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Resilient Cooling in Buildings – A Review of definitions and evaluation methodologies

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Abstract. The concept 'Resilience' has gained wide international attention by experts and is now seen as the future target for the design of buildings. However, before using the word 'resilience', we must understand the semantics of the word. Resilience is not 'resistance' and is not 'robustness and is not 'sustainability', it is a more complex definition. As part of the International Energy Agency Annex 80 on resilient cooling in buildings, this paper focuses on formulating a definition for resilient cooling. Resilient cooling is used to denoting low energy and low carbon cooling solutions that strengthen the ability of individuals, and our community as a whole to withstand, and also prevent, the thermal and other impacts of changes in global and local climates; particularly concerning increasing ambient temperatures and the increasing frequency and severity of heatwaves. This paper focuses on the review of most of the existing resilient cooling definitions and the various approaches towards possible resiliency evaluation methodologies. It presents and discusses possible answers to the abovementioned issues to facilitate the development of a consistent resilient cooling definition and a robust evaluation methodology. The paper seeks to impact national building codes and international standards, through a clear and consistent definition and a commonly agreed evaluation methodology.

Keywords. robustness, resistance, discomfort, thermal comfort, ventilation, concepts
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1. Introduction

Resilience is a central feature of the United Nations (UN) Sustainability Development Goals (SDGs) and is reflected in a range of SDG targets [1]. According to the UN General Assembly Resolution 71/276 [2], the term "resilience" describes "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management."

The need for resilient building design and construction is urgent to anticipate climate change and disruptions caused by weather extremes, increasing carbon emissions, and resource depletion [3]. Our well-being depends on reducing the carbon emissions in our built environment and other sectors [4]. While solving the root-cause problem of climate change, we need to address its effects. Avoiding excessive temperatures induced by overheating is one of the most critical challenges that the building industry will face worldwide in the coming decades [5,6].

Increasing electricity demand during heat stresses can lead to blackouts and grid failures. This can leave buildings out of thermal comfort range and threaten the lives of vulnerable people at risk, as happened during the 2003 Europe heat wave [7]. As building disruptions may have severe and long-term economic impacts, resilient building cooling solutions are an essential strategy to mitigate threats to occupants [8]. There is an urgent need for resilient cooling solutions in buildings to keep comfort despite extreme weather events due to climate change [9]. Meanwhile, the use of fuelintensive mechanical cooling should be reduced to slow climate change [10]. Greenhouse gas (GHG) emissions from buildings air conditioning stand at around 210–460 gigatonnes of carbon dioxide equivalent (GtCO2e) over the next four decades, based on 2018 levels [11].

It is of principal importance to define buildings' resilient cooling to maintain indoor environmental quality against unexpected events, e.g., extreme weather conditions, heat waves, power outages, etc. However, the definition of resilience and resilient cooling is challenging and complex [12]. Research on resilience associated with human-nature interactions is still in an explorative stage with few practical methods for real-world applications [13,14].

This article presents the main concepts of resilience. It proposes a definition of resilient cooling of buildings based on the discussion taking place in the International Energy Agency (IEA) - Energy in Buildings and Communities Programme (EBC) research project "Annex 80: Resilient Cooling of Buildings" [9]. The essence of this paper is to define resilience against overheating and power outage. It seeks to answer the following research questions:

What are the existing concepts of resilience in the built environment?

How to define resilient cooling of buildings?

The article presents a definition framework based on reviewing almost 90 studies of resilience, including RELi 2.0 Rating Guidelines for Resilient Design and Construction [15]. One of the challenges of this study is to define resilience on the building scale beyond what is present in literature, which mainly addresses the definition of resilience on an urban scale. This reinforces the importance of resilient cooling as an integral approach for building design and operation concerning comfort (including indoor environmental quality), carbon neutrality, and environmental friendliness [4].

2. Methodology

The research methodology is qualitative and relies on literature review, focus group discussions, and follow-up discussions with individuals.

2.1 Data Collection

A literature review was conducted aiming to define resilience against different climate change associated disruptions in the built environment worldwide. The publications included scientific journal articles, books and building rating systems. Our initial Scopus and Web of Science research resulted in almost 90 publications relevant to resilience and resilience criteria in the built environment. To examine the definitions of resilience and the associated resilience criteria such as vulnerability, resistance, robustness and recoverability, we surveyed resilience in ecology, resilience in engineering and resilience in psychology.

