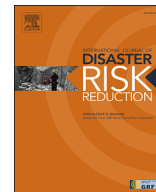


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# Identifying and prioritizing climate change adaptation measures in the context of electricity, transportation and water infrastructure: A case study

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## ABSTRACT

Climate Change Adaptation (CCA) has become a vital measure within every nation due to the significant impacts posed by climate change on Critical Infrastructures (CIs) and human lives. Despite scholars' identification of possible impacts on CIs, a lack of consideration for CCA measures to mitigate these impacts can be observed. This study aims to identify and prioritize CCA measures in the assets and infrastructure of critical sectors; electricity, transportation, and water supply considering Sri Lanka as a case study. The present study employed an Analytical Hierarchical Process (AHP) to prioritize CCA measures of these three infrastructure sectors as a system considering their interconnected and systematic nature. The prioritization process was informed by 42 open-ended expert interviews, and these interviews were also instrumental in validating the criteria used to evaluate the CCA measures. The study identified and discussed several CCA measures for different stages of the infrastructure life cycle, including planning, design and construction, and maintenance and retrofitting. The CCA measures were prioritized based on eight criteria obtained from a detailed review analysis. The results revealed that an asset management system at the planning stage is the most significant CCA measure for CIs. Furthermore, the study emphasizes that proper planning of evacuation routes, consideration of operational loads imposed by climate change, and nature-based solutions are significant CCA measures that need to be incorporated during infrastructure development. The outcome from this study provides insights for built environment professionals to adapt infrastructures to climate change. Additionally, the results of the study can be integrated into the rules and regulations of the developing countries to enhance climate resilience within the built environment.

## 1. Introduction

Climate change has become a predominant problem that the world is confronted with. The Intergovernmental Panel on Climate Change (IPCC) sixth assessment report highlights anthropogenic Green House Gas (GHG) emissions as a key driver of climate change

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[1,2] which significantly impacts the built environment [1–4] and the community [1,5–12]. In fact, past climate-related disasters such as cyclones, sea-level rise, and coastal flooding have highlighted the vulnerabilities of built environments in different regions [13,14]. The built environment emits a significant amount of GHGs, which significantly influences the local climate [3,15,16]. Additionally, the built environment is densely populated with urban centers having a higher concentration exacerbating the issues associated with climate change within the built environment [17–19].

The built environment mainly consists of buildings (residential and commercial) and infrastructure such as water supply, transportation, electricity, energy, telecommunications, health, wastewater management, etc. [20–22]. Some infrastructure sectors are more critical than others because societal well-being is more dependent on their reliability, which is openly defined as Critical Infrastructure (CI) [23–25]. The electricity, transportation, and water sectors are commonly regarded as the dominant sector among the CIs due to their vital importance to modern societies (See Section 2.1). These three sectors provide essential services that are necessary for daily life, economic activity, and public safety, making them essential pillars of a nation's development [26–29].

During the past few decades, CIs have been significantly affected by disasters exacerbated by climate change and related extremes (See Section 2.2) [1,30–34]. Sea-level rise, extreme weather, and rising temperatures are just a few of the challenges that these CIs are currently facing [2,35]. These impacts highlight the importance of taking adaptation and resilience measures to protect these CIs from the effects of a fast-changing climate while also ensuring their dependability and sustainability [2]. Adaptation is referred to as “an adjustment in the natural or human system to a novel or shifting environment or in response to actual or expected stimuli or their effects, which moderates harm or utilizes beneficial opportunities” by IPCC [2,36]. It is imperative that proactive steps are required to maintain the sustainability of these key infrastructure sectors for future generations [1,37]. Ensuring the resilience and security of these CI sectors is crucial to maintaining the health, safety, and economic prosperity of communities. It is clear that the improved integration of CCA measures will assist in reducing damages and increasing economic and environmental benefits [19,36,38]. Researchers have devoted considerable attention to different CI sectors, exploring the vulnerability of the systems, the causes of failures, and measures to enhance resilience and security, among other aspects [13,24].

While there is a growing body of literature on the possible impacts of climate change on CIs systems, there is a lack of attention given to CCA measures for these key CIs that can be taken to mitigate these impacts as revealed from the literature analysis [4,39–41]. As climate change related extremes have a significant impact on these key infrastructure sectors, there is a dire need for research in the present landscape of scientific research to identify and prioritize CCA measures that can be taken to safeguard these three key infrastructure systems. Also, given the systemic nature of CI systems, it is crucial to consider these three infrastructure sectors as a system while identifying potential CCA measures. This study aims to address this gap by identifying and prioritizing CCA measures for the electricity, transportation, and water supply sectors utilizing the Sri Lanka as a case point. The study employs an Analytical Hierarchy Process (AHP) to prioritize CCA measures which have been identified through a series of expert's interviews.

## 2. Background

### 2.1. Importance of electricity, transportation and water supply infrastructure

Among different CI sectors, electricity, transportation, and water supply systems have become more critical within every nation. For instance electricity sector, powers homes, businesses, hospitals, and other CIs [9,10,35]. Among different sectors of CIs, electricity and energy, has been a dominant sector worldwide [36–39]. Given that the country depends on a consistent and uninterrupted energy supply, safeguarding such infrastructure is of utmost importance in the country [8,40]. According to the Asian Development Bank, primary energy demand in Asia and the Pacific is expected to grow by 2.4% per year or more between 2005 and 2030 [9,10]. Over the past several years, adverse effects of climate change have also affected the electricity and energy sectors. Many incidents have proved that the electricity infrastructure can be severely affected by climate change related extreme events [1,8,26,27].

In order to ensure access to clean water, effective movement of goods and people, and an overall high quality of life, water and transportation infrastructure are crucial for contemporary societies. Water systems supply clean and safe water for drinking, washing, and other uses. The criticality of these sectors implies that any disruption or failure can have significant negative impacts on society, such as power outages, transportation delays, and water contamination, leading to economic losses and adverse public health effects [24,41–43]. The global efforts being made to enhance and protect these key infrastructures demonstrate their importance [14,17,18,25,38]. Governments and international organizations have launched a number of initiatives to improve the dependability and resilience of transportation and water systems, with a focus on addressing the expanding demands of a population that is quickly urbanizing [18,44–47]. The United Nations estimates that more than half of the world's population already resides in cities, and that percentage is anticipated to increase to two-thirds by 2050 [48–50]. Therefore, it is crucial to find ways to ensure the sustainability of the water and transportation systems due to the tremendous pressure that the fast urbanization has put on them. Access to clean drinking water is crucial for maintaining excellent health and well-being, according to the World Health Organization [17,18]. Similarly, the transportation industry plays a critical role in facilitating the movement of goods and people, contributing to the economic and social growth of a nation [35,51].

### 2.2. Climate change impacts on transportation, water supply and electricity sectors

Previous research work investigated the effects of climate change on the transportation, electricity and water infrastructure sectors [1,25,42]. Figs. 1–3 illustrate the identified climate change impacts on electricity and energy, drinking water and distribution system, and road infrastructure as summarized from a detailed review analysis. It reveals that the rising temperature has a detrimental influence on these infrastructures [1,43–45]. It reduces the efficiency and capacity of these infrastructures. Also, more losses will

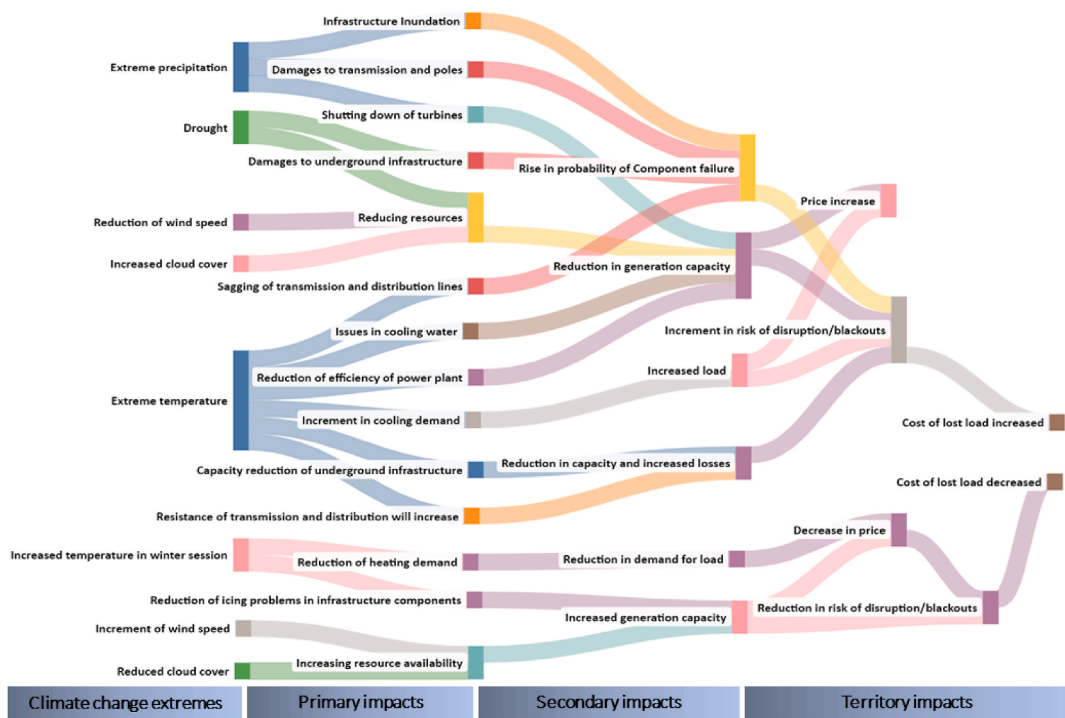


Fig. 1. Climate change impacts on electricity infrastructure (Adopted from: [1]).

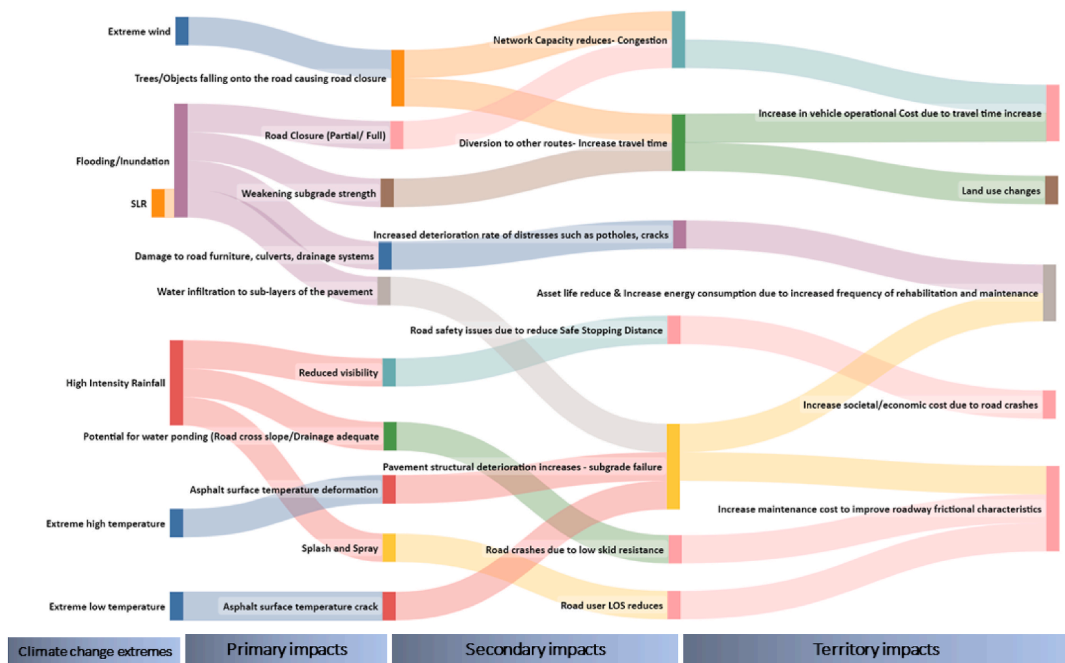


Fig. 2. Climate change impacts on the road infrastructure (Adopted from: [1]).

occur in the transformers and substations due to the temperature rise [5,30,31,43,46]. In thermal power plants, coal storage may be spontaneously self-ignite due to an increase in temperature [7,16].

