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Developing an innovative framework for enhancing the resilience of critical infrastructure to climate change

Louisa Marie Shakou[a,*], Jean-Luc Wybo[b], Genserik Reniers[c,d], Georgios Boustras[e]

[a] Faculty of Business and Economics, University of Antwerp, Antwerp, Belgium
[b] Centre of Risk and Decision Sciences, European University Cyprus, 6 Diogenes Street, Egkomi, 2404 Nicosia, Cyprus
[c] Delft University of Technology, TPM Faculty, Safety & Security Science Group, Jaffalaan 5, 2628 BX Delft, the Netherlands
[d] Engineering Management (ENM), Faculty of Business and Economics, University of Antwerp, Antwerp, Belgium
[e] Centre of Risk and Decision Sciences, European University Cyprus, 6 Diogenes Street, Egkomi, 2404 Nicosia, Cyprus

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ABSTRACT

Adaptation of our built environment and our Critical Infrastructures will be required to enhance their resilience to climate change. Resilience, as currently promoted for CIs, focuses primarily on minimisation of disruption from extreme weather events and rapid recovery to pre-disruption service levels. Anticipation, absorption through robustness and redundancy, adaptation and recovery are the key attributes in such approaches. Climate change, however, is a unique challenge in that it is characterised by various timescales (short, medium and long), predictable and unpredictable events and slow-onset and rapid-onset events. Severe climate change will also result in a climate regime that is significantly different to our current regime. This requires transformation of our CIs to ones that are flexible, modular and diverse. We propose a framework for enhancing CI resilience to climate change which will move from incremental change to transformation of our CIs. Our framework proposes three timescales (short, medium and long term) and the properties needed at each timescale to achieve the transformation required.

1. Introduction

The first two decades of the twenty-first century have experienced several high profile and high impact weather events such as Hurricane Sandy (2012), heavy flooding in Thailand (2011), Hurricane Harvey (2017), wildfires in Portugal, Spain and California (2017), etc. Such events often have far reaching impacts on societal functioning, including disruption or even destruction of Critical Infrastructures (CIs), such as energy, transport, ICT and water networks resulting in both direct and indirect economic, social and environmental losses (Lauge et al., 2015).

The incidence of such weather related disasters or extreme weather events (EWEs) has exhibited an increase in frequency, intensity and impact over the past decade, with various impacts to CIs documented, for example, for energy, transport, water and wastewater, and ICT etc. (EU-Circle, 2016; Mikellidou et al., 2017). With anthropogenic climate change implicated in the changing frequency and intensity of EWEs (Herring et al., 2018; IPCC, 2014; Mann et al., 2016; Mann et al., 2017; van Oldenborgh et al., 2017; Uhe et al., 2016), any approach by CI operators to manage the risks and impacts of EWEs must also take into consideration the effects of a changing climate.

Whilst CI operators are increasingly expected to manage their exposure to climate related risks, action to date has been incremental. Factors thought to contribute to this are largely related to the nature of climate change which is characterised by uncertainty in relation to the magnitude, geographical distribution, and the timing the impacts (IPCC, 2012) with climate change likely to occur over long timescales that do not necessarily align with short-term business and political timescales. Nevertheless with reports from the Emergency Events Database (EM-DAT) and reinsurers MunichRe demonstrating that the number of weather-related events has exhibited an upward trajectory, the resilience of CIs to natural disasters has become a key policy goal of many Governments and international organisations (US DHS, 2013), (UK Cabinet Office, 2014), (UNISDR, 2015a).

Resilience has a long history of application (see Alexander, 2013 for a good overview), however its current use was widely popularised by Holling (1973) in his seminal paper on ecological dynamics. Several definitions of resilience have since been formulated, by various disciplines, an overview of which is presented in Table 1.

As can be seen resilience is a concept that has been co-opted by

* Corresponding author.
E-mail address: louisa.shakou@student.uantwerpen.be (L.M. Shakou).

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Table 1
Definitions of Resilience across scientific fields.

Definition of Resilience	
Ecological Resilience Capacity to persist in the face of change. Capacity to withstand shock and maintain function.	Holling (1973), Folke (2006)
Socioecological Resilience Amount of disturbance a system can absorb and remain within the same state, the capacity for self-organisation and the capacity to build learning and adaptation.	Carpenter et al. (2001), Folke (2006)
System Engineering Resilience Resilience is the ability of a system to keep or recover to a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous stresses. It is the ability to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks.	Hollnagel et al. (2006), Haimes et al. (2008)
Disaster Resilience The ability of social units (e.g., organisations, communities) to mitigate hazards, contain the effects of disasters when they occur and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters.	Bruneau et al. (2003)
Urban Resilience Urban resilience refers to the ability of an urban system and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales, to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.	Meerow et al. (2016)
Organisational/ Enterprise Resilience Enterprise resilience is the ability and capacity to withstand systemic discontinuities and adapt to new risk environments. A resilient organisation effectively aligns its strategy, operations, management systems and decision-support capabilities so that it can uncover and adjust to continually changing risks, endure disruptions to its primary earnings drivers and create advantages over less adaptive competitors.	Starr et al. (2003)
Community Resilience The ability of a community to prepare for anticipated hazards, adapt to changing conditions and withstand and recover rapidly from disruptions.	NIST Vol 1 (2015)
Infrastructure Resilience Infrastructure resilience is the ability to reduce the magnitude and/or duration of disruption. Resilience is the ability to absorb, adapt to and/or rapidly recover from a potentially disruptive event.	NIAC (2009)

various disciplines (as well as governments and other bodies), which have developed their own definitions. These definitions have some common and unifying features (e.g. absorption of a disturbance, adaptation), but also conflicting and contradictory features (e.g. persistence vs transformation) (Alexander, 2013) illustrating the difficulty of putting into practice the term resilience (Francis and Bekera, 2014). With the increasing calls for improving the resilience of CIs to climate hazards (Forzieri et al., 2016) this paper will try to unify these differences in a multi-dimensional framework.

This paper briefly considers how the climate is changing in the near and long term and the impacts that climate change will have on CIs. It discusses two approaches used for managing impacts, mainly risk assessment and resilience, with a particular focus on the concept of resilience in its different forms (disaster, systems engineering, socio-ecological and ecological resilience). The paper takes the features identified in the different approaches to resilience in order to define a conceptual multi-dimensional framework that aims to enhance the climate resilience of CIs under various time-scales (short, medium, and long term) and bridge the different features of resilience (Fig. 1). The paper addresses the following research questions:

- What challenges does climate change present to Critical Infrastructure operations?
- Why move from risk management to managing resilience?
- What are the features of resilience theory across the various disciplines?
- How can these features be unified under one framework and enhance the resilience of critical infrastructures towards climate change?

2. Methods

To address the research questions a review of the relevant literature has been conducted. The databases consulted were Scopus, Science Direct and Google Scholar and sources include (1) academic publications with a focus on the journals Safety Science, Risk Analysis, Reliability Engineering and System Safety, Global Environmental Change, Resilience; and (2) key documents from organisations involved in climate change resilience and transitions, including vision documents, position papers and other reports, all published within 1990 to 2017. The review does not aim to be a comprehensive assessment of all the literature related to climate change, risk management and resilience, but focuses on the aims of the paper which is the development of a framework for enhancing the resilience of CI to climate change in order to better manage the potential risks and impacts.

The context for developing the framework is the changing climate, and so a review of current impacts and future projected impacts was conducted. Sources include reports by the Intergovernmental Panel on Climate Change (IPCC), which synthesise all the latest climate science, as well as scientific articles related to climate change attribution, and institutional reports and databases by MunichRe and EM-DAT related to extreme weather events. Keywords used include attribution of climate change, extreme weather events and climate change, and extreme weather attribution. The impacts of climate change to CI were addressed in a previous report (EU-Circle, 2016), which is briefly summarised. Section 3 outlines the results of this review and provides an overview of impacts posed by climate change generally and to CI operations more specifically.