2.2 Data Processing

The content of the full text of every identified article was analyzed, and an analysis protocol and coding schema was developed to record its content attributes. The entire text of the full article was read multiple times as the search for coding words was completed by the coders (authors). Coding is a way of indexing or categorizing the text in order to establish a framework of its themes [16]. We used the framework method commonly used for the management and analysis of qualitative data in health research [17], [18].

2.3 Development of definition

For the definition development we used the framework method, which is the most commonly used technique for the management and analysis of qualitative data in health research [17], [18]. The framework method allows systematically analysis of the text data to produce highly structured outputs and summarized data. It can also compare and identify patterns, relevant themes, and contradictory data [17]. We categorized the codes (resilience concepts) by theme. Our classification resulted into four concepts that define resilient cooling of buildings.

2.4. Focus group and follow-up-discussions

Qualitative research is primarily a subjective approach as it seeks to understand human perceptions and judgements. However, it remains a solid exploratory scientific method if bias is avoided. The suggested definition validated through focus group discussions to provide reliable and consistent results. Several validation measures were implemented including member checking, memo logs, and peer examination following the work of Attia et al. [19]. The study validation allowed emphasizing credibility and strengthening the relevance of the conducted study and results. Focus groups were convened during IEA Annex 80's first expert meeting in Vienna, Austria (21 October 2019) and during its second expert meeting, held online (21 April 2020). Each focus group comprised 15 people. The invited experts for the focus-group discussion represented the scientific and professional experts in the field of building performance assessment and comfort. A list of the IEA Annex 80 participants can be found on the Annex website [20]. The goal of the focus-group discussions was to validate the suggested definition and associated main criteria.

Follow-up discussions with RELi steering committee members and UN resilience experts helped articulate and validate the framework and included detailed elaboration of some criteria. The follow-up discussions took place between the first authors and some of the co-authors via teleconference and emails.

3. Results

3.1 Resilience against what?

One critical prerequisite for a comprehensive definition and assessment of resilience is the identification of threats (shocks) or disruptions to the stability of these systems. An essential question to answer is “resilience against what?”.

As shown in Table 1, several types of disruptions or emergencies can lead to the systemic failure of buildings to be resilient—e.g., air pollution, fires, and earthquakes. Disruptions are increasingly presented by unexpected phenomena outside or inside the building [21]. The rate and pace of disturbances that the built environment faces have been accelerating significantly over the past three decades [22]. Understanding and identifying the phenomena that disrupt a building and threaten the well-being of its occupants is fundamental.

Table 1 - Different types of disruptions affecting the built environment

	Description
Air Pollution	- **Outdoor air pollution** refers to the air pollution experienced by populations living in and around urban and rural areas. Air pollution derives from poor combustion of fossil or biomass fuels (e.g., exhaust fumes from cars, furnaces or wood stoves) or wildfires. Buildings require efficient air filters and ventilation systems that mitigate the impact of air pollution.
Fire	**- Wildfires** are sweeping and destructive conflagrations, especially in a wilderness or a rural area, that cause significant damage. Most building codes adequately addresses common fire hazards with mandatory fire-resistant stairwells, fire-resistant building materials, and proper escape methods.
Earthquakes	- **Earthquakes** are the most common disruptions covered in all building codes. Trembling of the ground caused by the passage of seismic waves through earth's rocks. This natural disaster can damage a building by knocking it off its foundations and harm the occupants. Seismic testing should be used on components of buildings to determine their resilience to earthquakes.
Wind storms	- **Hurricane** have the potential to harm lives and property via storm surge, heavy rain, or snow, causing flooding or road impassibility, lightning, wildfires, and vertical wind shear.
Flooding	- **Flooding** is the inundation of land or property in a built environment, particularly in more densely populated areas, caused by rainfall overwhelming the capacity of drainage systems, such as storm sewers.
Heatwaves	- **Heat waves** are a period of excessively hot weather, which may be accompanied by high humidity. They cause overheating in the building and intensify the urban heat island effect. This event can potentially risk the health and lives of occupants if no measures are taken.
Power	**- Power outages** and blackouts are common occurrences that can be caused by natural disasters cited earlier like flood or hurricane. It can lead to overheating in buildings when air conditioners do not operate.
Water	**- Water shortage** is the lack of freshwater resources to meet water demand. Lack of water has a significant impact on irrigation and urban use, degrading food security, public health, and overall stability.
Pandemic	- **Pandemics** can impact the built environment of societies is how spatial and social aspects are intertwined to constitute everyday lives mutually. During active outbreaks, minimizing the risk of disease spread in buildings starts with keeping people out of them. For those who occupy a building, increasing the ventilation and filtration of the inside air is essential.