Moreover, climate change is having significant impacts on transportation worldwide. Extreme weather events such as floods, hurricanes and storms are increasingly affecting transportation systems, causing disruptions and damage to transportation infrastructure [34,47–50]. For example, flooding can lead to road and rail closures making it difficult for people and goods to move around while storms can damage transport infrastructure such as bridges, tunnels and railways [1,51]. Extreme heat can also cause problems for

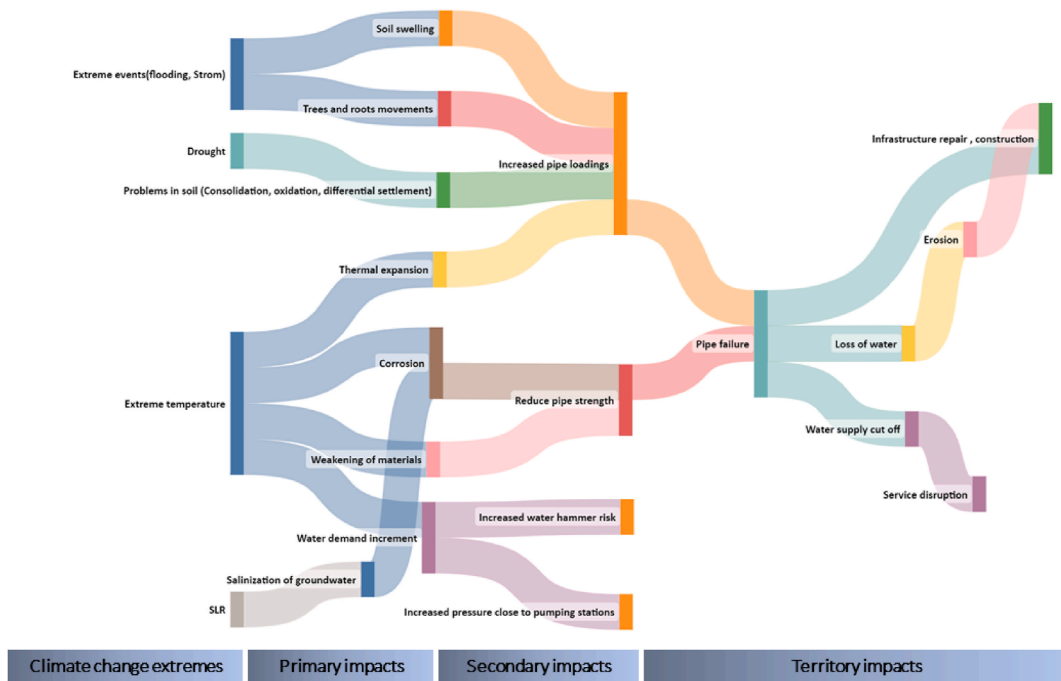


Fig. 3. Climate change impacts on drinking water production and distribution infrastructure (Adopted from: [1]).

transportation systems such as the expansion of rails which can cause buckling. In addition road infrastructure will deteriorate due to prolonged temperature rise and adverse weather conditions. For instance, extreme rainfall events and flooding can reduce the strength of the subgrade of the road pavement, eventually increasing the maintenance and operational cost of road infrastructure [50,52–56]. Fig. 2 illustrates these impacts on road infrastructures.

Similarly, water distribution systems are being impacted by climate change [19,57,58]. Increasing temperatures are causing more water to be lost through evaporation, reducing the availability of water in many regions. Climate change is also leading to changes in precipitation patterns, with some areas experiencing more frequent and intense rainfall events, leading to flash floods and landslides [1,59]. At the same time, other areas are experiencing more extended periods of drought, reducing the availability of water for human consumption and agriculture. These changes are challenging the resilience and security of water distribution systems, which are critical for ensuring that people have access to clean and safe water. Fig. 3 illustrates the climate change impacts on water production and distribution system under various climate change related extremes [19,57,58,60].

### 2.3. Climate change adaptation (CCA) and built environment development

Even if significant actions are taken to limit GHG emissions, climate change will inevitably occur, leading to dire economic, social and environmental repercussions for communities [60–62]. Nations will need to adapt in order to mitigate the negative effects of climate change [2,8]. In this context, CCA of the built environment is a crucial aspect to cope with the associated impacts [2,41,63–65]. To address above mentioned negative impacts from climate change on CIs, it is essential to develop and implement adaptation measures for CIs. These measures could include improving infrastructure design to be more resilient to extreme weather events, enhancing early warning systems to help anticipate and prepare for hazards, and using advanced technologies to manage and monitor CIs in real-time [41,64,66–68]. By investing in climate-resilient infrastructure and adopting sustainable management practices, societies can be confident on the critical systems for uninterrupted essential services and support in the face of climate change [2,36]. Efforts to lessen vulnerability and increase capacity through system alterations and adjustments are included in CCA [65,69,70]. Understanding how systems may adapt, change, and cope with changes in their environment is a must for CCA [36,71–74]. Adaptation focuses on mitigating negative effects while also building resilience and reaping any benefits that may arise. It is all about preventing disasters, dealing with existing hazards or planning for a future threat that is not (yet) recognized as imminent [36,71–74]. Adaptation can be reactive, occurring in response to impacts, or proactive, emerging before the impacts of climate change become apparent. Most often, proactive adaptations will be less expensive in the long run and more effective than reactionary adaptations [59,66,68]. Many nations have devoted significant attention to CCA and mitigation. Mitigation (efforts to minimize emissions and future climatic changes) is more important than adaptation in dealing with climate change causes. Mitigation aims to address the underlying causes of climate change and provides long-term benefits by minimizing damages and consequent adaptation costs. However, mitigation is inadequate but adaptation is also necessary to manage the impacts of climate change [4,59,66,75,76]. Adaptation actions include large-scale infrastructure changes, like building coastal defenses, heat insulation, revised standards, improved drainage or behavioral shifts like individuals using less water. Such adaptation is closely associated with the development of built environment.

“Built environment development” can be defined as the process of developing and sustaining the fundamental facilities, systems and structures required for a healthy society [77,78]. This encompasses everything from public transportation, water and sewage systems, communication networks, and energy facilities to roads, bridges, and other forms of mobility [17,18,39]. In the context of built environment development, various phases of built environment development can be identified. Generally, these development can be divided into three main phases as planning, design and construction, and maintenance and retrofitting [79–81]. It is vital to consider appropriate CCA in each phase for better resilience of infrastructure against climate change.

Many attempts can be found in the literature in the context CCA of the built environment [37,82–85]. There is a vast body of literature on CCA in the context of agriculture, food security, and other CI sectors [86–89]. Much of this literature focuses on the impacts of climate change on these sectors and on the strategies that can be employed to adapt to these impacts [84–86,88,89]. Several strategies are suggested in literature to adopt for climate change impact. These include the implementation of infrastructure hardening measures, the development of backup systems, and the implementation of disaster response plans [39,39,90–95]. However, there is still a lack of exploration of possible CCA measures that can be integrated into infrastructure development phases. Additionally, literature rarely prioritizes these CCA measures based on infrastructure development.

### 3. Significance of the study

Without any doubt, electricity, transportation, and water play a major role in humanity's essentials, The degradation of these necessities due to inadequate service would lower the quality of life. Thus, it follows that improving the quality of life and ensuring the efficient supply of the above services is essential for an industry-based economy and sustainable lives. It has been discovered that in most countries, there is a causal link between the effective functioning of the infrastructure and the rate of economic growth. Unequivocally, the impacts on the electricity, transportation and water infrastructures are increasing with climate change extremes as revealed by the recent statistics. Hence, implementing the CCA is vital for building climate resilience of electricity, transportation and water infrastructure and reducing the damages due to disaster. CCA considers exertions to lessen vulnerability and increase capacity through system alterations and adjustments. Many adaptation practices for climate change can be found in the literature for other infrastructure sectors while prioritizing CCA measures in the electricity, transportation and water infrastructure has been rarely captured in past studies. This study attempts to prioritize the CCA measure in the context of these three vital infrastructure sectors utilizing AHP process and expert opinions.

### 4. Methodology

#### 4.1. Study area

The current study has selected Sri Lanka as a suitable case point to identify and prioritize measures for CCA measures in selected infrastructure sectors. Sri Lanka is an island nation located at the southern end of the Indian subcontinent and it is surrounded by the Indian Ocean. Being a tropical country, it is highly susceptible to the impacts of climate change, as indicated by its ranking as the second most affected country by climate change in 2017 according to the Global Climate Risk Index 2019 [96]. Sri Lanka's vulnerability to climate change is further compounded by various political, geographic, and social factors as evident by its rank of 100 out of 181 countries in the 2017 ND-GAIN Index [97]. The country's coastline covering approximately 1620 km is a significant feature of its landscape and provides numerous economic and societal benefits. However, coastal habitats in Sri Lanka are vulnerable to disasters, as demonstrated by the severe damage and massive impact to human lives from the 2004 Tsunami. Development activities along the coast are critical to Sri Lanka's economy but also expose the country to environmental risks, such as coastal erosion and saltwater intrusion [98–103]. Additionally, the impacts of climate change on Sri Lanka are further evidenced by a study conducted by Bakker in 2018, indicating that a significant number of beaches in Sri Lanka are at risk of disappearing by 2100 due to potential sea-level rise impacts [104]. The CI sectors in Sri Lanka, specifically transportation, water and electricity are facing the impacts of climate change which are hindering the country's economic development [101,105]. The transportation sector is experiencing increased rainfall intensity and flooding, leading to significant damage to roads, bridges, and railways, thereby disrupting transportation networks and access to essential services [101,106]. In the water sector, changes in rainfall patterns and temperatures are reducing the quality and availability of water resources, affecting the provision of safe drinking water, irrigation, and hydropower generation [101,106]. Similarly, the electricity sector is facing significant challenges, with droughts affecting hydropower generation and thermal power plants experiencing reduced efficiency due to higher temperatures [101]. These impacts are resulting in increased economic costs and social vulnerabilities, underscoring the need for the identification and prioritization of CCA measures [106–108]. The country has been facing a severe energy and economic crisis in recent times, resulting an acute shortage of electricity and high inflation. This situation has been attributed to several factors, including prolonged drought, low hydroelectric power generation, and delayed investments in the electricity sector [109,110]. Climate change has been a significant contributor to this crisis with the country experiencing more frequent and severe weather events, including droughts and floods, which have adversely affected energy and food production. The energy and economic crisis in Sri Lanka underscore criticality of these infrastructure sectors [111]. Strengthening the resilience of CIs can help mitigate the impacts of climate change and ensure the smooth functioning of essential services, such as electricity, water and transportation, during times of crisis. Considering the climate change impacts and the criticality of the CI sectors, Sri Lanka presents a suitable case point for this study.

### 4.2. Survey design and data collection

Fig. 4 elaborates the overall methodology of the present study. The data for the study was collected in two stages. In the first stage, an expert interview was carried out. The interview questions were designed to identify the major assets/facilities/infrastructures belonging to the selected CIs, to determine the CCA measures, and validate the criteria to evaluate the CCA measures for prioritization. In the first data collection stage, 42 experts in the field of infrastructure planning, design, construction, and maintenance were interviewed. The “purposive sampling technique” was utilized for the selection of the experts for the interview, since this method was preferred by most of the studies [112,113]. The experts were selected based on their working profession and experience. In the second stage, an online questionnaire was designed to determine the relative weights for selected criteria for the CCA measures and to determine the applicability of the identified CCA measure for the selected infrastructure. The respondents were asked to indicate the applicability of the CCA measures in 1 (Not applicable)-5 (Most applicable) Likert scale. The online questionnaire was distributed among the same experts who participated in the first stage of data collection. Table 1 shows the work experience of the experts involved in this study.

### 4.3. AHP process

The literature review identified that there are two main types of methods to assign weights in a Multi-Criteria Decision-Making scenario: objective and subjective. Objective methods allow weights to be calculated independently of the decision maker's perceptions. According to Tzeng, Chen, & Wang (1998), the Extreme weight approach, Random weight approach, and Entropy method are a few examples of such practices. Subjective methods, on the other hand, allow the decision maker to input their perceptions. Two of the popular subjective methods are the Best worst method (BWM) and AHP [114,115]. Out of these, the latter is usually preferred (i.e., AHP process).