Risk assessment is widely used to manage risks, however the uncertainty related in both projecting the potential impacts of climate change as well as the ability to characterise the risks and manage them presents challenges. The literature relating to uncertainty in climate change risks and how risk assessment and management treats uncertainty was reviewed using the keywords uncertainty and risk assessment in critical infrastructure, types of uncertainty in risk management, climate change uncertainty and risk, and is presented in Section 4. Resilience has been promoted as an approach to managing uncertainty in risks and impacts across many fields and so a review of how resilience is conceptualised across the different sets of literature in the disaster, systems engineering, socio-ecological and ecological disciplines was conducted (these disciplines were chosen as they are considered relevant to both climate change and CIs). This review

Table 2
Observed climate change.

Variable	Observed Changes (since 1950)	Attribution of Observed Changes to Climate Change
Temperature	↑ Increase in the number of warm days and warm nights	Very likely[a]
	↓ Decrease in the number of cold days and cold nights	Very likely
	↑ Increase in the frequency and intensity of daily temperature extremes	Very likely
	↑ Increase in the frequency of heatwaves in Europe, Asia and Australia Heat extremes warmer than a century ago	Likely
Precipitation	↑ Increase in frequency and intensity in most land areas	Likely
Droughts	*Global* trends in drought are uncertain and depend on the definition of drought	Due to insufficient data, global trends related to drought cannot be attributed with confidence to climate change
	↑ Regions such as the Mediterranean and West Africa have experienced an increase in frequency and intensity	Likely
	↓ Regions such as central North America and north-west Australia have seen a decrease in frequency and intensity	Likely
Floods	Uncertainty in the sign of trend in the magnitude and/or frequency of floods	Lack of evidence
Extreme Sea Levels	↑ Increase mainly as result of mean sea level rise	Likely
Tropical Cyclones	↑ Increase in extreme precipitation associated with hurricanes and tropical cyclones	Likely
	↑ Small increase in higher storm surges from cyclones due to sea level rise	

Sources: IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012) and Van Oldenbourgh, 2018.
[a] Virtually certain for 99–100%, very likely for 90–100%, likely for 66–100%, more likely than not for 50–100%, about as likely as not for 33–66%, unlikely for 0–33%, very unlikely for 0–10% and exceptionally unlikely for 0–1%.

identified a set of key resilience attributes that can improve climate resilience of CIs which are discussed in Section 5 and which inform the development of our theoretical framework which is presented and discussed in Sections 6 and 7 respectively. Finally, emerging questions for future study of CI resilience to climate change are identified.

3. Climate change and critical infrastructure

EM-DAT data indicates that in the period between 1995 and 2015, the majority of natural disasters recorded were weather related events (90 per cent), with a total of 6,457 weather-related disasters reported in the same period (Wahlstrom and Guha-Sapir, 2015). MunichRe has recorded 710 relevant loss events through its NatCatSERVICE in 2017 alone, above the average for the last ten years, making 2017 the second costliest year ever for natural disasters (93% of them being weather-related disasters) (MunichRe, 2018). These observed changes in EWEs are increasingly attributed to warming of the climate system due to anthropogenic emissions of greenhouse gases (GHGs) (Mann et al., 2016; Mann et al., 2017; van Oldenborgh et al., 2017; Uhe et al., 2016). This section briefly examines both the observed and predicted impacts of climate change as reported in the literature, with an overview of potential impacts to CIs. The aim of this section is to contextualise the need for enhancing the resilience of CIs to climate change.

3.1. Observed climate change and extremes

Current observations of the climate system show that global mean surface temperatures have risen by 0.85 °C, sea surface temperatures of oceans have increased, sea levels have risen by 19 cm and the amounts of snow and ice have shrunk since pre-industrial times (IPCC, 2014). These anthropogenic changes to the climate system have been linked to observed changes in extreme events, including an increase in the number of hot days and nights, an increase in the frequency and intensity of daily temperature extremes, an increase in the frequency of heat waves and an increase in the frequency and intensity of heavy precipitation events (Table 2) (Groisman et al., 2005; Donat et al., 2013; Westra et al., 2013; IPCC, 2014). For some extreme events the link to a warming climate is direct. An increase in warming results in an increase in the likelihood of extremely hot days and nights whilst higher temperatures from warming increase the amount of water vapour held in the atmosphere (following the Clausius-Clapeyron relation), increasing the frequency of heavy precipitation events (Min et al., 2011; Zhang et al., 2013; Fischer and Knutti, 2015; Stott et al., 2016; Diffenbaugh et al., 2017; Van Oldenborgh 2017). The effect of a warming climate on *current* trends of other EWEs such as cyclones/hurricanes, droughts and wildfires, is uncertain, requiring further evidence and improvements in attribution science (National Academies of Sciences, Engineering, and Medicine, 2016). Nevertheless, EWEs are at present occurring in (and are influenced by) a climate system that is warming, making understanding of projected climate change over the upcoming decades important for effective management of the impacts of EWEs on our societies. Near-term and long-term projections of climate change by scientists can aid in this direction and are a vital source in long-term management of climate change impacts.

3.2. Near-term and long-term projections of climate change

Climate change projections reported by the IPCC, in its Fifth Assessment Report (AR5), indicate that warming of the climate system will continue throughout the 21st century.

The IPCC's near-term projections (2016-2035) indicate that global mean temperatures will continue to increase, with a concurrent increase in the number of warm days and warm nights and a decrease in the number of cold days and cold nights. Near-term projections further indicate an increase in precipitation in high and mid-latitudes and a decrease in precipitation in sub-tropical and arid regions, confirming the trend of wet-getting-wetter and dry-getting-drier (Kirtman et al., 2013). The frequency and intensity of heatwaves and extreme precipitation events are likely to increase, however the projections for other extremes such as droughts and extreme sea levels are less certain, see Table 3.

Long-term projections[1] (2081–2100) by the IPCC indicate that temperatures will continue to rise, with the degree of warming determined by the emissions scenario (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5), with higher GHG concentrations resulting in a higher degree of warming. An in-depth discussion of the different scenarios and their projections is provided by (Moss et al., 2010; IPCC, 2014; van Vuuren et al., 2011). In this section the long-term projections discussed refer to

[1] In this paper we focus on near-term and long-term projections of climate change, which were the focus of the IPCC's AR5.

Table 3
Near-Term and Long-Term Projections of Climate Change.

Variables	Near Term Projections[a] (2016–2035)	Likelihood[b]	Long-Term Projections[a,c] (2081–2100)	Likelihood[b]
Temperature	↑ Increase (0.3–0.7 °C)	Likely	↑ Increase (1.1–2.6 °C)	Likely
Temperature Extremes	↑ Increase in the frequency of warm days and warm nights ↓ Decrease in the frequency of cold days and cold nights	Likely Likely	↑ Increase in the frequency of warm days and warm nights ↓Decrease in the frequency of cold days and cold nights	Virtually certain Virtually certain
Precipitation	↑ Increase in high & mid-latitudes ↓ Decrease in subtropics	Very likely About as likely as not	↑ Increase in high & mid-latitudes ↓ Decrease in subtropical arid and semi-arid areas	Likely Likely
Heavy precipitation events	↑ Increase in frequency and intensity	Likely	↑ Increase in frequency and intensity	Very likely
Heatwaves	↑ Increase in frequency and intensity	Very likely	↑ Increase in frequency and intensity	Very likely
Winds	*Uncertainty* in trends due to insufficient evidence	Insufficient evidence		
Monsoons	*Uncertainty* in trends due to insufficient evidence	Insufficient evidence	↑ Increase in area and intensity ↑ Increase in length of monsoon season ↑ Increase in precipitation extremes related to the monsoon in certain regions	Likely Likely Very likely
ENSO	There is low confidence in changes in the intensity and spatial pattern.	Insufficient evidence	There is low confidence in changes in the intensity and spatial pattern.	Insufficient evidence
Tropical Cyclones	Direction of trend *uncertain*, will vary year on year	Very likely	↑ Increase in average maximum wind speed	Likely
Droughts	Large *uncertainties* in direction of trend	N/A	↑ Increase in drying in certain regions e.g. Mediterranean, Southern Africa increasing risk of drought	Likely
Floods	Uncertainty in trends due to insufficient evidence	Insufficient evidence	↑ Increase in intense precipitation leading to more floods	Likely
Extreme Sea Levels	Unavailable for 2016–2035 ↑ Increase of mean global sea level of 0.26 m (0.19–0.33 m) for 2046–2065	Likely	↑ Increase of mean global sea level of 0.47 m (0.32–0.63 m) ↑ Significant increase in the occurrence of future sea level extremes in some regions by 2100	Likely Very likely
Waves			↑ Increase in the height of waves in the Southern Ocean	Likely