For our study, we decided to identify heat waves and power outages as the major disruptions that can influence occupant indoor environmental quality conditions on the building scale [4]. The paper is focused on the definition of resilient cooling of buildings as part of the IEA Annex 80 activities that aim to define resilience. Crawley et al. [23] identified heat waves as the significant climate change disruption in buildings. Baniassadi et al. [24] identified the frequency and duration of power outages as a significant cause of disruption for buildings in the near future. Both studies confirmed that the increase of mean outdoor temperatures and the frequent and intensive nature of heat waves disrupt power and degrade comfort.

Disruptions are shocks or events that have an origin, a nature, an incidence, a scale, and duration. Therefore, we define disruptions in buildings as shocks that degrade the indoor environment and, therefore, require resilient cooling strategies and technologies to maintain it [21].

3.2 Resilience: At which scale? And for how long?

The resilience of a system cannot be studied without examining the scale of the system, and the relation between the shock cause and its effect(s). Resilient systems function through the interaction of complex processes operating at different scales and times frames [22]. Therefore, it is essential to characterize the scale of the system that is expected to be resilient in a time-bound way. The definition of resilience should always reflect whether the disturbance affects the performance or operation of a single building element, or building service or the entire building [23]. As shown in Figure 1, the definition of resilience should always characterize the resilience to disturbance of a system in relation to its scale within a specific time frame for the disturbance.

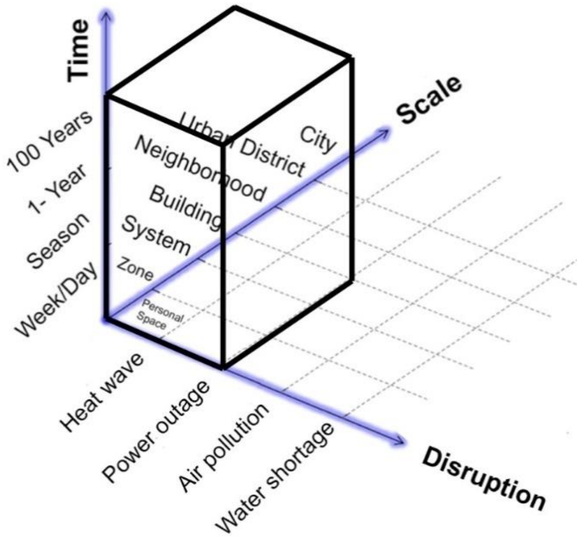


Fig. 1 - the components of a resilience definition within a specific field or domain

For our study, we define heat waves and power outages as the primary disruptive events to be addressed by resilient cooling for buildings. Our proposed definition considers the indoor environmental conditions on the building scale for long periods. Climate scenarios represent historical and future outdoor conditions and consider both short-term and long-term heat waves. Resilience in the building engineering field is strongly associated with long-term climate projections that encompass both the increase in the average temperature due to a global warming effect and a further temperature rise due to the urban heat island effect [27].

Defining and identifying disruptions and specifying their associated events that impact healthy and comfortable buildings is the first step to determine a building's resilience. As shown in Figure 1, heat waves and power outages are events that may impact the thermal conditions in buildings. The identification of heat-wave events is based on their intensity, duration, and frequency coupled with power outages [28]. It is expected that a building with a resistant cooling design (strategy) can withstand short and extensive heat waves. A building with a robust cooling design can withstand short, intense, and prolonged lengthy heat wave. The performance of a building with a resilient cooling design could surpass that of a robust building by reacting to power outages and longer intensive heat waves. The literature review confirms that resilience must be associated with response to system failure [15]. A system is robust when it can continue functioning in the presence of internal and external challenges without a system failure. However, a system is resilient when it can adapt to internal and external challenges by changing its method of operations while continuing to function. The ability of the building to recover after disruptive events is a fundamental feature of resilience. Therefore, the ability to model the occurrence and consequences of discrete heat-wave events is crucial to prepare the building for the response.