Furthermore, AHP has frequently been utilized to address various decision-making issues as a multi-criteria technique [116–118]. It gained prominence in a variety of sectors because of its capacity to analyze numerous and varied criteria qualitatively, quantitatively, and occasionally with limited data availability [118,119]. The key benefit of AHP is that users may better concentrate on the criteria at each level during weight allocation due to its hierarchical nature [116]. Instead of providing a single solution due to this structure, AHP assists the decision-makers in making the optimal choice depending on the needs and concerns of the situation. The pairwise comparison method emphasizes the options that result in higher goal achievement in AHP implementation. An indicator matrix is built to enable pairwise comparison, allowing users to compare the indications and rank them using a standard comparison scale. The original Saaty scale was employed as the standardized comparison scale in this investigation [120], consisting of 9 levels.

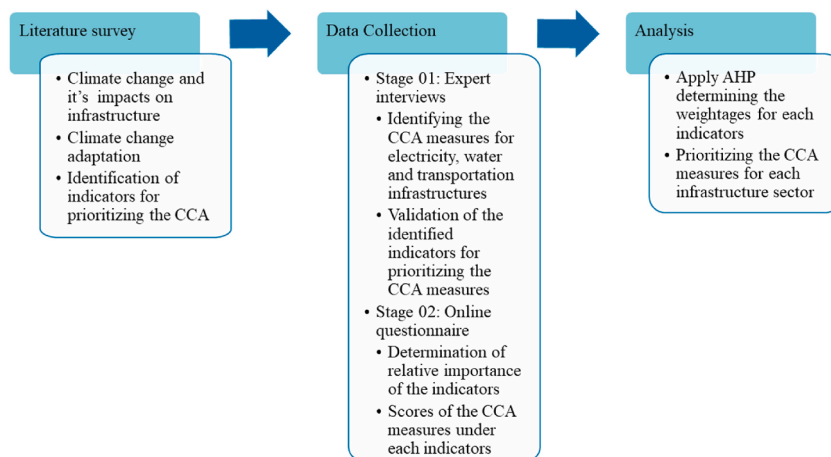


Fig. 4. Overall methodology of the study.

Table 1  
Working experience in years of the experts involved in the study.

Working experience (x) (Years)	Percentage of experts		
	Transportation	Water	Electricity
$x \leq 15$	0%	0%	0%
$15 < x \leq 20$	13%	20%	20%
$20 < x \leq 25$	19%	33%	20%
$25 < x \leq 30$	44%	20%	33%
$30 < x \leq 35$	13%	7%	13%
$35 < x$	13%	20%	13%

In order to mitigate biasness in the AHP, a number of measures have been implemented. Firstly, the selection of experts has been carefully considered to ensure that they possess the requisite expertise and have diverse perspectives. Criteria such as organizational affiliation, professional experience, involvement in past projects, and expertise in the field of climate change and built environment were employed to identify suitable experts. Secondly, the questionnaire employed for pairwise comparison has been meticulously prepared to ensure clarity, unambiguity, and impartiality of questions. Thirdly, the pairwise comparison process has been conducted in-person utilizing a well-structured protocol aimed at minimizing the impact of extraneous factors on the experts' judgments. Participants were required to maintain consistency ratios below 10%, which falls within the acceptable limits. Finally, data filtering was performed to identify and remove outliers that may skew the results of the AHP analysis [120]. These measures have significantly reduced the potential impact of bias on the AHP process, resulting in more objective and precise results.

## 5. Results

Results from the expert interview are first presented in Section 5.1 and 5.2. The CCA measures for the selected infrastructure sectors are presented within these two sections. Sections 5.3 and 5.4 present the results of the AHP analysis of the online questionnaire carried out in this study.

### 5.1. Analysis of interview responses from expert interviews

This section presents the qualitative and quantitative analysis of the interviewees and online questionnaire responses. A total of 17 measures were suggested as CCA measures for selected infrastructure. These 17 measures have been identified throughout all phases of the infrastructure development, as presented in Sections 5.1.1–5.1.3.

#### 5.1.1. CCA measures for the planning stage of the infrastructure

This section discusses the identified CCA measures under the planning stage for the selected infrastructure. The first CCA measure identified under the planning stage of an infrastructure is the consideration of anticipated loads in the designing of infrastructure which will be subjected to various loading conditions under changing climate conditions. The infrastructure will fail unless they can accommodate the unexpected loading from different climate change scenarios. Therefore, it is vital to consider these anticipated loading conditions that can be imposed by climate change (P1 in Table 2). Properly planned evacuation routes are critical in evacuating places in an emergency, especially in enclosed infrastructure facilities. Furthermore, these evacuation routes reduce the difficulty of maintenance and retrofitting activities. Eventually, this will enhance the recoverability of the infrastructure. Therefore, proper planning of evacuation routes has been identified as another CCA measure for the selected infrastructure under the planning stage (P3 in Table 2). Building codes, standards, guidelines, and rules are essential components of an effective governance structure. Furthermore, these components are crucial to infrastructure growth. But it was evident that the existing building codes, rules and regulations need to be revised with the changing landscape of the climate. Hence revision of the building codes, rules and regulations integrating climate resilience is a much more vital CCA measure (P2 in Table 2). Interview respondents agreed that unequivocally climate-related disasters affect infrastructure performance. Hence, evaluating risk towards the infrastructure is crucial in the planning stage of infrastructure development. Therefore, adopting a risk assessment tool to assess the risk from climate change-related shocks and stresses can be considered another important CCA measure for the selected infrastructure. This will enable risk-informed infrastructure planning and help to make them more climate resilient. Moreover, the creation of maps of infrastructure assets and facilities assists asset managers in effectively managing the infrastructure in disaster situations. Furthermore, this enables engineers to plan the infrastructure, accounting for interdependencies among the infrastructure. Therefore, preparing integrated assets management system that includes the maps of infrastructure assets and facilities, and a risk evaluation tool has been mentioned as another vital CCA measure during expert interviews (P4 in Table 2). Integrating nature-based solutions effectively reduces the damage to infrastructures from disaster events. This will be more effective in reducing the damage from storm surges, especially in coastal areas. Consequently, better land use planning with greener/nature-based solutions has been identified as the fifth CCA measure under the infrastructure planning stage (P5 in Table 2). Table 2 illustrates the snapshot of the identified CCA measures under the planning stage of the selected infrastructures.

The CCA measures listed above are relevant for selected infrastructure sectors, regardless of their function. Table 3 illustrates how these identified CCA measures can be applicable to the selected infrastructure in this study. Specifically, for the water sector, it is critical to design and plan water infrastructure that is resilient to extreme weather events, assess potential impacts of climate change on water availability, and incorporate adaptive management strategies to ensure continued access to safe and reliable water supplies. In addition, water infrastructure needs to comply with rules, regulations and codes related to water quality, water supply and water

**Table 2**  
Identified CCA measure during the planning stage.

Code	Adaptation measure
P.1.	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure
P.2.	Revision of the construction codes, rule and regulations
P.3.	Proper planning of evacuation routes
P.4.	Asset management system incorporating disaster resilience to include additional requirements for post-disaster event rehabilitation and relevant resource requirement at the planning stage
P.5.	Integrating nature-based solutions when infrastructure planning

**Table 3**  
Applicability of identified CCA measures under planning phase for the selected infrastructure.

Code	Water Sector	Electricity sector	Transportation sector
P.1: Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	Water infrastructure is particularly vulnerable to climate change impacts such as droughts, floods and sea-level rise. Therefore, it is critical to consider these factors when designing and planning water infrastructure. This includes designing water infrastructure to be resilient to extreme weather events, assessing the potential impacts of climate change on water availability and incorporating adaptive management strategies to ensure continued access to safe and reliable water supplies.	Extreme weather events caused by climate change, such as heat waves, storms, and floods can impact electricity infrastructure, leading to power outages and disruptions. Therefore, it is critical to consider these risks when designing and planning electricity infrastructure. This includes designing energy systems that are resilient to extreme weather events and can continue to function under changing climatic conditions.	Extreme weather events caused by climate change, such as heat waves, storms and floods can impact transportation infrastructure, leading to road closures, disruptions to public transport, and delays. Therefore, it is critical to consider these risks when designing and planning transportation infrastructure. This includes designing transportation systems that are resilient to extreme weather events and can continue to function under changing climatic conditions.
P.2: Revision of the construction codes, rule and regulations	Water infrastructure is subject to various codes, rules and regulations including those related to water quality, water supply and water treatment. These rules and regulations need to be updated to incorporate climate change considerations to ensure that the water infrastructure is resilient to changing weather patterns, can withstand extreme weather events, and can continue to provide clean and safe water to communities.	Electricity infrastructure is subject to various codes, rules and regulations, including those related to grid design, electrical safety and power quality. These rules and regulations need to be updated to incorporate climate change considerations to ensure that the energy infrastructure is resilient to changing weather patterns, can withstand extreme weather events, and can continue to provide reliable electricity to communities.	Transportation infrastructure is subject to various codes, rules and regulations including those related to road safety, bridge design and public transport. These rules and regulations need to be updated to incorporate climate change considerations to ensure that the transportation infrastructure is resilient to changing weather patterns, can withstand extreme weather events, and can continue to provide safe and reliable transportation to communities.
P.3: Proper planning of evacuation routes	The provision of the evacuation route is essential from the point of view for maintaining the infrastructure's functionality during disruptions. It is crucial to plan and maintain evacuation routes to supply the tools and other essential services such as electricity, repairing, etc. This ensures functionality of facilities during the disaster event Also these evacuation routes can be acted as evacuation paths for workers inside facilities for ensuring the health and safety of the workers. Further, this ensures speedy recovery in the aftermath of the severe disruption.	In electricity related infrastructure facilities, it is essential to plan and maintain access routes for the service team to access these facilities for maintaining the infrastructure's functionality. Furthermore, these access routes can be acted as the evacuation routes for the inside workers in case of emergency in facilities and assets. That ensures the safety and health of the workers.	Transportation infrastructure provides accessibility and connectivity for the community, emergency respondents, maintenance and retrofitting services during disaster events. In the evacuation planning in the context of transportation infrastructure provision of evacuation routes should ensure accessibility and connectivity.
P.4: Asset management system incorporating disaster resilience to include additional requirements for post-disaster event rehabilitation and relevant resource requirement at the planning stage	Water infrastructure is critical to the functioning of cities, towns, and rural communities, and disruptions can have serious consequences for public health and the economy. An asset management system that incorporates disaster resilience is essential to ensure that water infrastructure can quickly recover from disasters, continue to operate during and after emergencies and provide uninterrupted access to safe and clean water.	Electricity infrastructure is critical to the functioning of cities, towns, and rural communities, and disruptions can have serious consequences for public health and the economy. An asset management system that incorporates disaster resilience is essential to ensure that energy infrastructure can quickly recover from disasters, continue to operate during and after emergencies, and provide uninterrupted access to reliable electricity.	Transportation infrastructure is critical to the functioning of cities, towns and rural communities, and disruptions can have serious consequences for public health and the economy. An asset management system that incorporates disaster resilience is essential to ensure that transportation infrastructure can quickly recover from disasters, continue to operate during and after emergencies, and provide uninterrupted access to safe and reliable transportation.
P.5: Integrating nature-based solutions when infrastructure planning	Nature-based solutions can play an important role in water infrastructure planning by reducing the impacts of climate change such as flooding and drought. For example, incorporating green infrastructure such as rain gardens and permeable pavement can help to reduce the amount of stormwater runoff, recharge groundwater supplies and protect water quality. Other nature-based solutions such as restoring wetlands can also provide valuable ecosystem services such as water filtration and flood control while providing habitat for wildlife.	Nature-based solutions can also play an important role in electricity infrastructure planning by reducing the impacts of climate change such as reducing the urban heat island effect and mitigating the effects of extreme weather events. For example, integrating green infrastructure such as urban forests and green roofs can help to cool urban areas and reduce the energy demand for air conditioning. Renewable energy technologies such as solar, wind and hydropower can also be used to diversify the energy mix and reduce greenhouse gas emissions.	Nature-based solutions can also play an important role in transportation infrastructure planning by reducing the impacts of climate change such as reducing the urban heat island effect and mitigating the effects of extreme weather events. For example, integrating green infrastructure, such as green spaces and urban forests, can help to cool urban areas and reduce the energy demand for air conditioning. Other nature-based solutions, such as natural drainage systems, can also help to reduce the impacts of flooding on transportation infrastructure.

treatment that need to be updated to incorporate climate change considerations. Similarly, for the electricity sector, it is critical to design energy systems that are resilient to extreme weather events and can continue to function under changing climatic conditions. Electricity infrastructure needs to comply with rules, regulations and codes related to grid design, electrical safety and power quality that need to be updated to incorporate climate change considerations. For the transportation sector, it is critical to design transportation systems that are resilient to extreme weather events and can continue to function under changing climatic conditions. Transportation infrastructure needs to comply with rules, regulations and codes related to road safety, bridge design and public transport that need to be updated to incorporate climate change considerations. Moreover, all infrastructure types are critical to the functioning of cities, towns and rural communities, and disruptions can have serious consequences for public health and the economy. Therefore, an asset management system that incorporates disaster resilience is essential to ensure that infrastructure can quickly recover from disasters, continue to operate during and after emergencies, and provide uninterrupted access to services. Finally, nature-based solutions can play an important role in infrastructure planning by reducing the impacts of climate change such as flooding and drought. For example, incorporating green infrastructure can help to reduce the amount of stormwater runoff, recharge groundwater supplies, and protect water quality. Similarly, green infrastructure can help to cool urban areas and reduce energy demand for air conditioning in the electricity and transportation sectors.