Sources: Collins et al. (2013) and Kirtman et al. (2013).
[a] Projections are relative to the reference baseline period 1986–2005.
[b] Virtually certain for 99–100%, very likely for 90–100%, likely for 66–100%, more likely than not for 50–100%, about as likely as not for 33–66%, unlikely for 0–33%, very unlikely for 0–10% and exceptionally unlikely for 0–1%.
[c] Projections are stated for the scenario RCP 4.5, for information on the projections of the remaining RCPs seeCollins et al. (2013).

projections under the RCP4.5 scenario[2], which is an intermediate emissions pathway[3]. RCP 4.5 is the scenario that is most aligned with the current emission reductions set out by the parties to the UN Framework Convention on Climate Change (UNFCCC) in their Intended Nationally Determined Contributions (Fawcett et al., 2015; EC-JRC, 2015; IEA, 2015). Under the RCP4.5 scenario, global mean surface temperatures are likely to exceed 1.5 °C. The number of hot days and hot nights is virtually certain to increase, extreme precipitation will become more frequent and intense and monsoon precipitation will become more intense. Heatwaves will very likely increase in intensity and frequency, droughts are likely to increase in some regions and sea level extremes will become significant as sea levels rise by 0.47 m by 2100 (see Table 3). It is evident that as warming of the climate increases, the effects on extreme events become more likely.

Beyond the effects of climate change on EWEs, a warming climate may also result in a crossing of critical thresholds of the climate system leading to a drastically different climate regime to the one to which modern societies are accustomed and, importantly, are built for. An example of such a climate threshold would be a significant weakening or even collapse of the Atlantic meridional overturning circulation (AMOC), an important component of the global climate system. Recent studies (Ceaser et al., 2018; Thornalley et al., 2018) indicate that the AMOC has weakened as a result of climate change and is the weakest it has been in the last 1600 years. Impacts of a significant weakening or collapse of the AMOC include widespread cooling throughout the North Atlantic and northern hemisphere in general, an increase in severe winters in Western Europe, an increase in summer heatwaves in Europe and increased storminess in Europe due to a strengthening of the North Atlantic storm track (Jackson et al., 2015).

The trends highlighted in Table 3 will result in significant risks which societies will have to plan for and adapt to, including (IPCC, 2014):

- Risk to health and livelihoods arising from EWEs.
- *Risk of a breakdown of CIs and their ability to provide critical services due to EWEs* (emphasis author's own).
- Risk of loss of ecosystems, biodiversity and ecosystem goods and services.
- Risks related to the migration of animal and vegetal species (mosquitos and other pests, invasive and allergenic plants, etc.).
- Risk of food and water insecurity, particularly for poorer populations.
- Social risks related to the migration of populations threatened by the effects of climate change on agriculture, water resources and employment.

3.3. Impacts of extreme weather and climate change on critical infrastructures

The potential risks faced by CIs due to climate change have been documented (Mikellidou et al., 2017; EU-Circle, 2016) and include a wide range of impacts, from direct damage to infrastructure physical assets to indirect impacts related to supply chains and raw materials as shown in Table 4.

The projected increase in EWEs is expected to result in more frequent breaching of CI design thresholds, which are based on the climate conditions and frequency of EWEs of the past which however, under climate change, are no longer good predictors of the future (Ben-Haim, 2012; ASCE, 2015). Any increase in the frequency of EWEs may also result in tighter operating margins between 'normal operation' and disruptive events, reducing CI efficiency (Vallejo and Mullan, 2017) as well as lifetime, as CIs have shorter recovery periods between disruptive EWEs.

The risks of climate change must therefore be taken into account, both by CI operators and governments, and managed appropriately to ensure the continued smooth functioning of societies. Whilst risk assessment/management are routinely undertaken by CI operators, climate change risk presents challenges due to the uncertainty related to its extent and magnitude (which will differ across regions) as indicated in the Likelihood columns of Table 3.

4. Challenges to risk management in critical infrastructures from climate change

Risk is a central consideration of Critical Infrastructure (CI) operators, in which hazards/threats to CI assets and networks and their potential consequences, are identified and managed across the design, development, operation and maintenance phases using risk assessment and management (Aven and Zio, 2011). Through risk assessment, CI operators and authorities responsible for CIs consider they are adequately able to answer the questions of (1) What can go wrong? (2) What is the likelihood? (3) What are the direct and indirect consequences? (Haimes et al., 2008).

4.1. Risk assessment

There are many risk assessment methods available for Critical Infrastructure, and whilst it is not the aim of this paper to go in-depth into the risk assessment methods available, a short overview is presented. Readers interested in an extensive overview of such methods are referred to Marhavilas et al. (2011). Risk assessment techniques in CIs can be divided into three main categories (1) qualitative, (2) quantitative, and (3) hybrid (Reniers et al., 2005; Marhavilas et al., 2011). Qualitative techniques include, amongst others, checklists, Hazop, What-if-analysis, safety audits and the Sequentially Timed Event Plotting (STEP) technique. Techniques such as quantitative risk analysis (QRA) and Probabilistic Risk Assessment fall within the quantitative category, whilst failure modes and effects analysis (FMEA), fault-tree analysis and event-tree analysis are examples of hybrid techniques (Reniers et al., 2005; Marhavilas et al., 2011).

Consequence assessment techniques are part of the toolkit of the deterministic risk-based approach, in which the potential consequences of a specific hazard scenario/event are identified and an optimal solution is developed (Decker, 2018). For example, CI operators use deterministic risk assessment to quantify the loss in functionality of their system due to the occurrence of a hazard, and manage the risk by hardening the vulnerable system components so that they withstand the identified hazard and prevent system failure (Linkov et al., 2014).

Probabilistic Risk Assessment (PRA) approaches, on the other hand, analyse *all* feasible scenarios and their consequences, with the probability of occurrence of each scenario and its consequences described as a probability distribution over their severity (Kaplan and Garrick, 1981; Rasmussen 1981; Aven and Zio, 2011; Francis and Bekera, 2014), resulting in the risk equation[4]:

[2] RCP 4.5 scenario stabilises radiative forcing of the climate system to 3.8 Wm^{-2} by 2100 and is associated with relatively ambitious GHG emissions reductions whereby CO_2 emissions slightly increase before declining after 2040, a transition to renewable energy, stable methane emissions and strict climate policies (Thomson et al., 2011).

[3] RCP 2.6 is the most ambitious emissions scenario which limits warming to 2°C, the goal of the Paris Climate Agreement (2016). For the purposes of the discussion, however it is not used, as the long-term emissions trajectory most closely aligned to the "Intended Nationally Determined Contributions" submitted by the UNFCCC parties result in a global average temperature increase of 2.7 °C which is more consistent with RCP 4.5.

[4] The authors note that there are several interpretations and conceptualisations of risk. It is not the aim of this paper to discuss these differences for a discussion see Giannopoulos et al. (2012), Aven (2012), Francis and Bekera (2014) etc.

Table 4
An illustration of selected impacts to CI assets due to climate change.

