dynamic stability, and process conformance [55]. In the framework of resilience, control systems can operate in two initiatives: maintaining their original objectives or changing their nominal objectives to security objectives [52].

Note that undesirable incidents, failures or threats can also happen at the human layer, such as incorrect commands or configurations; in the process layer, like a broken wire; in the automation layer, such as sensor damage and actuator malfunctions [56].

G. Resilience analysis and assessment
Resilience analysis has been synthesized into several processes evident in the literature. These processes are mostly cyclical, step-by-step processes that seek to inform the reader on how to orient and focus the required analysis independent of the system being addressed. Generally, they are a general guide to the implementation of resilience analysis systems in a system; these processes provide the minimum steps for the correct accomplishment of the analysis [31,37,44,57–59].

As literature findings related to resilience, three analysis processes stand out (Table 2): "resilience analysis process" [31], "resilience assessment framework" [60] and "resilience assessment process" [44].

Table 2. Resilience Analysis Processes.

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
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<tbody>
<tr>
<td>Resilience analysis process [31]</td>
<td>Define resilience goals: It is essential to define resilience goals.</td>
</tr>
<tr>
<td>Resilience Assessment Framework [60]</td>
<td>System identification: Definition of the system domain; delimitation of</td>
</tr>
<tr>
<td></td>
<td>fundamental and strategic objectives</td>
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<tr>
<td>Resilience Assessment Process [44]</td>
<td>Define a resilience metric: An appropriate metric should be quantitative,</td>
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<td></td>
<td>useful for decision making, which may reflect uncertainty, it must</td>
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<tr>
<td></td>
<td>consider recovery time, which may take different approaches.</td>
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<td></td>
<td>As literature findings related to resilience, three analysis processes</td>
</tr>
<tr>
<td></td>
<td>stand out (Table 2): &quot;resilience analysis process&quot; [31], &quot;resilience</td>
</tr>
<tr>
<td></td>
<td>assessment framework&quot; [60] and &quot;resilience assessment process&quot; [44].</td>
</tr>
<tr>
<td>Characterize Threats: Assess the sources of threats</td>
<td>Determine the scope and limits of the analysis.</td>
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<tr>
<td>Establish the resilience objectives: The normal system will be defined</td>
<td>Determine the disruptive events of interest.</td>
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<td></td>
<td>Characterizes the threat: Causes, effects and physical (and/or cybernetic)</td>
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<td></td>
<td>aspects are modelled.</td>
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<td>Determine the level of disruption: Determine the amount of system</td>
<td>Stakeholder engagement: Stakeholders are an integral part of resilience</td>
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<td></td>
<td>analysis and management.</td>
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<tr>
<td></td>
<td>Carry out proactive management: Preparing for possible future problems.</td>
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<tr>
<td>Define and apply system models: Identify the resilience capacities:</td>
<td>It is evaluated through the set of resilience capacities.</td>
</tr>
<tr>
<td></td>
<td>Define a resilience metric: An appropriate metric should be quantitative,</td>
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<td>assessment framework&quot; [60] and &quot;resilience assessment process&quot; [44].</td>
</tr>
<tr>
<td>Calculate the consequence: The system models become the metrics.</td>
<td>Evaluate the level of resilience: With resilience metric, the expected</td>
</tr>
<tr>
<td></td>
<td>value will be determined.</td>
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<tr>
<td>Evaluate resilience improvements: Make operational decisions to improve</td>
<td>Recover the system affected by events: Define the recovery process</td>
</tr>
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<td></td>
<td>recession.</td>
</tr>
</tbody>
</table>

Generally, metrics can be grouped into one of two categories: attribute-based and performance-based metrics. Which respectively answer "What makes my system more/less resilient?" and "How resilient is my system?" [59]. Two types of validity are considered for metrics, content "depends on whether an empirical measurement reflects a specific domain of content" construction "refers to the fact that a particular measure is related to other measures" [44,58].

H. Building operation in tropical areas

In the tropical context, the resilience of buildings is subject to a greater extent to the increase in global temperature. Then, the prompt adoption of an updated or new building code that considers indoor thermal comfort requirements, among others, could benefit countries with hot tropical cities [61], together with the use of more resilient envelopes as a strategy to mitigate climate change [62]. As a consequence of the union of resilience in design and systems, a variation in energy demand is caused [63].

4. Conclusions

Historically, resilience has been a concept implemented in mostly natural events, in which the restoration capacity of systems is evaluated. However, resilience is easily extrapolated to other types of events, mainly those that may have high repercussions and uncertainty of occurrence. Identifying quantifiable characteristics for those disruptive events represents the outstanding result of the state of the art studied. Resilience in buildings has been studied from a seismic-resistant and structural approach. However, since the acceptance of the definition of resilience for dynamic systems, it is evident that the analysis of energy resilience in buildings should be expanded to the definition and consensus of methods of analysis, calculation and
evaluation of all the systemic actors of a building, together with a process of integration and unification of criteria that allows the measurement and comparison of resilience levels between buildings.

Using resilience as an evaluative element of the systems is possibly the next step in the analysis of their management and efficiency. By quantitatively establishing a consensus value of resilience, it would be possible not only to determine the resilience of the systems to known events, but also to assess the adaptive, recovery and robustness capacities of the systems.

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