Fig. 5 illustrates the applicability of the identified CCA measures under the planning stage for each selected infrastructure sector as a proportion of respondents. For instance, in the Transportation sector, the highest-rated measures for the applicability of CCA are “Incorporating nature-based solutions in transportation infrastructure planning” and “Asset management system incorporating disaster resilience to include additional requirements for post-disaster event rehabilitation and relevant resource requirements at the planning stage”, both receiving the same proportion of respondents. Meanwhile, in the water sector, the highest-rated measure for the applicability of CCA is “Proper planning of alternative routes,” while “Incorporating nature-based solutions in transportation infrastructure planning” received the second-highest proportion of respondents for applicability. In the Electricity sector, the highest-rated measure for the applicability of CCA is “Proper planning of alternative routes,” while “Consideration of operational loads in the designing of infrastructure” and “Revision of the construction codes, rules, and regulations” both received the same proportion of respondents for applicability.”

Overall, measures related to disaster resilience, nature-based solutions and proper planning of alternative routes are considered highly applicable for CCA across all three infrastructure sectors. There are several reasons for this. With the increasing frequency and severity of extreme weather events and other climate-related hazards, it has become crucial to incorporate disaster resilience measures into infrastructure planning to minimize the impacts of such events. This includes using design standards that can withstand extreme weather events, providing backup systems and contingency plans for disruptions to service delivery, and ensuring that infrastructure is adaptable and resilient to changing climate conditions. Nature based solutions involve using natural systems or processes to help protect, manage, and restore ecosystems and their services. They can be used to reduce the vulnerability of infrastructure to climate risks and enhance the resilience of infrastructure systems to climate change impacts. For example, green infrastructure solutions like green roofs, rain gardens, and permeable pavements can help to reduce the impacts of flooding and stormwater runoff while also providing other environmental and social benefits. Climate change can increase the likelihood of disruptions to infrastructure services, such as transportation and water supply, due to extreme weather events or other hazards. Proper planning of alternative routes can help to minimize disruptions to service delivery by providing alternate routes for transportation or alternate sources of water supply during periods of disruption. This can help to ensure that critical services are maintained during and after climate-related

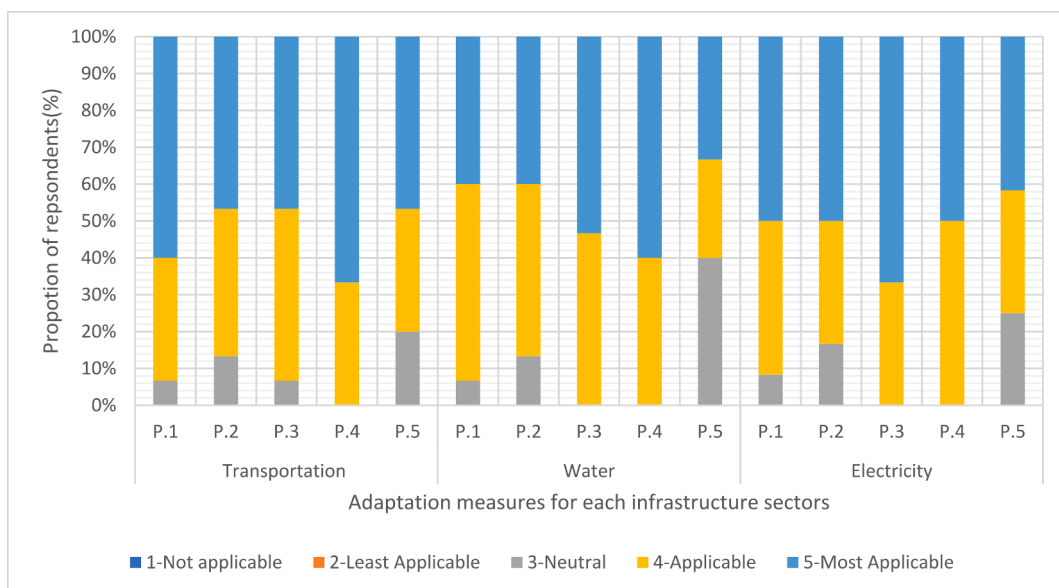


Fig. 5. Applicability of identified CCA measures for planning stage from the interview responses.

events. In summary, incorporating disaster resilience measures, nature-based solutions, and proper planning of alternative routes can help to ensure that infrastructure is better prepared to withstand climate-related hazards and adapt to changing climate conditions. By considering these measures during infrastructure planning, decision-makers can help to minimize the impacts of climate change on CI services and ensure that they remain functional and resilient over the long-term.

### 5.1.2. CCA measures for design and construction stage of the infrastructure

This section discusses measures (summarized in Table 4) that can be taken to ensure the resilience of infrastructure during the design and construction stages. The first measure identified was the use of proper materials in design and construction. Proper material provides strength to infrastructure against disasters. Also, when selecting the materials, designers and engineers can give attention to integrating the greener materials where it can be appropriate. This can reduce GHG emissions, which are a major driver of climate change. Thus, integration of greener materials will be a value-added advantage. However, it should not dismiss the key function which is the enhancing the resilience of the infrastructure against disasters. Therefore, the proper material selection during the design and construction phase is a crucial CCA measure (D.C.1 in Table 4). Another CCA measure identified was safe engineering design. Such designs provide reliable infrastructure with lower life cycle costs and can fail under specific conditions with less damage and cost. Safe engineering designs can be used to adapt infrastructure to climate change and reduce risks during disasters (D.C.3 in Table 4). Designing infrastructure to accommodate future modifications was identified as another CCA measure. Accommodating modifications in the future is essential as infrastructure may face unforeseen climate change impacts during its lifecycle. Hence, infrastructure design should consider future climate change scenarios and provide adequate flexibility to accommodate modifications without hindering performance (D.C.5 in Table 4). Stormwater accumulation is a significant challenge for infrastructure during heavy precipitation. Proper stormwater management techniques can mitigate the impact of high rainfall, such as the implementation of a stormwater management system that drains excess water from infrastructure facilities (D.C.2 in Table 4). Protective measures, such as cut-off walls and gabion walls, can also be used to protect infrastructure during disasters (D.C.4 in Table 4). Raising the elevation of infrastructure is a common measure adopted by most countries to cope with climate change impacts. Most coastal infrastructure raises its foundation level above the high flood level to continue performing during disaster events (D.C.6 in Table 4). Designers can also consider alternative infrastructure designs such as floating infrastructure in conditions where climate change impacts are dominant, and traditional engineering designs may not be applicable (D.C.7 in Table 4).

The CCA measures listed above are relevant for selected infrastructure sectors in design and construction stage, regardless of their function. Table 5 provides a comparison of how adaptation measures can be applied to the selected infrastructure in this study. While there are some variations depending on the infrastructure type, these measures are generally similar across the sectors. The key measures to protect water infrastructure from the impacts of climate change include selecting materials that can resist prolonged exposure to water, implementing proper stormwater management techniques, and constructing physical barriers. Additionally, designing adaptable infrastructure and raising the elevation of water infrastructure are effective measures. In the electricity sector, selecting materials that can resist prolonged exposure to weather and extreme temperatures, safe engineering designs, and constructing physical barriers are important measures. Adaptable infrastructure and raising the elevation of infrastructure, such as power lines and transformers, are also critical. Similarly, in the transportation sector, selecting materials that can resist prolonged exposure to weather and extreme temperatures, proper stormwater management techniques, and constructing physical barriers are critical measures to protect infrastructure. Adaptable infrastructure and raising the elevation of infrastructure, such as bridges or roadways, are also effective measures. Alternative designs, such as floating infrastructure, renewable energy sources, or floating transportation infrastructure, can provide more sustainable and resilient options in the face of climate change impacts across all three sectors. In summary, the identified CCA measures discussed above are applicable to all types of infrastructure, and they are critical in ensuring the resilience and sustainability of these infrastructures in the face of changing climate conditions.

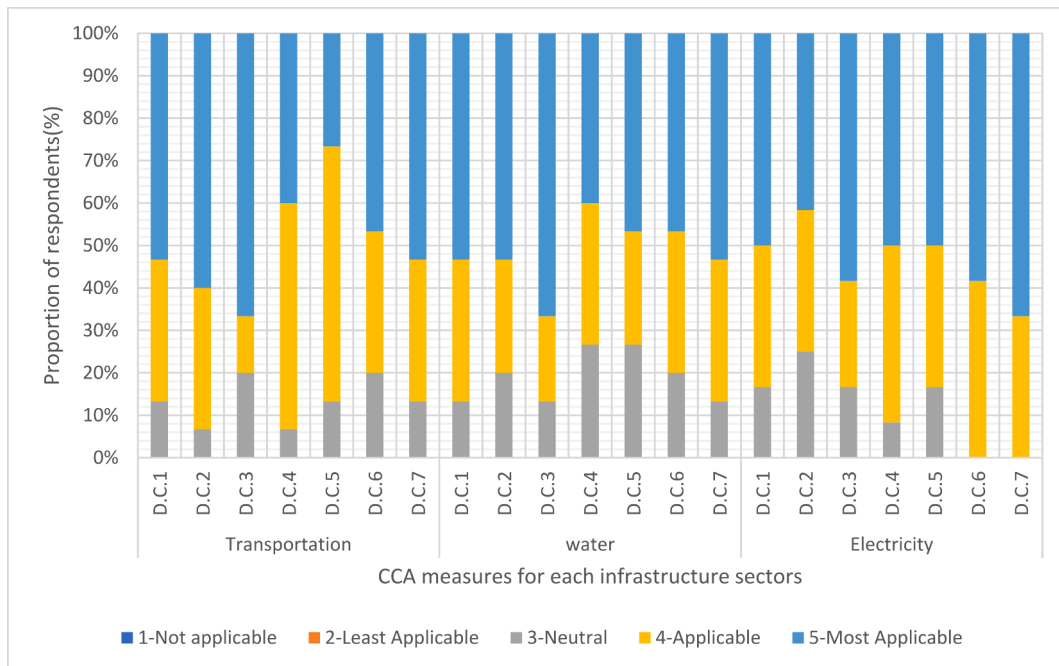
Fig. 6 illustrates the applicability of the identified CCA measures during the design and construction stage for each selected infrastructure sector. For example, in the transportation sector, the measures with the highest applicability scores are proper material design, stormwater management, protective measures (such as flood protection barriers), and alternative infrastructure designs. This suggests that these measures are likely to be more effective in reducing the potential impacts of climate change on transportation infrastructure such as roads, bridges, and tunnels. Similarly, for water infrastructure, the CCA measures that have the highest applicability scores include proper material design, storm water management, using protective measures (such as flood protection barriers and cut off walls), and infrastructure design that can accommodate future modifications considering future climate change impacts. These measures are expected to help improve the resilience of water infrastructure systems against climate change impacts such as flooding and water scarcity. In the case of electricity infrastructure, the CCA measures that have the highest applicability scores are

**Table 4**  
Identified CCA measures during the design and construction stage.

Code	Adaptation measure
D.C.1.	Proper material design to accommodate prolonged climatic conditions
D.C.2.	Proper stormwater management techniques/Drainage system designs
D.C.3.	Considering safe engineering designs
D.C.4.	Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)
D.C.5.	Infrastructure design to accommodate future modifications considering future climate change impacts
D.C.6.	Raising the elevation of infrastructure
D.C.7.	Alternative infrastructure designs (e.g., Floating infrastructures)