Climate Change Projection	Type of Critical Infrastructure	Impact
Increase in Temperature and Extreme Temperatures	Energy-Electricity	Reduction in the electricity capacity of transmission lines/grids
	Water Supply	The impact of rising ambient air temperatures and changes in annual and seasonal precipitation will have impacts for raw water quality and resource availability and reliability
	Transport-Roads & Rail	Increased temperatures can result in damage to roads and rail tracks through buckling and deformation
	ICT	Increased risk of overheating in data centres, exchanges, base stations affecting service availability
Increase in extreme precipitation events	Energy-Electricity	Heavy rains and flooding can lead to erosion, weakening transmission tower structures
	Water-stormwater network	Extreme rainfall may exceed the capacity of the stormwater network, causing flooding or even destroying parts of the network
	Transport-Roads & Rail	Heavy rains can trigger landslides in affected areas, damaging and closing off roads and railways
	ICT	Reduction in the quality of the wireless service with higher rainfall rates affecting service availability
Extreme sea level rise	Energy-Electricity	Increased sea levels and storm surges could damage coastal electricity infrastructure e.g. transmission towers, substations
	Water-stormwater network	Sea level rise may affect the operation of water intakes and stormwater outlets to the sea, and will need to be redesigned to avoid backflows and sea water entering the water network system
	Transport-Roads & Rail	Inundation of coastal road and rail infrastructure, e.g. coastal roadways, rail tracks and railway stations
	ICT	Increased flooding and salt water corrosion of infrastructure in low-lying/coastal areas
Increase in intensity of extra tropical cyclones	Energy-Electricity	Hurricanes and high wind speeds can damage overhead transmission and distribution lines and can damage or break down cooling towers in power plants
	Water-stormwater network	Extreme winds may damage tall structures such as water towers
	Transport-Roads & Rail	Cable bridges, signs, overhead cables, railroad signals, tall structures at risk
	ICT	Damage to above-ground assets such as masts, antenna and overhead lines

Sources: Mikellidou et al. (2017), EU-CIRCLE (2016) and EU-CIRCLE Wiki (2018).

$$\text{Risk of a scenario}_i = \text{probability of occurrence of scenario}_i \times \text{consequences of scenario}_i$$

Or

Risk triplet = $\langle s_i, p_i, x_i \rangle$ where s_i is scenario identification or description, p_i is the probability of that scenario occurring, and x_i is the consequence of that scenario, i.e., the measure of damage (which can be also characterised by a probability distribution over its severity) (Kaplan and Garrick, 1981; Francis and Bekera, 2014). Probability of occurrence is also a component of CI technical design standards which take into account the probability of occurrence of hazards, e.g. natural hazards such as floods and storms, and set climatic thresholds for the design of a CI. Technical design standards also take into account the probability distribution curve of the severity of the consequence of a natural hazard occurring, for example flood damage functions. CI operators use such technical standards in the design (and renovation/ maintenance) phase of their infrastructure as a means of managing the risks of climate hazards to their assets and networks.

In assessing risks, CI operators thus often draw on failure probabilities and hindsight in which systems withstand disruptions faced in the past (Woods and Hollnagel, 2006; Madni, 2009); or assign subjective probabilities to future outcomes through expert elicitation, extrapolation of past knowledge, modelling of processes or a combination of all three (Hallegatte, 2012).

4.2. Types and sources of uncertainty

An emphasis on understanding probabilities based on historical data and modelling of a system, however, is inadequate for predicting the future under climate change, as climate change probabilities are difficult to characterise and in some cases unknowable, as will be discussed (Park et al., 2012). Table 5 gives an overview of the several dimensions of uncertainty introduced by both climate change and the networked nature of CIs (Walker et al., 2003; Rowe, 1994) that make assessment of climatic risks to CIs challenging (Park et al., 2012).

It is unsurprising, then, that climate change is described as a ‘fantastic example of deep uncertainty’ arising as a result of (Hallegatte et al., 2012; Decker 2018): the possibility of a very large number of future states, with multiple divergent views on the possibility and timing of the emergence of those states; an inability to confidently assign probabilities to the likelihood of the various potential future states in the climate; and the use of many valid models to generate these potential future states.

As both the climate system and CI systems are complex, non-linear systems, our knowledge of them and ability to predict their future evolution in response to perturbations may never be complete (Berkes, 2007). Decision-making by CI operators under climate change must thus take place in the context of deep uncertainty (Fiksel, 2006; Decker, 2018), requiring a different approach to conventional risk management, one which can respond and adapt to new and unexpected conditions (Handmer and Dovers, 1996; Decker, 2018). This is particularly pertinent for CIs, which are built with long life-times (50–100 years), using climatic design thresholds based on the assumption of stationary return levels, i.e. no change to the frequency of extreme climate events over time (Auld and MacIver, 2005) but which may face a different climate with different return periods in the next 50–100 years to the one they were originally built for (Hallegatte, 2014).

An alternative approach to managing risks in uncertain conditions is resilience, with resilience approaches increasingly promoted as a response to risks that are defined by deep uncertainty, both in the field of engineering and of climate change.

5. Resilience of critical infrastructure

Whilst risk assessment begins on the basis that hazards can be identified or estimated, i.e. predicted and prevented (Park et al., 2011; Tyler and Moench, 2012), resilience advocates preparing for the unexpected and potentially unknowable (Longstaff et al., 2010; Steen and Aven, 2011). It has been advanced as a suitable framework for managing and responding to risks that are systemic and have a high degree of uncertainty. Resilience has now become a key element of several national policies related to CI protection, for example the US (DHS, 2013), Australia, (Australian Government, 2010), UK (Cabinet Office, 2011) (for an overview of resilience policies across countries, see Setola et al., 2016) and of organisations such as the European Union (Pursiainen and Gattinesi, 2014) and the United Nations (UN Resolution 2341, 2017). Resilience of CIs specifically to climate change is an explicit goal of

Table 5
Types of Uncertainty.

Type of uncertainty	Meaning
Epistemic uncertainty	a lack of knowledge and information on a system/phenomenon or on the distribution of a parameter (Aven & Zio, 2011; Paté-Cornell, 2012). The climate system's complexity means that we do not currently know how it will respond to external forcings such as greenhouse gases, an example of epistemic uncertainty. As a result, there is uncertainty in the direction and magnitude of climate change and its geographical distribution.
Aleatory uncertainty	randomness due to inherent variability of a system (Aven & Zio, 2011; Paté-Cornell, 2012). Aleatory uncertainty arises due to the nature of the climate system itself, which is chaotic and non-linear, with a great deal of internal variability limiting prediction abilities (Kirtman et al., 2013). Such uncertainty also arises in CIs due to their complexity and interdependency, resulting in coupled, non-linear emergent behaviour which cannot be fully understood and planned for (Dalziell and McManus, 2004).
Model-related uncertainty	uncertainty associated with the behaviour of a system being modelled (e.g. climate system) and the interrelationships between its variables and inputs (Walker et al., 2003). Projections of future climate change are achieved using climate models which simulate the response of the Earth to external forcings (e.g. GHGs). These models are built on the basis of the physical rules of the climate system and empirical observations (Neelin, 2010). They are characterised by uncertainty as some climate processes cannot be represented adequately (e.g. cloud processes), either due to an incomplete scientific understanding of the process or due to a lack of computing power.
Model input related uncertainty	uncertainty in the input data that is used to drive a model. Climate models are validated using observational data of the past climate, in which the results of model simulations of the past climate are compared with the observational record. For some components of the climate, for example the atmosphere, there is a long observational record. However, for ocean processes there are far fewer observations, introducing a source of past temporal uncertainty (Rowe, 1994) in model simulations. Downscaling global climate models to regional models also introduces input related uncertainty, as not all regions have high-resolution climate projections or long observational data sets for validating the models. A lack of availability of long-term observational records related to EWEs also produces challenges for attribution of any given EWE to climate change.
Scenario-related uncertainty	Climate models use future scenarios which determine the future amount and emissions of greenhouse gases and other external forcings in the atmosphere, in order to make climate change projections. Such scenarios are linked to prediction of socioeconomic development, i.e. prediction of societal behaviour, demographic changes, policy developments, technological advances, economic growth, etc. (Hallegatte et al., 2012; Collins et al., 2013). Projections in the IPCC's AR5 use the four RCPs. There are several limitations associated with RCPs which introduce uncertainty, a discussion of which can be found in van Vuuren et al. (2013).
Translational uncertainty	uncertainty in how different stakeholders with different backgrounds, training, capabilities, values and perspectives understand and interpret the types of uncertainties above. As Rowe (1994) describes it, translational uncertainty is 'uncertainty in explaining uncertain results.'

many policy initiatives such as Urban adaptation to climate change in Europe 2016 (European Environment Agency, 2016); the European Investment Bank's Climate Change Strategy (2015); Habitat III - New Urban Agenda (UN Habitat, 2016) and the Sendai Framework for Disaster Risk Reduction 2015–2030, which promotes the resilience of new and existing critical infrastructure to disasters. Also, the UN's Agenda 2030 (United Nations General Assembly, 2015) and its Sustainable Development Goals (2015) aim to increase urban resilience to climate change and natural disasters (Goal 11b) and strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries (Goal 13). In some cases, resilience to climate change has been introduced in the regulatory regimes of CIs, for example in England and Wales, the Water Act 2014 places on the economic regulator of the water industry, Ofwat, a resilience duty, as a direct response to concerns about climate change and population growth (Defra, 2016).

