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WP 2: Taxonomy of architecture and infrastructure indicators

D2.4

Adaptation measures and corresponding indicators for resilient architecture and infrastructure

Reference code: RAMSES – D2.4

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Short Description:

This report contains a taxonomy of adaptation measures and corresponding indicators for resilient architecture and infrastructure that can be implemented by public authorities at the building, neighbourhood and catchment scales of the city. The taxonomy was developed in cooperation between RAMSES researchers and city representatives (Deliverable 2.4 of the RAMSES project).

Authors: James Kallaos, Fernanda Acre, Gabriele Lobaccaro, Naia Landa, Floriana Ferrara, and Annemie Wyckmans

Partner owning: NTNU

Contributions: T6-ECO

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Executive Summary

This report presents a taxonomy of indicators and measures for resilient architecture and infrastructure, which can be used by cities in their efforts to create more robust strategies in the face of climate change. The measures and indicators are divided into different classification systems based on an array of attributes, allowing for a more flexible and customisable approach to their organisation.

The analysis is based on eight RAMSES case study cities (Antwerp, Bilbao, Bogotá, Hyderabad, London, New York, Rio de Janeiro, and Skopje) and scientific literature.

1 Introduction

The core goal of RAMSES Work Package 2 (WP2) is to provide a taxonomy of resilient architecture and infrastructure indicators, to facilitate the evaluation and monitoring of measures being deployed in response to climate change. The first deliverable of WP2, D2.1: "Synthesis review on resilient architecture and infrastructure indicators" attempted to identify resilience frameworks and associated indicators in use today (Kallaos et al. 2014). The research involved in that deliverable showed that resilience assessment is in its infancy, but is progressing rapidly.

This deliverable is a complement to RAMSES deliverables D2.2: "Physical and cost typology for buildings and infrastructure/project database" (Acero et al. 2014) and D2.3: "Climate resilience in architecture and infrastructure. Analysis of RAMSES case study cities" (Kallaos et al. 2015).

This report presents a taxonomy of adaptation measures and corresponding indicators for resilient architecture and infrastructure that can be implemented by public authorities at the building, neighbourhood and catchment scales of the city. The taxonomy was developed in cooperation between RAMSES researchers and city representatives, and comprises Deliverable 2.4 of the RAMSES project. This report (D2.4) focuses on structural and physical adaptation options for blue, green, and grey infrastructures, to support cost and impact assessment in the RAMSES project. Social and institutional measures are extremely important but not currently addressed in D2.4; they will be addressed in other work packages within the RAMSES project, e.g. WP7 (governance) and WP8 (transition). At the end of the project duration this report will be updated to include all measures that have been defined and evaluated throughout the course of the project.

2 Adaptation measures and attributes

The adaptation and resilience taxonomy currently includes 30 adaptation measures, where each measure comprises a single page consisting of 11 rows containing the relevant attributes of the measure:

- **Measure**
- **Title**
- **Description**
- **Type of infrastructure**
- **Scale of implementation**
- **Main threat addressed**
- **Expected outcome**
- **Performance indicator**
- **Affected urban surface parameters**
- **Resilience dimensions**
- **Scientific references**

The following sections explain the contents and options of each attribute field.

2.1 Measure

The measure field is a unique three letter identifier code. The measures are presented alphabetically in all lists and classifications.

2.2 Title

The title is a succinct description of the adaptation measure for clarity when referencing. Some measures address more than one potential climate threat or infrastructure type, and have different attributes - they therefore include an identifying element.

2.3 Description

A more complete description of the adaptation measure than provided by the title.

2.4 Type of infrastructure

The type of infrastructure for which the intervention is intended is divided into two categories: Green/Blue and Grey.

Green & Blue infrastructure: Blue infrastructure refers to water and water features, including but not limited to ponds, lakes, rivers, and coastal environments; Blue infrastructure is often included within the term Green infrastructure, which refers to the network of natural, manufactured, or restored multi-functional green spaces supporting natural and ecological processes in and around urban areas (DCLG 2008).

Grey infrastructure: Corresponds to the physical interventions and construction measures that use engineered artefacts to provide services for the social and economic well-being of society – including buildings and structures, transportation networks (e.g. roads, tunnels), water and wastewater networks (e.g. drains, sewers, treatment plants), and plants and networks for energy supply and transmission (EEA 2012).

2.5 Scale of implementation

Three scales of implementation are considered with respect to the implementation of adaptation measures:

- building/site,
- neighbourhood/district
- city/region (catchment)

2.6 Main threat addressed

The main purpose of the adaptation measures is to address or limit the threats resulting from climate change induced hazards. RAMSES focuses on threats from:

- flooding (sea, tidal, fluvial and pluvial)
- storms
- heatwaves (including air pollution)
- drought

2.7 Expected outcome

The outcome field presents the expected adaptation outcome specific to each measure.