**Table 5**  
Applicability of identified CCA measures under design and construction stage for selected infrastructure.

Code	Water Sector	Electricity sector	Transportation sector
D.C.1: Proper material design to accommodate prolonged climatic conditions	Selecting materials that are resistant to prolonged exposure to water can help prevent damage and degradation of water infrastructure such as pipes and tanks.	Selecting materials that are resistant to prolonged exposure to weather and extreme temperatures can help prevent damage and degradation of electricity infrastructure such as power lines, transformers, and substations.	Selecting materials that are resistant to prolonged exposure to weather and extreme temperatures can help prevent damage and degradation of transportation infrastructure such as roads, bridges, and tunnels.
D.C.2: Proper stormwater management techniques/ Drainage system designs	Proper stormwater management is critical for water infrastructure to prevent flooding, erosion and other damage caused by heavy rain and runoff.	Proper stormwater management is critical for electricity infrastructure to prevent flooding, erosion and other damage caused by heavy rain and runoff which can affect power lines and substations.	Proper stormwater management is critical for transportation infrastructure to prevent flooding, erosion and other damage caused by heavy rain and runoff, which can affect roads and bridges.
D.C.3: Considering safe engineering designs	Constructing physical barriers, such as flood protection barriers or cut-off walls can help protect water infrastructure from flooding and other impacts of climate change.	Safe engineering designs can help ensure that electricity infrastructure is resilient and can withstand the effects of climate change, such as more frequent and intense storms, extreme temperatures and flooding.	Safe engineering designs can help ensure that transportation infrastructure is resilient and can withstand the effects of climate change such as more frequent and intense storms and flooding.
D.C.4: Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)	Constructing physical barriers, such as flood protection barriers or cut-off walls can help protect water infrastructure from flooding and other impacts of climate change.	Constructing physical barriers, such as flood protection barriers or cut-off walls can help protect electricity infrastructure from flooding and other impacts of climate change.	Constructing physical barriers, such as flood protection barriers or cut-off walls can help protect transportation infrastructure from flooding and other impacts of climate change.
D.C.5: Infrastructure design to accommodate future modifications considering future climate change impacts	Designing water infrastructure that can be modified or adapted in the future to accommodate the changing climate and its impacts can help ensure its long-term sustainability.	Designing electricity infrastructure that can be modified or adapted in the future to accommodate the changing climate and its impacts can help ensure its long-term sustainability.	Designing transportation infrastructure that can be modified or adapted in the future to accommodate the changing climate and its impacts can help ensure its long-term sustainability.
D.C.6: Raising the elevation of infrastructure	Raising the elevation of water infrastructure can protect it from sea-level rise and flooding.	Raising the elevation of electricity infrastructure, such as power lines and transformers, can protect it from sea-level rise and flooding.	Raising the elevation of transportation infrastructure, such as bridges or roadways, can protect it from sea-level rise and flooding.
D.C.7: Alternative infrastructure designs (e.g., Floating infrastructures)	Considering alternative designs, such as floating water infrastructure can provide a more sustainable and resilient option in the face of climate change impacts.	Considering alternative designs such as renewable energy sources like wind turbines or solar panels can provide a more sustainable and resilient option in the face of climate change impacts.	Considering alternative designs such as floating transportation infrastructure can provide a more sustainable and resilient option in the face of climate change impacts.



**Fig. 6.** Applicability of identified CCA measures for design and construction stage from the interview responses.

those related to storm water management, safe engineering designs, using protective measures (such as flood protection barriers and cut off walls), and infrastructure design that can accommodate future modifications considering future climate change impacts. Additionally, raising the elevation of infrastructure may also be applicable to some extent.

These measures are likely to help reduce the potential impacts of climate change on electricity infrastructure, such as power plants and transmission lines. Overall, the results suggest that there are some common CCA measures that can be applied across different infrastructure sectors, such as proper material design, storm water management, and using protective measures. However, the most appropriate CCA measures may vary depending on the specific context, location, and infrastructure type. For example, some regions may be more vulnerable to flooding due to their proximity to rivers, coastlines, or low-lying areas, while others may be more vulnerable to droughts and water scarcity due to their arid or semi-arid climates. Similarly, some infrastructure projects may be located in areas that are more prone to extreme weather events, such as hurricanes, tornadoes, or wildfires, while others may be more susceptible to long-term changes in temperature and precipitation patterns. Therefore, to determine the most appropriate CCA measures for each infrastructure project, it is necessary to consider the specific climate change impacts and vulnerabilities of that project. This may involve conducting a detailed assessment of the current and projected climate conditions, identifying the potential impacts of climate change on the infrastructure project, and evaluating the effectiveness and feasibility of different CCA measures in mitigating those impacts. By taking a context-specific approach to CCA, infrastructure projects can be designed and constructed in a way that improves their resilience and adaptability to climate change reducing the risks and costs associated with climate-related disruptions and damages.

### 5.1.3. CCA measures for the maintenance and retrofitting stage of the infrastructure

This section elaborates on the identified CCA measures for the maintenance and retrofitting stage which is essential for its lifelong performance. Infrastructure performance will degrade due to different types of exposure during its life cycle. Adopting proper methods and techniques to predict maintenance will ensure appropriate infrastructure maintenance. Therefore, implementing methods and techniques that account for climate change will be a vital CCA measure under the infrastructure maintenance and retrofitting stage (M.R.1 in Table 6). The performance of the drainage system belonging to these infrastructure facilities will be reduced due to various factors. Nevertheless sometimes old, constructed drainage systems won't be able to cater to their services with the present landscape of climate change. Therefore, increasing and maintaining longitudinal drain capacities is important to mitigate climate change impacts, especially floods (M.R.2 in Table 6). Infrastructure will deteriorate during its service life. Deteriorated infrastructure affects the performance of other infrastructure sectors since these sectors are interdependent. Additionally, sometimes deteriorated infrastructure needs retrofitting and repair activities beforehand. Otherwise, failure of the deteriorated infrastructure will cause cascading impacts, affecting the performance of other infrastructures due to the interdependent nature of infrastructure systems. Most infrastructure owners and providers perform routine maintenance on their infrastructures. Such routine maintenance will assist in the smooth functioning of the infrastructure (M.R.4 in Table 6). The risk profiles of infrastructure can change with time and climate conditions. Therefore, updating the risk profiles of infrastructure and conducting a risk assessment will allow decision-makers to make risk-informed decisions and make infrastructure more resilient during its service life. This could be achieved using implemented asset management systems (M.R.5 in Table 6). Table 6 presents the above-described CCA measures in a tabulated format.

The identified adaptation measures under the maintenance and retrofitting stage are applicable to selected infrastructure regardless of their specific functions as illustrated in Table 7. In the water sector, several adaptation measures can be taken to ensure a reliable and safe water supply. These include using data analytics to monitor water quality and pressure in pipes, upgrading water treatment plants and pipelines, conducting regular inspections to ensure proper functioning and identifying potential problems, fixing leaks and replacing old pipes, and prioritizing repairs after natural disasters. For the electricity sector, adaptation measures include using predictive maintenance techniques to monitor equipment health, upgrading power transmission lines, conducting regular inspections, upgrading electrical wiring, and prioritizing repairs after natural disasters. Similarly, in the transportation sector, adaptation measures include using predictive maintenance techniques, expanding transportation infrastructure, conducting regular inspections, repairing potholes and upgrading outdated infrastructure, and prioritizing repairs after natural disasters. Taking these measures can help to identify potential problems early, improve safety, and ensure that CI is restored quickly after catastrophic events.

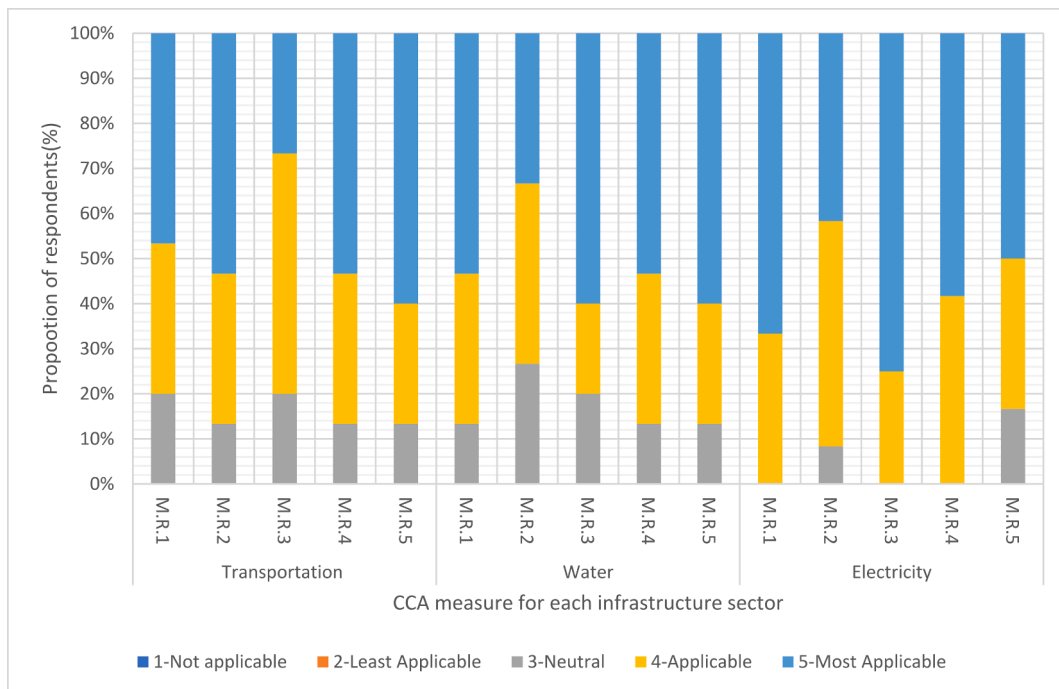
Fig. 7 shows the applicability of CCA measures in the maintenance and retrofitting stage for the selected infrastructure sectors in this study. For transportation, the most applicable CCA measure is the implementation of methods/techniques to predict maintenance, with the highest proportion of respondents indicating its applicability. Increasing and maintaining infrastructure asset capacities and performing retrofitting and repair activities in deteriorated infrastructure are second and third, respectively, in their applicability to transportation. Proper monitoring of routine maintenance services and asset management during maintenance seem to be moderately applicable for transportation infrastructure. For water, increasing and maintaining infrastructure asset capacities and the implementation of methods/techniques to predict maintenance are highly applicable, with the highest proportion

**Table 6**  
CCA measure for infrastructure maintenance and retrofitting phase.

Code	Adaptation measure
M.R.1.	Implementation of methods/techniques to predict the maintenance of the infrastructure
M.R.2.	Increasing and maintenance of infrastructure assets capacities
M.R.3.	Implementation of proper monitoring of routine maintenance service
M.R.4	Performing retrofitting and repair activities in deteriorated infrastructure
M.R.5.	Asset management during maintenance, prioritizing infrastructure for restoration after catastrophic events

**Table 7**  
Applicability of identified CCA measures under maintenance and retrofitting for selected infrastructure.

Code	Water Sector	Electricity sector	Transportation sector
M.R.1: Implementation of methods/techniques to predict the maintenance of the infrastructure	Implementation of methods/techniques to predict maintenance needs could involve using data analytics to monitor water quality and pressure in pipes and identify areas where maintenance is needed before issues arise.	Predictive maintenance techniques could be used to monitor electricity usage and equipment health to identify areas where maintenance is needed before failures occur.	Predictive maintenance techniques could be used to monitor traffic flow, road surface quality, and bridge conditions to identify areas where maintenance is needed before issues arise.
M.R.2: Increasing and maintenance of infrastructure assets capacities	Increasing capacity could involve upgrading or expanding water treatment plants, reservoirs, or pipelines to meet the growing demand for clean water.	Increasing capacity could involve expanding power plants, upgrading power transmission lines or building new power substations to meet the increasing demand for electricity.	Increasing capacity could involve expanding roads or building new transportation infrastructure, such as bridges or tunnels, to meet the growing demand for transportation.
M.R.3: Implementation of proper monitoring of routine maintenance service	Proper monitoring could involve regular inspections of water treatment facilities and pipelines to ensure that they are functioning correctly and identifying potential problems early.	Proper monitoring could involve regular inspections of electrical equipment and transmission lines to identify potential problems early and reduce the risk of power outages.	Proper monitoring could involve regular inspections of transportation infrastructure, including roads, bridges, and tunnels, to identify potential problems early and reduce the risk of accidents or service disruptions
M.R.4: Performing retrofitting and repair activities in deteriorated infrastructure	Retrofitting and repair activities could involve fixing leaks or replacing old pipes to prevent water loss and contamination.	Retrofitting and repair activities could involve replacing outdated transformers or upgrading electrical wiring to improve system efficiency and reliability.	Retrofitting and repair activities could involve repairing potholes, replacing worn-out road surfaces, or upgrading outdated bridges or tunnels to improve safety and functionality.
M.R.5: Asset management during maintenance, prioritizing infrastructure for restoration after catastrophic events	Asset management during maintenance could involve prioritizing repairs to critical water infrastructure after natural disasters or other catastrophic events to restore water services quickly.	Asset management during maintenance could involve prioritizing repairs to critical electricity infrastructure after natural disasters or other catastrophic events to restore power services quickly.	Asset management during maintenance could involve prioritizing repairs to critical transportation infrastructure after natural disasters or other catastrophic events to restore transportation services quickly.