5.1. Resilience approaches to critical infrastructure

An influential contribution to CI resilience originates from Bruneau et al. (2003) who define resilience of CIs as the ability of a CI system to reduce the probability of a disruptive event or shock, to absorb a disruption or shock if it occurs and to recover quickly after the disruptive event or shock. These three abilities (reduction, absorption and recovery) are made more concrete by considering a CI resilient if it is able to reduce the probability of failure, reduce the consequences of a failure (absorption) and reduce the time of restoration to 'normal' levels of performance (recovery). Properties or elements that promote resilience are advanced by the R4 framework of resilience and include (Bruneau et al., 2003; Tierney and Bruneau 2007):

- **Robustness**: the strength or the ability of CI elements or systems to withstand a given level of stress or demand without suffering degradation or loss of function. It is measured by the degree to which CI system functionality is impaired following an event such as an EWE (McDaniels et al., 2008).
- **Redundancy:** the existence of CI elements or systems that are substitutable, i.e. capable of assuming functions in the event of disruption, degradation or loss of functionality.
- **Resourcefulness**: the capacity of CI operators to identify problems, establish priorities and mobilise resources (monetary, technological, human, etc.) following an event that threatens to disrupt some CI element or system.
- **Rapidity**: the capacity to restore functionality in a timely manner in order to contain losses and avoid disruptions.

Madni and Jackson (2009) expand on this definition of resilience as the ability of a complex system to avoid (anticipation), absorb (withstand), adapt to (reconfigure) and recover (restoration) from a disruptive event. This is very similar to the definition of CI resilience adopted by the US National Infrastructure Advisory Council (NIAC), which considers a resilient CI system as one with the ability to anticipate, absorb, adapt to and/or rapidly recover from a potentially disruptive event (2010). Carlson et al. (2012) expand on these definitions to propose that CI resilience be considered as the ability to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance.

Systems and safety engineering introduce the concept of 'acceptable degradation' or 'safe-fail', whereby resilience of a CI is defined as the ability of a system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risks (Haimes et al., 2008; Haimes, 2009; Rogers et al., 2012). Similarly, Hollnagel et al. (2006) define resilience as 'the ability of an organisation (system) to keep or recover quickly to a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses.'

Resilience of CIs in the systems engineering, disaster and CI protection realms, is thus strongly linked to the continuity of normal system function (Francis and Bekera 2014) and the ability to 'bounce back' (Matzenberger et al., 2015). The main resilience abilities identified in our review are presented in Table 6 and are correlated with (i) the four phases of emergency management and (ii) the properties that grant these abilities, following the approach by Carlson et al. (2012). The extent to which these abilities are adequate for conferring resilience to climate change will be discussed in the next Section.

Table 6
Key features of CI resilience.

Phase of Emergency Management	Ability/Capacity		Properties
Preparedness	Reduction	Bruneau et al. (2003)	Anticipation is the ability to look or predict ahead and be prepared. Measures include threat and risk assessment, vulnerability assessment, interdependency identification, emergency plans, maintenance, etc. (McDaniels et al., 2008; Pursiainen and Gattinesi, 2014).
	Anticipation	Madni and Jackson (2009), NIAC (2009), Carlson et al. (2012)	
Mitigation	Absorption	Bruneau et al. (2003), Madni and Jackson (2009), Haimes et al. (2008), NIAC (2009), Vugrin et al. (2011), Carlson et al. (2012), Rogers et al. (2012), Francis and Bekera (2014)	Absorption or resistance is the ability to withstand a disruptive event, so as to preserve system function and service provision. The degree by which the consequences of a disruptive event can be minimised with minimum effort (Vugrin et al., 2011). This ability is attained through robustness and redundancy. Robustness measures may include levees that prevent coastal flooding or storm surges and other hardening measures, such as reinforcing flood walls and pumping systems (Haimes et al., 2008). Redundancy measures include back-up installations or spare capacity and may include, for example, alternative routes in CIs such as transportation or back up of power supplies in ICT systems.
	Resistance	Carlson et al. (2012)	
Response	Adaptation	Madni and Jackson (2009), NIAC (2009), Vugrin et al. (2011), Carlson et al. (2012), Francis and Bekera (2014)	In the case of service disruption, adaptation and response is the ability to rapidly recover system functionality and provision of service. This requires sensemaking (Weick, 1995), resourcefulness and the ability to self-organise and re-allocate resources. Substitutability (redundancy) and resourcefulness are properties which enhance adaptive/responsive capacity.
	Response	Carlson et al. (2017)	
Recovery	Recovery	Bruneau et al. (2003), Haimes et al. (2008), Madni and Jackson (2009), NIAC (2009), Carlson et al. (2012), Rogers et al. (2012), Francis and Bekera (2014)	The ability of a system to be repaired, restoring system functionality. It is the time needed for recovery to 'normal operating' conditions. It is related to the ability to access the required resources to carry out repairs, for example, recovery crew, access to materials, equipment, and supplies needed, etc. (Freckleton et al., 2012).
	Restoration	Vugrin et al. (2011)	

5.2. Suitability of approaches to CI resilience under climate change

Whilst resilience is promoted as an approach that enhances the ability of CIs to respond and positively manage a variety of risks, including risks that are unknowable, the review of resilience approaches and measures currently applied to CIs (Table 6) suggests that such approaches and measures do not go far enough for climate change. Climate change is a unique risk, in that it is characterised by rapid-onset *and* slow-onset events as well as predictable *and* unpredictable events as described in Table 7.

Resilience measures and approaches proposed for CIs focus on rapid-onset events such as EWEs and predictable events focusing on the ability of a CI to withstand or absorb the shock from such a rapid-onset event, degrade or safe fail once such a rapid-onset event has occurred and recover and restore functionality or services within acceptable time and cost (Bruneau et al., 2003; Haimes et al., 2008; Francis and Bekera, 2014). This is exemplified by metrics put forward for measuring resilience of CIs, e.g. availability of back-up duplicate systems, availability of operational power supply, restoration of 95% of pre-event level within one day (Bruneau et al., 2003), time to restore functionality, e.g. from 10% to 90% of full capability (Haimes et al., 2008), and degree to which pre-disruption state is restored (Madni and Jackson, 2009); etc.

We consider that current practices in resilience underestimate the scale of the challenge faced in enhancing the resilience of complex urban systems such as CIs (Fiksel, 2006) often proposing incremental changes. Such incremental changes or change at the margins are a Type 2 resilience as proposed by Dovers and Handmer (1992). According to their typology of resilience there are three types of resilience: Type 1, Type 2 and Type 3 resilience shown in Table 8.

The very nature of CIs (large, complex, long-lasting, built structures) is used to argue that they do not and cannot adapt, with weight given to

Table 8
Types of resilience.

Types of Resilience	Characteristics
Type 1	emphasises anticipatory capacity resources are allocated to maintain the status quo and resist change through identification of hazards/ risks and protection often inflexible slow to respond and adjust to sudden changes maintains existing structures uncontroversial and easily adopted
Type 2	incremental changes or change at the margins does not deviate too far from the status quo fits with existing institutional structures, described as pragmatic and realistic characterised by short-termism postponement of the necessary radical changes to a future in which options may have significantly narrowed
Type 3	open adaptable high degree of flexibility adopts long time-scales in planning and management adapts rapidly to changing circumstances and risks

Table 7
Types of events brought about by climate change.

Type of Event	Example
Rapid-onset	EWEs such as floods and storms. These are discrete events that take place over a short time period of hours or days.
Slow-onset	sea level rise, increasing temperatures and biodiversity loss are examples of slow-onset events which evolve gradually over many years (UNFCCC,2012).
Predictable	an increase in temperatures in response to an increase in GHG emissions is a predictable outcome based on the natural greenhouse effect.
Unpredictable	crossing of critical thresholds or tipping-points in the climate system, which may result in an abrupt transition in our climate, are hard to predict and some types of transitions may even be unpredictable (Ditlevsen and Johnsen, 2010).

recovery and ensuring the continued availability of critical services to communities (Manyena, 2006). This emphasis on recovery or a return to a 'normal' or pre-event state, is suboptimal or undesirable in the case of climate change, for which far-reaching transitions have been called for in order to mitigate the impacts of climate change (IPCC, 2018). Far-reaching transitions are necessary for CIs as well, due to the high levels of GHGs emitted in their building and operation. As the degree of climate change that will be experienced in the future (and thus the intensity and frequency of EWEs and the likelihood of crossing climate thresholds) is directly linked to GHG emissions, approaches to enhancing resilience of CI to climate change must take both *mitigation* and *adaptation* of climate change into consideration or risk proposing measures that are unsuitable to the challenge. They should also make a distinction between immediate or short-term action or 'recovery' to rapid-onset events and long-term action or adaptation to slow-onset events and a new climate regime (Madni and Jackson, 2009).