The interviewed experts agreed that climate change should be defined as the long-term disruptive event, and that heat waves and power outages should be designated short-term disruptive events. Based on our literature review and following Figure 2, we distinguish four major events categories that can challenge resilient cooling [28]:

- Event 1: Observed and future extreme weather conditions (extended, spanning years)
- Event 2: Seasonal extreme weather conditions (long, spanning months)
- Event 3: Short extreme weather conditions (short, spanning days)
- Event 4: Power outages (spanning hours)

Across the literature, several studies identified extended and long climate change associated temperature increase events (Events 1 and 2) [29], [30]. Other studies investigated the impact of short-term heat waves and power outages on thermal conditions and cooling systems' resilience [31], [32]. For example, the RELi rating system requires thermal safety during emergencies (Events 3 and 4) by maintaining indoor air temperature at or below outdoor air temperature up to seven days [15]. Designers need to demonstrate through thermal zoning and modeling that the building will maintain safe temperatures during a blackout that lasts four days. During a power outage, buildings must provide backup power to satisfy critical loads for 36 hours.

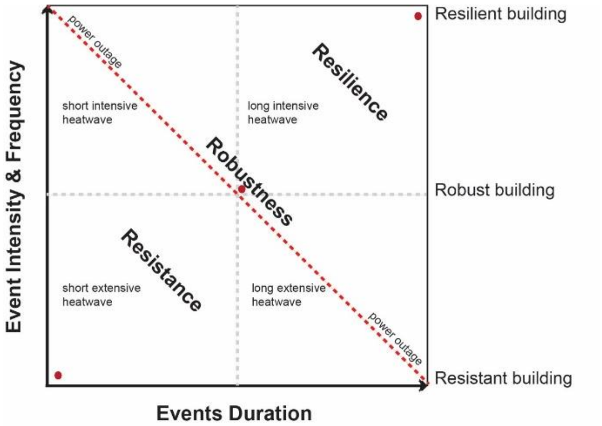


Fig. 2 - the components of a resilience definition within a specific field or domain

We define four major event categories that need to be tested and address in any resilience assessment for comfort in buildings. The following section provides further detailed explanation for Figure 1 in association with Figure 2.

3.3 Definition of "Resilient cooling for buildings"

Resilient cooling is used to denoting low-energy and low-carbon cooling solutions that strengthen the ability of individuals, and our community as a whole to withstand, and also prevent, the thermal and other impacts of changes in global and local climates - particularly concerning rising outdoor temperatures and the increasing frequency and severity of heat waves [33].

Resilient cooling for buildings is a concept that was not approached thoroughly in previous studies. Therefore, we developed the following definition based on the literature review and validated it through the focus group discussion with members of IEA Annex 80:

The cooling of a building is resilient when the capacity of the cooling system integrated in the building allows it to withstand or recover from disturbances due to disruptions, including heat waves and power outages and to adopt the appropriate strategies after failure (robustness) to mitigate degradation of building performance (deterioration of indoor environmental quality and /or increased need for space cooling energy (recoverability).

Resilience is a process that involves several criteria, including vulnerability, resistance, robustness, and recoverability [34]. Therefore, we include those four criteria in the definition formulation shown in Figure 1. The vulnerability involves the sensitivity or propensity of the building's comfort conditions to different disruptions. At this stage, it is vital to define disruptions, as discussed in Sections 3.1 (see Figures 1 and 2).

A resilient building must be conceived based on a vulnerability assessment that takes into account future climate scenarios and prepares the building system, including occupants, to adapt against failures. The vulnerability assessment should test the building performance against long-term disruptions using average weather conditions, extreme weather conditions, future weather conditions, and worst future weather conditions. It should also test the building against short-term disruptions, including brief heat waves and power outages. A vulnerability assessment stage should be part of the design process. A building cooling system is prepared to go through different disruption scenarios engaging different thermal conditions.