**Fig. 7.** Applicability of identified CCA measures for maintenance and retrofitting stage from the interview responses.

of respondents indicating their applicability. “Asset management during maintenance” and “retrofitting and repair activities in deteriorated infrastructure” are second and third, respectively, in their applicability to the water supply sector. Proper monitoring of routine maintenance services seems to be moderately applicable. For the electricity sector, the most applicable CCA measure is the implementation of methods/techniques to predict maintenance. Increasing and maintaining infrastructure asset capacities and asset management during maintenance seem to be moderately applicable. Proper monitoring of routine maintenance services and

retrofitting and repair activities in deteriorated infrastructure are less applicable in the electricity sector. Overall, it should be noted that the implementation of methods/techniques to predict maintenance and increasing and maintaining infrastructure asset capacities are the most applicable CCA measures for the maintenance stage across all infrastructure sectors. Proper monitoring of routine maintenance services, retrofitting and repair activities in deteriorated infrastructure, and asset management during maintenance are also important but may vary in their applicability depending on the specific sector.

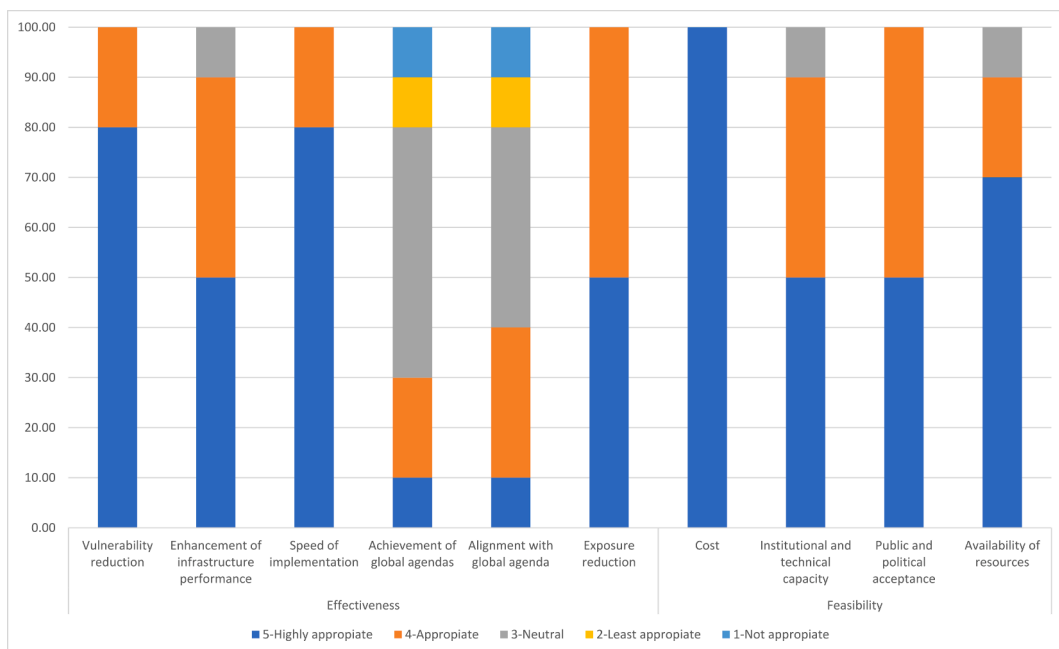
5.2. Validation of the selected criterion for prioritizing the CCA measures

One of the objectives of the expert interview is to validate and choose the most suitable criteria for evaluating the CCA measures. A suitable criterion was first identified from the literature, and experts were asked for the appropriateness of the criteria on a 1–5 Likert scale for evaluating the CCA measures. Table 8 presents the criteria identified through the initial literature survey. Fig. 8 illustrates the responses from the experts about the appropriateness of the criteria.

Obtained responses from the experts indicate that most of the selected criteria are highly appropriate for evaluating the CCA measures. Accordingly, two criteria, “Achievement of global agendas” and “Alignment with global agenda”, were deselected since responses obtained from the experts show less appropriateness for evaluating the CCA measures. The remaining criteria were selected, and a questionnaire was designed based on the criteria chosen to perform the AHP analysis.

**Table 8**  
Criteria suggested by literature for evaluating CCA measures.

Component	Criteria	Description	References
Effectiveness	Vulnerability reduction	Reduction of the vulnerability of infrastructure using adaptation measures	[66,121–124]
	Enhancement of infrastructure performance	Level of the enhancement of the infrastructure performance against climate conditions	[82,122,123,125]
	Speed of implementation	Time taken to implement the adaptation measures	[122,126,127]
	Achievement of global agendas	Level of achievement of global agenda by the implementation of adaptation measures	[90,121,128,129]
	Alignment with global agenda	Level of alignment with global agenda	[82,126,127]
	Exposure reduction	Reduction of exposure of the infrastructure by implementing adaptation measures	[82,122,127]
Feasibility	Cost	Direct costs for the implementation and maintenance of the adaptation measures	[82,121,127]
	Institutional and technical capacity	Institutional and technical capacity required to implement the adaptation measure	[82,123,127,130,131]
	Public and political acceptance	Public and political acceptance of the adaptation measure	[125,126,130,132]
	Availability of resources	Availability of the resources required to implement the adaptation measure	[82,125,126,132,133]



**Fig. 8.** Appropriateness of suggested criteria for evaluating CCA measures.

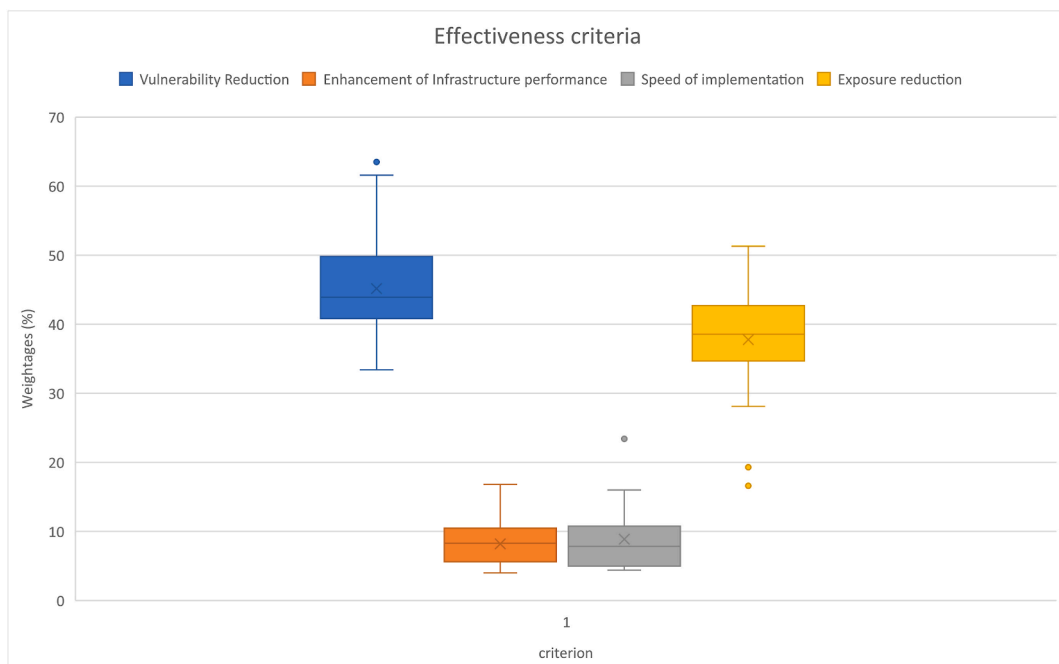
5.3. Determination of weights for indicators

This section presents the weights that were determined from the online questionnaire responses, which were used in prioritizing the CCA measures for the selected infrastructure sectors in this study. Table 9 shows the weights obtained from the AHP analysis. According to the experts' responses, the two main criteria, effectiveness, and feasibility criteria, were weighted 55% and 45%, respectively. This indicates that the CCA measures should be highly effective when they are implemented, meaning that they should have a significant impact on mitigating climate change impacts. At the same time, the criteria of feasibility should also be considered with high significance when implementing the CCA measures. Under the main criteria of "Effectiveness," four sub-criteria were suggested. Respondents gave more weightage to "Vulnerability reduction" (45%). The other sub-criteria under 'Effectiveness' was weighted at 15%, 17%, and 23% for performance enhancement, implementation speed, and exposure reduction, respectively, as indicated in Table 9. Under the "Feasibility" criteria, respondents assigned 55% weight to the cost criterion for evaluating the CCA measures. On the other hand, the other sub-criteria of technical capacity, public/political acceptance, and resource availability under the 'Feasibility' were weighted low at 10%, 14%, and 21%, respectively.

Fig. 9 illustrates the box and whisker plots of the weights assigned by the respondents under effectiveness criteria. It can be noted that vulnerability reduction and exposure reduction are the most important factors, with weightages of 45% and 23%, respectively. Enhancement of infrastructure performance and speed of implementation have weightages of around 15% and 17% respectively. The range of weightages for each factor is relatively narrow, with the lowest weightage being 4% and the highest being 50.9%. The interquartile range (IQR) for vulnerability reduction and exposure reduction is relatively narrow, indicating a relatively consistent distribution of weightages. The IQR for enhancement of infrastructure performance and speed of implementation is wider, indicating a greater variability in weightage. There are a few outliers, particularly for speed of implementation and exposure reduction. In conclusion, the data set suggests that vulnerability reduction and exposure reduction are the most important factors for the given context,

**Table 9**  
Weights for the main criteria and sub-criteria.

Main Criteria	Sub-criteria	Weights
Effectiveness	Vulnerability reduction	55%
	Enhancement of infrastructure performance	15%
	Speed of implementation	17%
	Exposure reduction	23%
Feasibility	Cost	45%
	Institutional and technical capacity	55%
	Public and political acceptance	10%
	Availability of resources	14%
		21%



**Fig. 9.** Box and Whisker plot of weightage assigned by respondents- Effectiveness criteria.

while enhancement of infrastructure performance and speed of implementation are of lesser importance. Fig. 9 also indicates that there is relatively consistent agreement among the participants regarding the importance of vulnerability reduction and exposure reduction, but there is greater variability in opinions regarding enhancement of infrastructure performance and speed of implementation.

On the other hand, “Cost” is the most important factor under the feasibility criteria, with a weightage of approximately 55%, followed by “Availability of Resources” at approximately 21%. “Public and Political Acceptance” is the least important factor, with a weightage of 14%. “Institutional and Technical Capacity” has a relatively low weightage, with the value of 10% (see Fig. 10). Overall, the participants indicate that “Cost” and “Availability of Resources” are the most important factors to consider when prioritizing CCA measures. Fig. 10 also indicates that there is relatively consistent agreement among the participants regarding the importance of the four criteria under feasibility.

#### 5.4. Prioritizing the CCA measures for selected infrastructure

As the final stage of the analysis of the study, the prioritization of the CCA measures was carried out using the weights determined by the AHP analysis. The prioritization of the CCA measures was carried out based on the life cycle phases of the infrastructure. This section presents the prioritized CCA measures.