Approaches as discussed in Table 6 may even be used to further entrench the current way of building and operating CIs (Manyena et al., 2011), when in the face of climate change radical transformation and innovative redesign is required to achieve both mitigation and adaptation (Park et al., 2012). We suggest that climate change requires a Type 3 approach, i.e. an approach which focuses on transformation and innovation.

5.3. Re-organisation, transformation and innovation as measures that enhance CI resilience to climate change

A review of alternative approaches to resilience offered by the ecological and socio-ecological fields offers options for augmenting current CI approaches to resilience from a Type 2 to a Type 3, which better meet the challenge of climate change.

Resilience in socio-ecological systems (SES) proposes that alongside absorption and recovery of a system, the capability to reorganise and transform should also be considered as one of several possible measures for achieving resilience (Folke et al., 2002). In a SES, resilience means reacting to changes and disturbances as opportunities to innovate and develop new ways of doing things (Folke, 2006). Berkes (2007) describes resilience as focusing on renewal and re-organisation processes rather than on stable states (i.e. status quo). Properties include flexibility, modularity, diversity, openness to learning, innovation and transformation (Folke et al., 2002; Fiksel, 2003; Cumming et al., 2005). Table 9 offers an overview of what these properties could mean for CI systems.

SES resilience offers a move away from current engineering approaches to CI resilience, which focus on maintaining CI systems and on incremental change, to providing an alternative regime in which CI services are provided in diverse ways (Rogers et al., 2012). It broadens the concept of resilience beyond the idea of absorption, conservation and recovery of CI systems to incorporating the ideas of novelty, innovation and transformability (Folke et al., 2010)

The socio-ecological approach to resilience further focuses strongly on coupled human-environment systems, eschewing the artificial divide between them (Berkes, 2007). It recognises that socio-technical systems designed by humans, such as CIs, are interlinked with the environment and the services it provides (Adger, 2000; Folke et al., 2010). For example, a water network and its infrastructure are strongly dependent and reliant on the presence of sources of potable water. SES resilience advocates for the incorporation and understanding of ecosystems and ecosystem services (Folke et al., 2002). It also emphasises monitoring of slowly-changing variables (slow-onset events) as a key to understanding interactions with the environment, which is particularly fitting in the case of climate change.

We consider that SES resilience with its emphasis on re-organisation, new equilibria, interactions with the environment and transformation (Fiksel, 2006), offers an approach that is better suited to meet the challenges posed by climate change. It promotes design of flexible CI systems that can continue to function under changing and unpredictable climatic conditions that have the potential for large-scale disturbances from an increasing intensity and frequency in EWEs (Dalziell and McManus, 2004).

6. Development of an innovative framework for climate resilient CIs

Combining the properties discussed in the preceding sections, we propose that a climate resilient CI is one which considers short, medium and long timescales and has the ability to:

1. Anticipate, absorb, adapt and recover from acute rapid-onset events such as EWEs in the short-term;
2. Invest in innovation with the aim of developing alternative solutions to the provision of CI services which are characterised by flexibility, diversity and modularity in the medium to long term;
3. Transform to both mitigate GHG emissions and to ensure continuity of service under a climate regime that is variable and unpredictable in the long-term;
4. Integrate ecosystems and ecosystem services and nature-based infrastructures.

Achieving this type of resilience requires a framework which promotes long-term thinking, consideration of climate impacts and ecosystem services, innovation, flexibility and transformation (Fig. 1).

In the short-term, resilience as conceptualised by the approaches discussed in Section 5.1 are suitable. The impacts of EWEs are being felt

Table 9
Features of SES resilience that can augment CI resilience approaches to better meet the challenge of climate change.

Ability	Property
Flexible	The presence of multiple pathways for service delivery. This suggests a move from centralised and command and control (Folke, 2006) CI systems to more decentralised and loosely coupled systems. Similar to diversity.
Modular	The presence of interacting components of similar parts that can replace one another if one fails (Tyler and Moench 2012). The presence of components that can be easily transposed and adapted in response to change.
Diverse	The ability of a CI system to perform under a wide range of situations through spatial and functional diversity. A resilient CI system has its key assets physically distributed so that they are not all affected simultaneously by the same event (physical diversity) and has numerous ways of providing its critical services (functional diversity) (Tyler and Moench 2012).
Open to learning	Openness to learning includes the ability to (1) identify and monitor trends to anticipate future events, thresholds and slowly changing variables, followed by integration and reflection on the new knowledge, (2) explore uncertainties, surprises through scenario planning and being open to unexpected connections and challenges to existing worldviews, (3) to 'learn as you go' or 'learn by doing' through an iterative process of action-reflection (Tschakert & Dietrich, 2010; Ahern, 2013) and the ability to treat interventions as experiments (Lebel et al., 2006)
Innovate	The ability to generate creative and novel ideas or solutions (Ness, 2012) with the purpose of problem solving in response to climate change.
Transform	The ability to effect structural change (Feola, 2015) in order to change a system into a different type of system (Folke et al., 2010). It represents a paradigm shift and aims to offer an alternative to existing processes and systems. The ability to transform promotes a shift in focus from CI *systems* to CI *services* and consideration of alternative ways through which to provide CI services that are more compatible with managing the realities of climate change.