2.8 Performance indicator

A performance indicator provides a methodology for providing quantifiable evidence of the results of implementation of an adaptation measure. These indicators are specific to the adaptation measure, at the scale considered, and for the main threat addressed.

2.9 Affected urban surface parameters

Some of the adaptation measures may induce direct changes to the climate model input parameters identified and used by RAMSES partners (De Ridder et al. 2014). These urban surface model (UrbClim) input parameters are described below:

Symbol	Units	Name	Description
λ_p	$m^2\ m^{-2}$	plane area index	the ratio of the plane area occupied by buildings to the total ground area
λ_f	$m^2\ m^{-2}$	frontal area index	the ratio of the frontal area of buildings to the total ground area
λ_v	$m^2\ m^{-2}$	vegetation fraction	proportion of the surface covered by (green) vegetation

α	fraction (0-1)	albedo	broadband reflectivity for shortwave (SW) radiation (ratio of incident to reflected radiation)
ε	fraction (0-1)	emissivity	broadband emissivity for thermal longwave (LW) radiation (ratio of surface radiation to ideal black body radiation)
h	m	building height	average building height
vtyp	-	vegetation type	e.g. crop, grass, … (information used to determine roughness, length, stomatal resistance, etc.)

Table 1. UrbClim input parameters (terrain) required at the model grid resolution, which is typically 250 m (De Ridder et al. 2014, p. 14)*.*

2.10 Resilience dimensions

This attribute consists of a set of streamlined resilience dimensions that may be affected by the adaptation measure. These ten core resilience dimensions are drawn from the table of main dimensions of resilient systems identified in RAMSES Deliverable 2.1:

1. Adaptability, flexibility
2. Connectivity, feedbacks, safe failure
3. Dependence on local ecosystems
4. Diversity
5. Learning, memory,
6. Performance
7. Rapidity, responsiveness
8. Redundancy, modularity
9. Resourcefulness
10. Robustness

The ten categories include the main dimensions of resilient systems identified in the literature and by RAMSES workshop participants (the latter's additional contribution in italic) shown in Table 1.

Characteristic	Description
Adaptability, flexibility	Capacity or ability to: • change while maintaining *or improving* functionality • evolve • adopt alternative strategies *quickly* • respond to changing conditions *in time* • *design open and flexible structures (in general)*
Connectivity, feedbacks, safe-failure	Functional interdependence of system components and processes (Effect of change in one part of the system on other parts of the system). Capacity or ability to: • absorb shocks • absorb cumulative effects of slow-onset challenges • avoid catastrophic failure if thresholds are exceeded • fail progressively rather than suddenly

	• fail without cascading impacts (domino effect) • *analyse and implement across spatial scales (city to site)* • *analyse as human-technology coupled system* • *identify lock-in effects and potential conflicts with mitigation* • *identify synergies with other city policies, added value assessment* • *balance clear distribution of responsibility with concerted action*
Dependence on local ecosystems	Local control over services provided by local and surrounding ecosystems. Maintaining health and stability of green and blue infrastructure, providing: • flood control • temperature regulation • pollutant filtration • local food production etc. • *bioclimatic design and management (adjusted to local conditions)*
Diversity	Spatial diversity - Key assets and functions physically distributed to not all be affected by a given event at any time • Functional diversity - Multiple ways of meeting a given need • *balance diversity with potential cascading effects*
Learning, memory, *foresight*	Individual and institutional. Capacity or ability to: • learn from past experiences and failures • use information and experience to create novel adaptations • avoid repeating past mistakes • accumulate, store, and share experience • *build on long-term cultural value and history of the city* • *integrate resilience in long-term development scenarios*
Performance	How well does the system perform in its role? • Functional capacity • System quality • *in an appropriate and efficient way* • *self-sustaining, reducing external dependencies* • *compared to others – "I want a bigger dike than my neighbours"*
Rapidity, responsiveness	Following a disruptive event, the capacity or ability to: • contain losses, including mortality and illness • reorganise • maintain and re-establish function • reinstate structure • restore basic order • avoid future disruption
Redundancy, modularity	The capacity or ability to: • substitute systems, or elements of systems • buffer from external shocks or demand changes • replace components with modular parts • *balance redundancy with potential cascading effects*
Resourcefulness	The capacity, ability, *resources and infrastructures* to:

	• identify (and anticipate) problems • establish priorities • mobilise resources • visualise, plan, collaborate and act • *re-evaluate* • *integrate resilience in governance and working processes* • *involve and co-create with citizens (e.g., crowd-sourcing and funding)*
Robustness	The capacity or ability to: • withstand a given level of stress or demand • without degradation or loss of function • *capacities that ensure sufficient margins*
Co-benefits	• Added value assessment of resilience • No/low regret measures

Table 2: Core dimensions of resilient systems, from RAMSES workshop participants and (Adger et al., 2005; Briguglio et al., 2008; Bruneau et al., 2003; Chang and Shinozuka, 2004; Chuvarayan et al., 2006; da Silva et al. 2012; Davis, 2005; Fiksel, 2003; Galderisi et al., 2010; Godschalk, 2003; ICSU, 2002; Longstaff et al. 2010a, 2010b; Maguire and Hagan, 2007; McDaniels et al., 2008; Reghezza-Zitt et al., 2012; Schultz et al., 2012; Tierney and Bruneau, 2007; Tyler and Moench, 2012; Van Der Veen and Logtmeijer, 2005; UN-ESCAP, 2008; Wilson, 2012).

2.11 Scientific references

Literature references for each adaptation measure are embedded within the one-page outline in order to facilitate transparency and maintain integrity.

3 Classification approaches and clusters

During the development of the taxonomy, many of the researchers found a division based on type of infrastructure (blue-green or grey) helpful as a starting point. We recognize, however, that stakeholders from different fields will inherently approach the set of measures through their own paradigm, and may prefer an arrangement that aligns better with their existing methods. Alternate taxonomies include classification based on other attributes:

1. Type of infrastructure
2. Scale of implementation
3. Main threat addressed

In addition to classifying the measures based on attributes, another approach is to group the measures based on a common methodology. These "action clusters" are collections of measures that work together.

Identified action clusters include:

1. Mixed-use spaces
2. Reduced energy consumption
3. Resilient infrastructure networks
4. Flood adaptation
5. Urban Heat Island (UHI) reduction

These groupings and classifications comprise different taxonomical interpretations or arrangements of the same set of measures. They are presented in order to provide options for comprehension, and not intended or expected to be thorough/complete.

3.1 Multipurpose spaces

We define versatile, multipurpose spaces as areas, spaces, structures, or facilities that provide a normal service, but which can provide functions for adaptation when required (or alternately - adaptation measures that provide other services).

3.2 Reduced energy consumption

Fossil fuel combustion for the production of energy is one of the key drivers of greenhouse gas (GHG) emissions (IPCC 2014b). Reducing energy demand and consumption (along with the adoption of lower impact and renewable energy sources) can help to mitigate the effects of climate change, reducing the need for and the scale of adaptation measures (IPCC 2014a). Mitigation is not only a complementary strategy to adaptation, but may offer co-benefits in the quest for resilient urban environments. Reduced energy demands coupled with multiple, decentralized energy sources can provide much needed flexibility in times of need.

3.3 Resilient infrastructure networks

Both transportation and energy network resilience are positively correlated with the number of options for paths and modes (Anderson, Maoh & Burke 2011; Ip & Wang 2009, 2011). Decentralised renewable energy (geothermal, bioenergy, wind, and solar) simultaneously addresses both adaptation and mitigation, and increases resilience by increasing flexibility, supply source options, and modularity, while reducing interdependencies, risks from disruptions, and cascade failures (Farrell, Zerriffi & Dowlatabadi 2004; Bouffard & Kirschen 2008; Venema & Rehman 2007; Colson, Nehrir & Gunderson 2011; McLellan et al. 2012; Hamin & Gurran 2009; Goldthau 2014; O'Brien & Hope 2010; Buldyrev et al. 2010)

3.4 Flood adaptation

Flooding is a particular challenge for adaptation, as different types of flooding entail different approaches, and prevention and response are often comingled. Flooding occurs when water and the built environment interact in unintended ways, and can be the result of several processes. The four types of flooding considered in RAMSES are sea, tidal, fluvial, and pluvial. As sea levels rise over the coming years, tidal flooding is expected to occur with higher frequency, causing increasing disruption (Spanger-Siegfried, Fitzpatrick & Dahl 2014). Sea and tidal flooding are coastal processes, while fluvial flooding refers to rivers exceeding their capacity, and surface water flooding from rainfall, stormwater, and exceeded drainage capacity is known as pluvial flooding.