Table 10 elaborates on the prioritized CCA measures under the planning stage for the selected infrastructure sectors in this study. It appears that the top-ranking adaptation measure for each of the three infrastructure sectors (electricity, transportation, and water) is an asset management system incorporating disaster resilience, which scored the highest overall with a score of 5.00 in each sector. This suggests that incorporating disaster resilience into the asset management system is seen as a highly effective measure for reducing vulnerability and enhancing infrastructure performance across all three sectors. For the electricity sector, the next highest-ranking measure is the proper planning of evacuation routes with a score of 4.72, indicating that proper planning of evacuation routes is seen as an effective measure for reducing vulnerability and enhancing infrastructure performance in the electricity and water sector. As a tropical nation, Sri Lanka is susceptible to numerous climate-related hazard, particularly floods [134]. There have been several instances of infrastructure disruptions reported in recent years due to these occurrences. Insights gained from interviews with experts underscored that the detrimental effects of these disruptions could have been mitigated if there had been unhindered access to CIs facilities during disasters. Furthermore, the experts noted that while pathways to these facilities did exist, they were either inundated or inadequately functional during the times of disaster. This aspect has emerged as a crucial factor contributing to the high ranking given to this measure by the experts. In the transportation sector, the second highest ranking measure is the consideration of operational loads in the planning stage, with a score of 4.94. This suggests that considering operational loads due to climatic conditions in the planning stage of infrastructure is seen as an effective measure for reducing vulnerability and enhancing infrastructure performance in the transportation sector. In the water sector, the second highest-ranking measure is the proper planning of evacuation routes, with a score of 4.59. This suggests that proper evacuation planning is identified as an effective measure for reducing vulnerability and enhancing infrastructure performance in the water sector. Additionally, integrating nature-based solutions in planning the infrastructure will reduce the negative impact on the transportation infrastructure. It can also be noted that many scholars have shown the integration of nature-based solutions as a vital CCA measure [135–137].

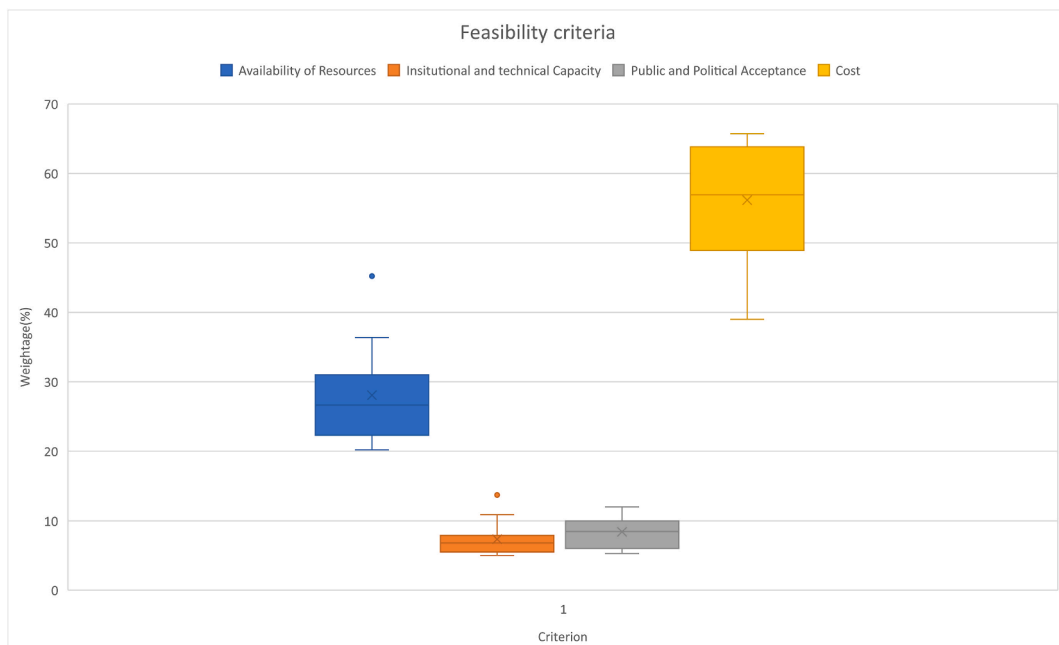


Fig. 10. Box and Whisker plot of weightage assigned by respondents- Feasibility criteria.

**Table 10**  
Prioritizing CCA measures in the planning stage.

Code	Criteria CCA Measure	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
Electricity infrastructure											
P.1	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	5	4	4	4	5	5	4	4	4.54	3
P.2	Revision of the construction codes, rule and regulations	5	4	3	5	4	4	4	3	4.19	4
P.3	Proper planning of evacuation routes	5	4	5	5	5	4	4	4	4.72	2
P.4	Asset management system incorporating disaster resilience to include additional requirements for post disaster event rehabilitation and relevant resource requirement at planning stage	5	5	5	5	5	5	5	5	5.00	1
P.5	Integrating nature-based solutions when infrastructure planning	4	4	3	4	4	4	4	5	4.00	5
Transportation sector											
P.1	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	5	5	5	5	5	5	5	4	4.91	2
P.2	Revision of the construction codes, rule and regulations	5	5	4	5	4	4	4	3	4.36	5
P.3	Proper planning of evacuation routes	5	4	5	5	5	3	4	4	4.67	3
P.4	Asset management system incorporating disaster resilience to include additional requirements for post disaster event rehabilitation and relevant resource requirement at planning stage	5	5	5	5	5	5	5	5	5.00	1
P.5	Integrating nature-based solutions when infrastructure planning	5	4	3	4	5	4	4	5	4.50	4
Water sector											
P.1	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	5	3	4	4	3	4	3	3	3.76	5
P.2	Revision of the construction codes, rule and regulations	5	4	2	4	3	5	4	3	3.76	4
P.3	Proper planning of evacuation routes	5	4	5	4	5	4	4	4	4.59	2

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Table 10 (continued)

Code	Criteria CCA Measure	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
P.4	Asset management system incorporating disaster resilience to include additional requirements for post disaster event rehabilitation and relevant resource requirement at planning stage	5	5	3	5	5	5	5	5	4.81	1
P.5	Integrating nature-based solutions when infrastructure planning	4	4	3	4	4	4	4	5	4.00	3

Table 11 elaborates on the prioritization of CCA measures in the design and construction stage of the selected infrastructure. It shows that “Consideration of safe engineering design”, “Proper material designs to withstand climate conditions”, and “Raising the elevation of the infrastructure” are the top ranked CCA measures for all three infrastructure sectors. In the electricity sector, proper material design, use of protective measures for infrastructure, and infrastructure design and construction accommodating future modifications were ranked as the most significant CCA measures in the design and construction stage. For the transportation infrastructure sector, consideration of safe engineering design, “proper material designs to withstand climate conditions”, “raising the elevation of the infrastructure”, and “infrastructure design and construction accommodating future modifications” have become significant CCA measures. Additionally, transportation infrastructure will deteriorate significantly due to climate change, especially as a result of prolonged temperature variations.

Table 12 shows the prioritized CCA measures for the selected infrastructure sectors in the maintenance and retrofitting stage. It should be noted that the participants' scores for the CCA measures under this stage are the same for all three infrastructure sectors. Therefore, the top-ranking adaptation measure for the maintenance and retrofitting stage of infrastructure is “Asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events,” with a score of 4.9. This suggests that proper asset management and prioritization of infrastructure for restoration after catastrophic events is seen as a highly effective measure for reducing vulnerability and enhancing infrastructure performance. The practice of prioritizing the essential infrastructure and resources for restoration after catastrophic events will provide a clear plan for the restoration process, which will be more efficient and effective. Additionally, a well-established asset management system will provide a better understanding of the infrastructure, thus allowing for a more informed decision-making process and cost-effective maintenance activities. The next highest-ranking measure is “Implementation of proper monitoring of routine maintenance service” and “Implementation of method/techniques to predict the maintenance of the infrastructure” both with a score of 4.5. This suggests that implementing proper monitoring and prediction techniques is seen as effective measures for reducing vulnerability and enhancing infrastructure performance. Incorporating monitoring and prediction techniques into the maintenance process will provide a better understanding of the infrastructure's current conditions and expected deterioration.

This will help to identify potential issues before they occur and to schedule maintenance activities more effectively. “Increasing and maintenance of infrastructure assets capacities” and “Performing retrofitting, repair activities in deteriorated infrastructure” both score 4.4, indicating that these measures are also seen as effective for reducing vulnerability and enhancing infrastructure performance. Increasing the capacity of the infrastructure and performing retrofitting and repair activities on deteriorated infrastructure will improve the overall performance and resilience of the infrastructure. It should be noted that the scores and rankings in the table are based on the criteria and weightings that have been assigned and may not necessarily reflect the actual effectiveness of the measures in reducing vulnerability and enhancing infrastructure performance. Other factors such as cost, institutional and technical capacity, public and political acceptance, and availability of resources should also be taken into consideration when evaluating the implementation of these measures. These factors play a critical role in determining the feasibility and implementation of adaptation measures.

## 6. Discussion

This study identified and discussed several CCA measures that are required to consider during the life cycle of the infrastructure components. Accordingly, five CCA measures were identified for the planning stage of the infrastructure. These measures include “Consideration of anticipated loads in the designing of infrastructure”, “Revision of the building codes, rules and regulations”, “Proper planning of evacuation routes”, “Asset management system incorporating disaster resilience to include additional requirements for post-disaster event rehabilitation and relevant requirement at the planning stage”, and “Integrating nature-based solutions”. Furthermore, seven and five adaptation measures were identified and discussed for the design and construction and maintenance and retro-

**Table 11**  
 Prioritizing CCA measures in the Design and construction stage.

Code	Criteria CCA measures	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
Electricity sector											
D.C.1	Proper material design to accommodate prolonged climatic conditions	5	4	5	5	5	5	5	5	4.92	4
D.C.2	Proper storm water management techniques/Drainage system designs	5	5	5	5	4	5	5	5	4.75	6
D.C.3	Considering safe engineering designs	5	5	5	5	5	5	5	5	5.00	1
D.C.4	Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)	5	5	5	4	5	5	5	4	4.78	5
D.C.5	Infrastructure design to accommodate future modifications considering future climate change impacts	5	5	5	5	5	5	5	4	4.91	3
D.C.6	Raising elevation of infrastructure	5	5	5	5	5	5	5	5	5.00	1
D.C.7	Alternative infrastructure designs (e.g., Floating infrastructures)	4	5	3	5	4	4	4	3	4.02	7
Transportation sector											
D.C.1	Proper material design to accommodate prolonged climatic conditions	5	5	5	5	5	5	5	5	5.00	1
D.C.2	Proper storm water management techniques/Drainage system designs	5	3	4	5	4	5	4	5	4.43	6
D.C.3	Considering safe engineering designs	5	5	5	5	5	5	5	5	5.00	1
D.C.4	Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)	5	5	5	4	5	5	5	4	4.78	5
D.C.5	Infrastructure design to accommodate future modifications considering future climate change impacts	5	5	5	5	5	5	5	4	4.91	4
D.C.6	Raising elevation of infrastructure	5	5	5	5	5	5	5	5	5.00	1
D.C.7	Alternative infrastructure designs (e.g., Floating infrastructures)	4	5	3	5	4	4	4	3	4.02	7
Water sector											
D.C.1	Proper material design to accommodate prolonged climatic conditions	5	4	5	5	5	5	5	5	4.92	3

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Table 11 (continued)

Code	Criteria CCA measures	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
D.C.2	Proper storm water management techniques/Drainage system designs	4	4	4	5	4	5	5	5	4.33	5
D.C.3	Considering safe engineering designs	5	5	5	5	5	5	5	5	5.00	1
D.C.4	Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)	5	4	3	4	5	4	4	4	4.40	4
D.C.5	Infrastructure design to accommodate future modifications considering future climate change impacts	5	5	5	5	5	5	5	4	4.94	2
D.C.6	Raising elevation of infrastructure	5	4	3	4	4	3	3	3	3.95	7
D.C.7	Alternative infrastructure designs (e.g., Floating infrastructures)	4	5	3	5	4	4	4	3	4.06	6

fitting stages, respectively. "Proper material design", "Storm water Management systems", "Safe engineering design", "Implementing protective measures for infrastructure such as flood barriers", "Infrastructure design accommodating future modifications", "Raising elevation of infrastructure" and "Alternative infrastructure design" are some CCA measures discussed under the design and construction stage of the infrastructure. Furthermore, implementation of "Proper monitoring and maintenance prediction methods", "Maintenance of drainage systems", "Performing retrofitting activities", and "Asset management during maintenance and retrofitting stage" are some identified and discussed CCA measures under the maintenance and retrofitting stage.