The building cooling system should be able to withstand short-term and long-term disruptive events. As shown in Figure 3, resistance involves the ability and the depth of reaction to the shock. Under disruptive events, the building may use performance drop backs to achieve the pre-defined minimal thermal conditions. After failure of the building cooling system, the building's resilience process moves to the most crucial stage—robustness, meaning reaction to failure. Robustness requires the building to be prepared to survive an otherwise-fatal shock by adapting its performance. The survivability of the system relies on its ability to assure the critical thermal conditions to maintain the functional activities of occupants during a crisis. As shown in Figure 5, a robust building will first fail and then adapt its performance conditions meeting critical or minimum thermal requirements to achieve a degree of survivability for occupants depending on the vulnerability assessment decisions made during design. The significant distinction between a resistant building system and a robust building system is that the latter is prepared to adapt based on a backup plan and ecosystem. Robustness involves how the building, including its services and occupants, adjusts and adapts to shocks.

The final stage of resilience involves the recoverability of the system. Recoverability consists of the extent and nature a occupants and building's services to recover, and returns to its equilibrium state and its speed to come back. As shown in Figure 5, recovering has a duration, performance, and learnability. The necessary speed for recovery and the recovery performance curve should be planned during the vulnerability assessment stage. The ability of the users, building, and systems to learn from the event is an integral part of this stage.

While the diagram in Figure 3 is linear, the process of resilience is cyclic and iterative. Resilient cooling of buildings is a continuous process that involves the commissioning and retro-commission of building elements and systems over the building's life cycle. It also includes the continuous education of occupants and the preparation for the adaptive measures during unforeseeable disruptions.

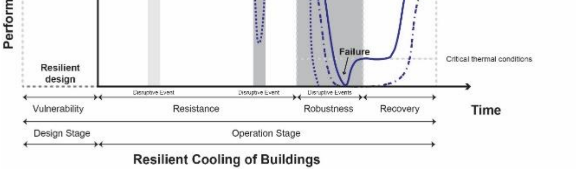
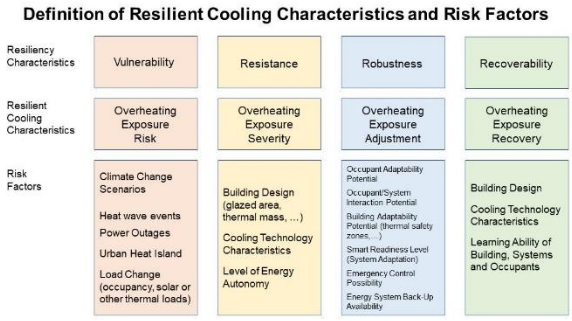


Fig. 3 -The components of a resilience definition within a specific field or domain (for higher resolution check [3])

Figure 4 provides a complementary definition framework that includes the main criteria of resilience. It presents an example of the factors that influence the performance of cooling in buildings under the four resilience criteria. Depending on the overheating definition and exposure risk, a resilient cooling design for buildings assures that the designed indoor environmental conditions are secured before the disruption. The risk factors should be identified during the design stage to assess vulnerability. Examples of risk factors include climate change scenarios, heat waves combined with power outages, or urban heat island effects. As shown in Figure 4, the resistance stage depends mainly on the building's design features and technologies and their ability to keep the building performing under severe overheating exposure until reaching failure. The failure is the essential disruption to start the third stage of resilience, namely robustness. The robustness of the cooling system the building must adapt to cover the critical thermal conditions temporarily until reaching the recovery stage. The ability to respond in an adaptive way that implements fundamental changes to the original thermal conditions involved occupants and systems adaptability. The presence of energy system backup and an emergency control possibility is part of the building's robustness. This is finally followed by a recovery stage and a shift in the building performance to achieve before designed thermal conditions that reflects adapting to the normal.