Urban flood adaptation measures can respond to three aspects of urban flooding: Source, Pathway, and Receptor (see e.g. Narayan et al. 2012; Schanze 2006; Sayers, Hall & Meadowcroft 2002). Sources, Pathways, and Receptors may be natural or designed, and intentional or unintentional. The Source of flooding (e.g. sea, river, runoff), generally follows a conveyance route or Pathway (e.g. beach, floodplain, drainage, canal, road) to a Receptor (e.g. reservoir, wetland, road, basements, buildings). The goal of flood adaptation measures is to provide flood waters with intentional and managed Sources, Pathways, and Receptors, minimising exposure, risk, and consequences to people and property.

3.4.1 Sustainable Urban Drainage Systems (SUDS)

SUDS refers to a set of decentralized approaches to urban drainage and stormwater management, focused on source and flow control. Compared to the existing urban paradigm of sealed surfaces, channelized drainage, and connections to the sewage system, SUDS seeks to introduce more surface-based and natural processes to manage surface water and runoff (Fryd et al. 2009; KK 2012; Fryd et al. 2012; CIRIA 2013; Ellis & Viavattene 2014; CIRIA 2014; PUB 2014; Zhou 2014; BES 2014).

The use of green and blue surfaces and areas (e.g. roofs, parks, swales, ponds, wetlands) in SUDS plays a key role in reducing peak and total runoff flow through detention, retention, and infiltration (BES 2014; CIRIA 2013; Ellis & Viavattene 2014). Green and blue infrastructure may also support multiple objectives (co-benefits) including reductions in pollutant load, groundwater aquifer recharge, and positive contributions to aesthetic, social, and environmental factors (BES 2014; CIRIA 2013; Ellis & Viavattene 2014; Zhou et al. 2013).

In addition to the use of blue and green infrastructure, a decentralised approach to urban drainage also includes smaller-scale grey infrastructure approaches. These approaches include reducing the sealed surface area, the use of pervious pavements, and rainwater, stormwater, and runoff detention and retention measures (e.g. rain barrels, cisterns, mixed-use zones) (BES 2014; CIRIA 2013; Ellis & Viavattene 2014; Zhou et al. 2013; Zhou 2014; Kazmierczak & Carter 2010).

The European Environment Agency (EEA) notes that "cities will need a smart urban design by reducing all soil sealing" and maximising "unsealed and green areas as well as further green elements like street trees, green walls and roofs while maintaining their compactness and urban density" (EEA 2011). The London Plan defines a hierarchy of approaches for managing urban drainage which promotes SUDS methods:

1. "Store rainwater for later use
2. Use infiltration techniques, such as porous surfaces in non-clay areas

3. Attenuate rainwater in ponds or open water features for gradual release
4. Attenuate rainwater by storing in tanks or sealed water features for gradual release
5. Discharge rainwater direct to a watercourse
6. Discharge rainwater to a surface water sewer/drain
7. Discharge rainwater to the combined sewer" (GLA 2011, p. 155).

3.4.2 Flood adapted planning

Flood adapted planning focuses more on the receptors, and is applicable to all types of flooding. These adaptation measures emphasise resilience in the face of unavoidable flooding - adapting the location, use, and construction to better be able to withstand and recover from floodwaters.

3.5 Urban Heat Island (UHI) reduction

UHIs are the result of two simultaneous processes within urban areas: solar and anthropogenic heat fluxes. Solar heat fluxes occur when incoming solar radiation is absorbed and detained within the urban fabric, while anthropogenic heat fluxes occur mainly from energy consumption due to human activity within the urban environment - converted to heat. Anthropogenic heat fluxes result from "heating of buildings, traffic, electrical appliances, industry, and air conditioning" (Pigeon et al. 2007, p. 1969).

3.5.1 Reduce anthropogenic heat sources

A reduction in anthropogenic heat sources requires a reduction in energy consumption. Buildings, vehicles, appliances, and air-conditioners are all energy consumptive devices in the direct control of consumers. All energy consumption within households involves conversion to heat; the energy consumption within buildings is approximately equal to internal heat gains (Peacock, Jenkins & Kane 2010; Wilkins & Hosni 2000; Park et al. 2013; Komor 1997; Goethals, Breesch & Janssens 2011; ASHRAE 2009). Energy consumption in buildings can be reduced through bioclimatic and space-efficient design, proper use of insulation and ventilation. Energy efficient appliances (and conservative use of appliances) can reduce energy consumption. Air conditioning, a common response to the UHI effect, is expected to increase with climate change (Davis & Gertler 2015), but only serves to increase energy consumption and total heat flux (Solecki et al. 2005).