The interview conducted in this study aimed to identify and validate the most suitable criteria for evaluating CCA measures for CI sectors. The effectiveness and feasibility criteria were weighted 55% and 45%, respectively. The sub-criteria for effectiveness included vulnerability reduction (45%), enhancement of infrastructure performance (15%), speed of implementation (17%), and exposure reduction (23%). The cost criterion under the feasibility criteria was given the highest weight of 55%. Institutional and technical capacity, public/political acceptance, and availability of resources were given lower weights of 10%, 14%, and 21%, respectively. The data analysis indicates that vulnerability reduction and exposure reduction are the most important factors for the given context, while enhancement of infrastructure performance and speed of implementation are of lesser importance.

The present study attempts to prioritize the identified CCA measures considering the eight criteria retrieved from the literature. From Tables 10–12, it appears that the scores for the different measures in each sector are relatively similar, with most measures scoring above 4 out of 5 in each sector. This could be due to a few different factors:

- **Similar vulnerabilities:** The infrastructure in each sector may face similar vulnerabilities and challenges when it comes to building resilience, such as extreme weather events, aging infrastructure, and limited resources. As a result, the measures that are most effective in addressing these vulnerabilities may be similar across sectors, leading to similar scores.
- **Subjectivity:** The scores may be influenced by the subjective opinions of the assessors, who may have had similar perspectives and biases when assessing the measures. As a result, the scores may not accurately reflect the effectiveness of the measures in enhancing infrastructure resilience.

It's important to note that the similarity of scores across sectors doesn't necessarily mean that the measures are equally effective in all sectors or that they address all vulnerabilities equally well. Rather, it suggests that the measures identified in the table are generally effective in enhancing infrastructure resilience across sectors, and that policymakers and planners should consider implementing them in their respective sectors, while also tailoring them to the specific needs and vulnerabilities of each sector.

Table 13 highlights the top-ranked adaptation measures for three stages of infrastructure development: planning, design and construction, and maintenance and retrofitting. These adaptation measures are ranked based on their perceived importance and effectiveness in addressing the impacts of climate change on different sectors. In the planning stage, the top-ranked adaptation measure is an asset management system incorporating disaster resilience to include additional requirements for post-disaster event rehabilitation and relevant resource requirements. This adaptation measure is crucial because having a robust asset management system in place can help to ensure that infrastructure is designed and built with the ability to withstand and recover from climate-related hazards. By incorporating disaster resilience into asset management, planners can identify the necessary resources and budget re-

**Table 12**  
 Prioritizing CCA measures under maintenance and retrofitting stage.

Code	Criteria CCA measure	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
Electricity sector											
M.R.1	Implementation of method/techniques to predict the maintenance of the infrastructure	5	4	3	4	5	4	4	5	4.46	3
M.R.2	Increasing and maintenance of infrastructure assets capacities	4	5	5	5	4	5	5	4	4.45	4
M.R.3	Implementation of proper monitoring of routine maintenance service	5	4	3	4	5	4	5	4	4.47	2
M.R.4	Performing retrofitting, repair activities in deteriorated infrastructure	4	5	4	5	4	5	5	4	4.35	5
M.R.5	Asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events	5	5	5	5	5	5	4	5	4.93	1
Transportation sector											
M.R.1	Implementation of method/techniques to predict the maintenance of the infrastructure	5	4	3	4	5	4	4	5	4.46	3
M.R.2	Increasing and maintenance of infrastructure assets capacities	4	5	5	5	4	5	5	4	4.45	4
M.R.3	Implementation of proper monitoring of routine maintenance service	5	4	3	4	5	4	5	4	4.47	2
M.R.4	Performing retrofitting, repair activities in deteriorated infrastructure	4	5	4	5	4	5	5	4	4.35	5
M.R.5	Asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events	5	5	5	5	5	5	4	5	4.93	1
Water sector											
M.R.1	Implementation of method/techniques to predict the maintenance of the infrastructure	5	4	3	4	5	4	4	5	4.46	3
M.R.2	Increasing and maintenance of infrastructure assets capacities	4	5	5	5	4	5	5	4	4.45	4

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Table 12 (continued)

Code	Criteria CCA measure	Vulnerability reduction	Enhancement of infrastructure performance	Speed of implementation	Exposure reduction	Cost	Institutional and technical capacity	Public and political acceptance	Availability of resources	Score	Rank
		45%	15%	17%	23%	55%	10%	14%	21%		
M.R.3	Implementation of proper monitoring of routine maintenance service	5	4	3	4	5	4	5	4	4.47	2
M.R.4	Performing retrofitting, repair activities in deteriorated infrastructure	4	5	4	5	4	5	5	4	4.35	5
M.R.5	Asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events	5	5	5	5	5	5	4	5	4.93	1

Table 13

Top ranked CCA measures for each sector.

Stage	Rank	Electricity sector	Transportation sector	Water sector
Planning stage	1	Asset management system incorporating disaster resilience to include additional requirements for post disaster event rehabilitation and relevant resource requirement at planning stage	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	Proper planning of evacuation routes
	2	Proper planning of evacuation routes	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	Proper planning of evacuation routes
	3	Consideration of operational loads due to the climatic condition in the planning stage of infrastructure	Proper planning of evacuation routes	Integrating nature-based solutions when infrastructure planning
Design and Construction stage	1	Considering safe engineering designs and Raising elevation of infrastructure	Raising elevation of infrastructure, Proper material design to accommodate prolonged climatic conditions and considering safe engineering designs	Considering safe engineering designs
	2	Proper material design to accommodate prolonged climatic conditions	Infrastructure design to accommodate future modifications considering future climate change impacts	Infrastructure design to accommodate future modifications considering future climate change impacts
	3	Infrastructure design to accommodate future modifications considering future climate change impacts	Using protective measures in infrastructure (e.g., Flood protection barriers, cut off walls)	Proper material design to accommodate prolonged climatic conditions
Maintenance and retrofitting	1	Asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events		
	2	Implementation of proper monitoring of routine maintenance service		
	3	Implementation of method/techniques to predict the maintenance of the infrastructure		

quirements for post-disaster event rehabilitation, ensuring that infrastructure is quickly restored after a catastrophic event. In the design and construction stage, the top-ranked adaptation measure is the consideration of safe engineering designs and raising the elevation of infrastructure. This adaptation measure is essential because safe engineering designs can help to ensure that infrastructure can withstand extreme weather events, while raising the elevation of infrastructure can reduce the risk of flooding in low-lying areas. Proper material design to accommodate prolonged climatic conditions is also important because it can increase the durability and resilience of the infrastructure.

In the maintenance and retrofitting stage, the top-ranked adaptation measure is asset management during maintenance, prioritizing infrastructure for restoring after catastrophic events. This adaptation measure is important because maintaining the infrastructure and prioritizing its restoration after catastrophic events can help to ensure its long-term resilience and minimize damage and downtime. Proper monitoring of routine maintenance service and implementation of methods/techniques to predict maintenance needs can also help to identify and address issues before they become major problems, reducing the risk of infrastructure failure due to climate-related hazards. Overall, the top-ranked adaptation measures for each stage of infrastructure development are critical in addressing the impacts of climate change on different sectors. By incorporating disaster resilience into asset management, considering safe engineering designs and raising the elevation of infrastructure during the design and construction stage, and prioritizing infrastructure restoration after catastrophic events during maintenance and retrofitting, planners can help to ensure that infrastructure is resilient to the effects of climate change. These adaptation measures are essential to reduce the risk of infrastructure failure, minimize damage and downtime, and ensure that infrastructure is quickly restored after a catastrophic event, ultimately contributing to the sustainability and resilience of our communities.

The study provides tailored recommendations for water, electricity, and transportation infrastructure sectors, emphasizing the importance of proactive adaptation and ongoing monitoring and evaluation of adaptation strategies. The key recommendations from this study include as follows.

- **Prioritize Disaster-Resilient Asset Management System:** This recommendation underscores the importance of implementing a robust asset management system that integrates disaster resilience considerations. This system should encompass requirements for post-disaster event rehabilitation and relevant resource allocation. By doing so, infrastructure stakeholders ensure swift recovery and restoration following climate-related events. The rationale behind this recommendation lies in the fact that prioritizing disaster-resilient asset management facilitates efficient recovery, minimizing disruptions and enhancing the overall resilience of infrastructure systems.
- **Integrate Climate Considerations in Planning:** The second recommendation highlights the necessity of incorporating climate change considerations during the planning stage of infrastructure development. This involves revising building codes and regulations and strategically planning evacuation routes to withstand anticipated climate impacts. The rationale behind this recommendation is rooted in the idea that integrating climate considerations early in the planning process leads to infrastructure that is better equipped to handle extreme weather events, consequently reducing vulnerability.
- **Implement Safe Engineering Designs:** The third recommendation emphasizes the adoption of safe engineering designs that account for climate resilience. This involves prioritizing designs that can accommodate prolonged climatic conditions.
- **Promote Nature-Based Solutions:** The fourth recommendation advocates for integrating nature-based solutions into infrastructure planning, particularly within the transportation and water sectors. Utilizing natural elements to enhance infrastructure resilience against climate impacts can provide sustainable and effective strategies for CCA. This approach aligns with the rationale that nature-based solutions, such as vegetation and natural buffers, can mitigate flooding and erosion, reducing the negative impacts of climate-related events.
- **Enhance Monitoring and Predictive Maintenance:** The fifth recommendation underscores the importance of implementing monitoring systems for routine maintenance and adopting predictive techniques to identify infrastructure maintenance needs. This proactive approach aids in addressing issues before they escalate, contributing to infrastructure longevity and resilience. Regular monitoring and predictive maintenance are thus crucial to minimizing the risk of failures due to climate-related stressors.
- **Tailor Measures to Sector-Specific Needs:** The sixth recommendation recognizes the similarities across sectors while emphasizing the need to tailor CCA measures to the specific vulnerabilities and challenges of each sector. While sectors may share vulnerabilities, unique challenges exist within each sector. Customizing CCA measures ensures that they effectively address the distinct risks faced by each sector, maximizing their impact.

By integrating these recommendations into infrastructure development and policy-making processes, stakeholders can enhance the resilience of CI across sectors in the face of climate change impacts. These recommendations collectively contribute to a comprehensive and strategic approach to CCA, resulting in more robust and sustainable infrastructure systems. However, this study has some limitations as follows:

- The CCA measures were identified and validated for three CI sectors, but these measures could also be applicable for other CI sectors. Further investigations are required for validity and applicability for the other sectors.
- Due to time limitations and expert availability, the number of experts was limited to 42 in this study.
- This study chose Sri Lanka as a case point for conducting the research work and data collection. However, the prioritization could be changed based on the geographic location and climatic conditions.

## 7. Conclusion

The present study focuses on identifying and prioritizing CCA measures for CI sectors, namely water, electricity, and transportation. The study employs the Analytic Hierarchy Process (AHP) to prioritize the identified CCA measures in different stages of the infrastructure life cycle. Data collection for the study was carried out in two stages. First, an open-ended interview was conducted with 42 industry experts from the selected infrastructure sectors to identify the CCA measures and validate the evaluation criteria. During the second stage, data was collected through an online questionnaire to conduct the AHP analysis and to check the applicability of the identified CCA measures. Accordingly, five CCA measures were identified for the planning stage, seven for the design and construction stage, and five for the maintenance and retrofitting stage. Vulnerability reduction and exposure reduction were identified as the most important criteria for effectiveness, while cost was the most critical criterion for feasibility.

This study offers several benefits for understanding the effects of climate change on CI and identifying effective mitigation measures. It includes the identification of specific CCA measures for CIs, which are prioritized based on effectiveness and feasibility criteria, and tailored to meet the needs of specific infrastructure sectors. Also, it validates criteria for evaluating CCA measures and employs a systematic approach to prioritize the measures using the AHP process.

In conclusion, the impacts of climate change on CIs, such as the electricity, transportation, and water sectors, are a significant concern that necessitates the prioritization of adaptation measures. These systems are fundamental to the functioning of modern society, and their disruption can have far-reaching consequences. Therefore, it is imperative that climate change considerations are integrated into the planning, design, management, and operation of such infrastructure. This can include the incorporation of resilient technologies and materials, as well as the implementation of climate-sensitive design and planning practices. Moreover, it is important to acknowledge that adaptation to climate change is an ongoing process that requires continuous monitoring, evaluation and updating of

strategies. By proactively addressing the impacts of climate change on CIs, we can ensure that these systems are resilient and capable of meeting the needs of society both in the present and in the future.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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