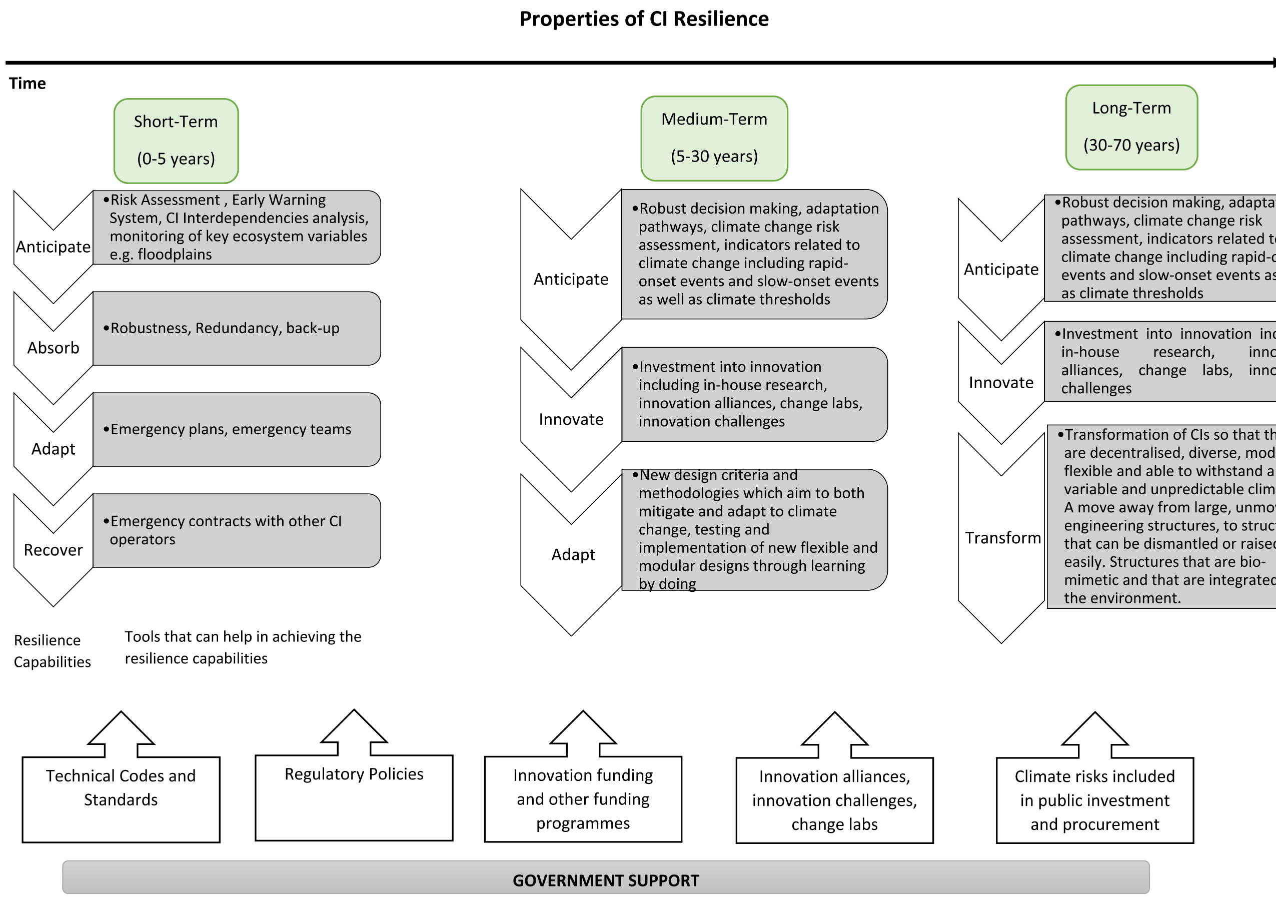

Fig. 1. Framework for climate resilient CIs.

across the world, with significant impacts to CI reported. Tools and approaches such as risk assessment, early warning systems, back-up and redundancy, emergency plans etc. are currently needed to manage acute threats and events. In the medium and long term, more innovative approaches are called for, with a change in the technical codes for CIs, new design criteria and methodologies for new types of CI that are diverse, modular, flexible and that will be able to be modified as climate change conditions change. An emphasis and investment in innovation for transformation of our CIs is needed. We briefly discuss some of the key features in the medium to long term resilient development of CIs such as flexibility, modularity, diversity, innovation and transformation.

7. Discussion

7.1. CIs that are flexible, modular and diverse

We propose that climate resilient CIs are flexible, diverse and modular. For example, an approach in achieving this is to design CI systems for present climatic conditions, while building in flexibility to add additional capacity as required. Infrastructure could be built with a shorter design life and then retrofitted or replaced as climatic conditions change (Arisz and Burrell 2006). Principles of eco-mimesis, or industrial ecology, can aid in the modularity and flexibility properties of climate resilient designs. Eco-mimesis and industrial ecology principles of design encompass the use of green materials and assemblies of materials and components that allow for ease of dismantling, reuse, recycling and re-integration into the environment, resembling the cyclical flows of ecosystems (Fiksel, 2003; Yeang, 2010).

The growing field of 3D concrete printing is an example of a potentially disruptive innovative technology that can help in the design of modular CIs, in which components of a structure are printed out in a precast factory and then assembled (Salet et al., 2018). Applications of 3D concrete printing to date include design and manufacture of bridges, offices and homes (Salet et al., 2018; 3ders, 2016, 2018). The aim of such approaches is to avoid the current structural rigidity of CI systems, which do not impart the flexibility required to be responsive as the climate changes. Further research in industrial ecology should investigate how 3D printing could be applied to CIs such as large power plants, large road networks and water networks, as a solution for increasing their modularity and flexibility.

A move from centralised systems to an increase in decentralised systems, is another example of adding diversity and modularity to CI systems. Decentralisation or modularisation[5] spreads the risk; a modular CI system is less vulnerable to failure and thus more resilient, whilst a diversity of responses increases the options available for responding to shocks and disturbances (Berkes, 2007; Ahern, 2011). Inclusion of nature-based infrastructure options, for example permeable pavements and bioswales in urban storm water management which can enhance the ability of a conventional system to cope with different disturbances, is an example of a diversity of options (Arisz and Burrell 2006; Yeang, 2010; Ahern, 2013) which simultaneously achieves integration with the environment. A decentralised electricity network at the local and community scale is another example of a modular and diverse electricity system (Thornbush et al., 2013). The concept of virtual power plants (Pudjianto, Ramsay and Strbac, 2007) which

[5] The hypothesis that modular systems are more resilient is based on the fact that each module has a great level of autonomy and doesn't depend on resources or information provided by other modules. If this is not achieved, the modular system is less resilient as it is at risk when links between modules are threatened, and this must be taken into account when designing modular CIs.

facilitates management of distributed renewable energy sources, integrating them into the grid, can promote decentralisation and is currently being tested in Australia, Germany, the UK, etc. (Klein, 2018)[6]. Implementation of virtual power plants using renewable energy sources, such as solar PV and thermal, wind, geothermal, would simultaneously add a diversity of low-carbon supply (fulfilling the transition of low carbon CIs) and fulfil the modular requirement of resilience.

7.2. CIs that are integrated into ecosystems

Climate resilient CIs are integrated with the environment through the use of green and blue infrastructure, known as nature-based infrastructure. Nature-based infrastructure includes windbreaks, floodplains, wetlands and vegetation that are crucial for ground stability and permeability (Wamsler et al., 2013).

Integration with such nature-based infrastructure means understanding ecosystems, their structure, species diversity, flows and other processes in a given location (Yeang, 2010). It also means rehabilitation of any degraded or destroyed ecosystems and natural habitat and understanding of the impacts of climate change, so that CIs are planned and designed to integrate with the local environment and also to be able to adapt and change as the climate changes. Integration with the environment also entails accepting natural hazards such as floods, and building CI systems that accommodate them, i.e. that live with the hazard. The concept of floodable lands is based on accommodating floods, in which some built areas are allowed to flood and CIs are built in such a way as to accommodate the floods, e.g. with structures built on poles or with modified foundations that can be elevated and are floatable/amphibious, or building structures that are removable and of a more temporary nature (Guikema, 2009; Liao, 2012).

7.3. Innovation and transformation of CIs

Making climate resilient CIs that are flexible, diverse, modular and that are integrated into the environment, requires innovation and a willingness to think outside the box in order to transform how CIs provide their services.

Radically innovative and transformative technologies or systems are often developed in niches that cannot easily break through the status quo due to an interacting web of elements such as regulations, existing infrastructure, business practices, and consumer/user practices that are oriented towards current CI systems (Geels, 2002). However, a change at the macro level in the landscape within which CIs operate, i.e. climate change, can create an opportunity for such innovations to break out of such niche positions (Geels, 2002). The role of Government is important as it can build a regulatory and policy setting that stimulates both public and private sector investment in innovation into novel and transformative solutions which enhance resilience of CIs to climate change. This is advocated by the World Bank (2013) which recommends sustained and flexible programmes with predictable, long-term financing of over a decade for building climate change resilience. Policymakers and CI operators can promote alternative design methodologies in which several innovative design proposals for CIs are structured as experiments, with the deep uncertainty related to climate change acknowledged and tested for in a process known as adaptive design (Ahern, 2013). CI operators can further enhance CI climate resilience by increasing in-house innovation and increasing levels of RD&D funding (World Economic Forum, 2018). As resilience is directly linked to competitiveness (Starr et al., 2003; Lee et al., 2013), promotion of the link between resilience and competitiveness can encourage support for investment in innovation and transformation by CI operators. Lee et al. (2013) suggest that being resilient makes good business sense, as it entails monitoring and understanding of an organisation's environment, identifying its vulnerabilities and adapting its product ahead of competitors in response to changes in the market (in our case a CI's environment). Resilience can be re-framed beyond the ability to adapt to disruptive and unexpected circumstances into the ability to continuously design and develop solutions to match or exceed the changes in the operational environment (Starr et al., 2003; Lee et al., 2013). Innovation and transformation of CI systems in response to changes in the climate should be framed as vital for ensuring continuity of operations into the future.

7.4. Barriers to innovation and transformation of CIs

Barriers to climate resilient CIs include the short-term business cycles of CI operations, the difficulty for CI operators to plan under conditions of uncertainty, perceived lock-in and path dependency, resistance to change, disregard of the importance of the environment and underinvestment in radical innovation.