Definition of Resilient Cooling Characteristics and Risk Factors

Resiliency Characteristics	Vulnerability	Resistance	Robustness	Recoverability
Resilient Cooling Characteristics	Overheating Exposure Risk	Overheating Exposure Severity	Overheating Exposure Adjustment	Overheating Exposure Recovery
Risk Factors	Climate Change Scenarios Heat wave events Power Outages Urban Heat Island Load Change (occupancy, solar or other thermal loads)	Building Design (glazed area, thermal mass, …) Cooling Technology Characteristics Level of Energy Autonomy	Occupant Adaptability Potential Occupant/System Interaction Potential Building Adaptability Potential (thermal safety zones,…) Smart Readiness Level (System Adaptation) Emergency Control Possibility Energy System Back-Up Availability	Building Design Cooling Technology Characteristics Learning Ability of Building, Systems and Occupants

Fig. 4 - Influencing factors of resilient cooling of buildings (for higher resolution check [3])

4. Discussion

The review of the main concepts on resilient cooling for buildings and the proposal for a definition and assessment framework indicates the complexity of the idea. We found varying and inconsistent definitions of resilience in the context of building comfort and in the context of the overall built environment. The following sections discuss possible questions that we answered in this study.

- What are the existing concepts of resilience?

- How to define resilient cooling for buildings?

Few studies and case studies succeeded in defining resilience and applying its principles on a building scale. Across our review, we found some studies that focus mainly on robustness as a proxy for resilience [35-38]. However, none of those reviewed studies embraced a multi-criteria approach for resilience that involves vulnerability, resistance, robustness, and recoverability. Therefore, based on our literature review and focus group discussions, the suggested definition and framework, in this study, is a step forward. The following recommendations can be helpful for designers and building operators that seek to achieve resilient cooling of buildings in a holistic way:

1. Any definition of resilience must be based on the identification of a specific shock or disruption. In the case of resilient cooling of buildings, heat waves and power outages are considered as the main shocks (extreme events). Designers should prepare buildings against those shocks.

2. Any definition of resilience should specify and distinguish, at the same time, the resistance and robustness conditions against heat waves and power outage events. The resistance period involves the building's ability to resist shock(s) with the same pre-shock operation conditions. However, robustness requires failure and adaptation after failure. The robustness mechanism involves building users and building systems adaptation and their ability to adjust after a shock.

3. Thus, the definition of resilient cooling for buildings involves four critical criteria, mainly vulnerability (preparation), resistance (absorption), robustness (adaptation after failure), and recovery (remedy). The building design, construction, and operation processes should address these criteria.

4. Resilient cooling design is an urgent requirement for future proof buildings. Weather extremes must be anticipated to assume well-being. The choice of comfort models is elementary to prepare buildings. Resilient cooling design involves the combination of passive and active cooling design measures, on-site renewable production, and the coupling to storage capacities. Our suggested definition for resilient cooling of buildings can help to develop in the future resilience performance indicators that account for the impacts of global warming for long and short assessment periods. This can allow comparing the carbon emissions and primary energy use at different stages of the building life stages. As part of the activities of IEA - Annex 80, there is a need to assess the performance of conventional and advanced cooling technologies. Without a multi-stage definition, it will be challenging to develop universal indicators that allow assessing the active and passive cooling technologies listed above.

5. Building operation systems and building management systems will play a significant role in applying the adaptation strategies and risk mitigation plans in collaboration with buildings users. For resilient cooling, HVAC systems and envelope features are a prime target for real-time optimization. Different dynamic control strategies with predictive algorithms should be embedded in building operation systems using a deeply coupled

network of sensors. The smart readiness of buildings is part of resilience because it considers the fact that buildings must play an active role within the context of an intelligent energy system [39].

6. Resilience is a process, and its criteria should be addressed following a circular, iterative approach. Extracting learned lessons and integrating user experience during shocks is essential to increase the emergency learnability and feed the preparedness loop.

5. Conclusion

A definition of resilient cooling for buildings is developed and discussed in this paper as part of the IEA Annex 80 research activities. The definition's main concepts and criteria are based on qualitative research methods. The paper presents a set of recommendations to adopt the definition in practice and research. Future research should build on our findings and create more consistent frameworks with useful quantifiable indicators, quantitative metrics, and performance threshold limits. Additional definitions of overheating and modeling of overheating events are required for different building types and climates. The research should be extended to identify benchmarks and case studies with reference values, threshold ranges, and to seek tools and reporting mechanisms for the resilient cooling of buildings. The suggested framework should evolve as research and experience build a greater understanding of resilient and sustainable buildings.

6. Acknowledgemnt

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