The long timescales associated with climate change and the fact that historical return periods of EWEs are longer than most organisations' planning horizons, represent significant barriers to building resilience of CIs to climate change (Dalziell and McManus, 2004). The short-term planning horizons of most organisations (months and years), as opposed to long-term horizons (years and decades), make any additional costs that may be incurred in the short-term to ensure climate resilience in the long-term undesirable (Woods and Hollnagel, 2006). Often, achievement of short-term goals results in actions that endanger achievement of long-term goals (i.e. resilience to climate change), as short-term goals are valued more due to the immediacy of their results (Woods, 2006). The financial discounting of private investment is inadequate to address the needs for long-term innovation and transformation in CIs (Fiksel, 2006). Impacts of climate change on CIs, however, are likely to result in public costs (due to the interconnectedness of CIs in modern economies) that are much larger than private utility costs (Francis and Bekera, 2014).

The deep uncertainty associated with climate change, as discussed in Section 4.2, is an oft-cited reason for making incremental changes and applying Type 2 resilience approaches. This is analogous to Jackson's (2007) 'destructive paradigms' including the Predictability Paradigm, the belief that there is not enough statistical data, in this case related to climate change, to make the requisite changes and the Traditional Paradigm Change (TPC) Paradigm, the belief that paradigms cannot be changed, i.e. path dependency, CIs are designed and built in a certain way and must continue to be designed and built the same. According to the TPC Paradigm, critical services such as energy and water, etc., can only be provided within the current CI regime and there are no alternative regimes to service provision. However, particular engineered systems have been promoted due to the values and ideals of certain groups. Whilst such systems appear optimal from the narrow perspective of our existing timeframe, taking open-ended timeframes, as mandated by climate change, allow for the possibility of alternative options.

Whilst incremental or step-wise innovation is common, radical innovation as required by climate change is rare. Current technological regimes result in technological trajectories that guide innovation towards incremental activities as the community of engineers searches and innovates in the same direction (Geels, 2002). Moreover, because radical innovation challenges the status quo and existing business models, there is often strong resistance towards it (Ness, 2015). Radical innovation is high risk, with long lead times to maturity and with years of misses before yielding pay-offs, which has resulted in very low levels of in-house investment in research and innovation activities (Ness,

[6] Such test cases entail fitting homes with solar panels and energy storage batteries, with each home producing electricity and storing the excess in the batteries. Software oversees these virtual power plants and shares the energy produced in the most cost-efficient way between battery-fitted households and the main grid allowing for a diversity of power supply (Klein, 2018).

2010; World Economic Forum, 2018). Ness (2010) posits that a tolerance for greater risk and for a greater likelihood of failure should be cultivated to enhance transformation, and that research and development decisions should move from the basis of what is feasible to what is transformational. Differentiating between CI systems and CI services can allow innovative and transformative solutions to enter the mix.

7.5. Promoting climate resilient CIs

Governments, institutions, research organisations and CI operators each have a role in our climate resilience framework (Fig. 1).

Governments can promote climate resilient CIs through revising and updating technical codes and standards, so that they reflect the change in EWEs and integrate insights from climate projections and climate change risk assessments into infrastructure design codes (Vallejo and Mullan, 2017; Union of Concerned Scientists, 2017). Such design codes can be developed with a long-term view with the aim of promoting and enabling transformation of CIs (Anderies, 2014) so that they are able to cope within an environment characterised by deep uncertainty, high levels of variability and potential abrupt change. Governments can further set policies, including spatial planning policies, regulatory policies (for example economic regulators of utilities can set climate change resilience standards), carbon pricing policies, technology policies, etc. (Vallejo and Mullan, 2017; World Economic Forum, 2018) that can advance climate resilient CIs. Policies should also promote the use of indicators for monitoring ecosystem variables and promote ecosystem-friendly technology (Folke et al., 2002).

Governments can further set up public funding programmes, which direct funding towards research and development for innovative and transformative solutions, e.g. innovation funds (Westley et al., 2011; World Economic Forum, 2018) and can give tax incentives and subsidies (Westley et al., 2011) for CIs that are climate resilient. Public financial institutions can screen climate risks into investment decisions and public bodies can integrate resilience criteria in public procurement (Vallejo and Mullan, 2017; Union of Concerned Scientists, 2017).

CI operators can implement the practice of “adaptive management” which combines a management culture that places a premium on risk taking and experiential learning (Longstaff et al., 2010). This entails the design of actions as ‘experimental probes’ which promote ‘learning by doing’ and allow for adaptation if the results are not the ones expected (Ahern, 2011). Innovations can be piloted as safe to fail (Ahern, 2011). Complementary to this practice is the use of decision-making approaches under deep uncertainty, including robust decision-making (Lempert et al.,2013), adaptive policy-making (Walker et al., 2001;), adaptation pathways (Ranger et al., 2010) and dynamic adaptive policy pathways (Haasnoot et al., 2013). Such approaches identify solutions that will be robust under a large set of possible futures/outcomes (Decker, 2018) and have been implemented in planning for sea level rise in the Thames Estuary (Ranger et al., 2013) and the Rhine Delta in the Netherlands (Haasnoot et al., 2013).

CI operators can further facilitate the transition to climate resilience through the development and use of indicators that enable them to practice systems thinking; understand the complexity and interdependencies of global dynamics and recognise patterns of change (Lonsdale et al., 2015). Examples of such indicators may include indicators of gradual change both of the climate system and of ecosystems; indicators of key variables related to ecosystem and climate system thresholds (Folke et al., 2002) for the area in which CIs are situated; indicators for monitoring the interconnections between CI systems; indicators related to innovation, for example percentage of profits invested in innovation (e.g. of materials, systems i.e. from centralised to decentralised); percentage of CI system which has been upgraded and transformed to improved climatic design etc. Such indicators can ensure that any innovative or transformative interventions enhance climate resilience instead of eroding it (Lonsdale et al., 2015). Indicators can also be effective in building the investment case for resilience to climate change (Dalziell and McManus, 2004).

Governments, research organisations and CI operators can together work to promote climate resilience in CIs through change labs and design labs (Lonsdale et al., 2015); innovation challenges or competitions (Westley et al., 2011); and innovation alliances, coalitions of public and private sector research and technology entities, that promote increased collaboration with the aim of developing innovative technologies and solutions. Examples include Mission Innovation, Innovation Alliance, Hydrogen Coalition, etc. (World Economic Forum, 2018).

In summary, governments, institutions, research organisations and CI operators can together promote CIs that are resilient to climate change through:

- Updated design codes and other regulatory policies which consider climate change and the changing nature of EWEs;
- New indicators that take into account climate change, global environmental change, and transformation of CIs;
- New management and decision-making approaches such as adaptive management and robust decision making; and
- Collaboration in innovation and research into new modes of service delivery and infrastructure for CIs.

8. Conclusion

Approaches to enhancing the climate resilience of CIs must be augmented with capabilities that allow for innovation and transformation to CIs that are flexible, modular, diverse and better integrated with the environment. Such capabilities must be built over several timescales, in order to ensure that in the long-term CIs are flexible enough to perform under a climate that is variable and potentially different to our current climate. We propose a framework for enhancing the resilience of CIs to climate change, which is divided into short-term, medium-term and long-term timescales allowing for a planned transformation of CIs. This follows on from the idea that resilience cannot be a static feature of a CI, but rather an ongoing process or an emergent property (Wang and Blackmore, 2009). The framework promotes the exploration of options of providing CI services in different ways, which are compatible with climate change and can meet both climate change mitigation and adaptation imperatives. In this way transformation of CIs not only reacts to the impacts of climate change but also offers alternatives to the underlying drivers, i.e. emissions of GHGs (Pelling et al., 2015).

There is currently a golden opportunity for implementing these recommendations, as ageing CIs will be replaced and retrofitted, whilst an increasing trend in urbanisation and population growth will require new CIs to be built. Implementation of the framework will allow CIs to be built that are better aligned to a new climate regime. The challenge remains on how to build flexible, modular and diverse CIs (Anderies, 2014). This is the role of innovation, through which disruptive technologies and systems can be developed. A focus on and funding for transformative innovation is a necessity. It is far better to plan transformations to climate change and governments can play a role through technical codes and standards, regulatory policies, innovation funding and innovation alliances. Further research should be undertaken into: decentralised CI systems that can complement existing centralised CI systems making them more flexible; materials science, green architecture and civil engineering for the development of designs that allow building of modular CIs that can easily be dismantled or retrofitted as the climate changes; financial instruments and other funding schemes, that would incentivise transformative innovation in the design and building of critical infrastructures.

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Appendix A. Supplementary material

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