All energy consumed by a vehicle in use is eventually converted to heat. "Fuel combustion is the main source of heat from motor vehicles" (Allen, Lindberg & Grimmond 2011, p. 1991). Electric vehicles consume less energy per distance overall, with proportionally less flux occurring during the driving cycle (combustion cycle and drivetrain friction) and emitted to the immediate environment than Internal combustion Engine (ICE) vehicles (Nylund 2013; Lorf et al. 2013; Howey et al. 2011; Geyer, Stoms & Kallaos 2013). While some efficient ICE vehicles can approach the overall (well to wheel – WTW) efficiencies of electric vehicles reliant on (and including losses from) the current electrical grid mix (Nylund 2013; Lorf et al. 2013), driving cycle efficiencies (tank to wheels - TTW) of electric vehicles are superior (Nylund 2013; Lorf et al. 2013; Howey et al. 2011; Geyer, Stoms & Kallaos 2013). Conversion of the electrical grid to renewable sources would mitigate the indirect emissions and fluxes occurring in different vehicle life-cycle stages and help increase the overall efficiencies of electric vehicles.

3.5.2 Reduce absorption & accumulation of solar heat

Roof surfaces make up 40-50% of impervious surfaces in urban areas (Mentens, Raes & Hermy 2006), providing a large surface area exposed to incoming solar radiation. Green roofs and cool roofs are two approaches to reducing the absorption and retention of solar heat.

Green roofs are partially or completely covered with vegetation. About 20-30% of incoming solar radiation is reflected from the plant surfaces, while the rest is absorbed by the plants, substrate, and other surfaces (Berardi, GhaffarianHoseini & GhaffarianHoseini 2014). The plants and substrate buffer the transfer of this heat to the surroundings through convection (including advection), conduction and/or radiation, with the relative distribution of heat transfer modes depending on both environmental, as well as building/surface characteristics. Besides these sensible heat fluxes, green roofs have latent heat fluxes in the form of evaporation and evapotranspiration, covered below.

Cool roofs and surfaces incorporate materials and pigments that increase solar reflectance, reducing the absorption of sunlight and resulting solar heat gains. Solar heat gains on incident surfaces may transfer heat to the surroundings through convection (including advection), conduction and/or radiation, with the relative distribution of heat transfer modes depending on both environmental, as well as building/surface characteristics. These sensible heat fluxes to the local environment are one of the factors promoting the UHI effect. The goal of cool roofs is the reduction of sensitive heat flux into the surrounding environment. Heat flux itself is not easy to measure, but the flux profile correlates very closely with (peak and average) roof surface temperature (Scherba et al. 2011), which we use as the metric to determine the effectiveness of this measure. "The increased albedo of white roofs effectively reduces their surface temperature and decreases sensible flux into the urban atmospheric system" (Scherba et al. 2011, p. 2550).

Environmental characteristics affecting the distribution of the benefits of green/cool roofs and surfaces include air pollution, wind, urban context, and other factors. Some building characteristics, such as insulation, can affect the distribution of the benefits of green/cool roofs and surfaces; insulation affects the direction in which heat will flow, affecting to which actor (the building or the environment) the most direct benefits accrue (Berardi, GhaffarianHoseini & Ghaffarian Hoseini 2014). In an uninsulated building, conduction of heat through building materials into the building may be a large factor. The addition of green/cool surfaces may reduce conductive heat flux, with direct influences on indoor temperatures and energy loads within the building (Castleton et al. 2010). The application of green/cool surfaces to a well-insulated building will have less of an effect on the interior of building, as the insulation already acted to reduce thermal conduction. In these cases, the benefits of reduced surface temperatures and thermal emittance will indirectly accrue to the surrounding surfaces and environment (and theoretically back to the building). As noted above, interdependencies between temperature and energy consumption also involve a feedback loop between increasing temperatures, increasing heat pump use, and thus increased external temperatures, necessitating increased cooling.

3.5.3 Increase evaporation and evapotranspiration

Latent heat fluxes through evaporation and evapotranspiration can help to remove heat from the urban centre and attenuate the UHI effect. Green and blue surfaces both provide opportunities for heat rejection through latent fluxes, assuming there is enough water to evaporate or evapotranspire.

4 Adaptation measures and classifications

Measure	Title
ACF	Flood adapted construction
AHF	Flood adapted HVAC
ALF	Flood adapted location
AUF	Flood adapted use
BIE	Building insulation - energy
BIH	Building insulation - heatwaves
BRF	Blue roof
BSE	Building shading - energy
BSH	Building shading - heatwaves
CIR	Critical infrastructure location
CPH	Cool pavements
CRH	Cool roof
DER	Decentralised renewable energy systems
EEH	Energy efficient appliances
ETH	Electric transport
GFH	Green façade
GMR	Electrical grid monitoring & control systems
GRF	Green roof - flooding
GRH	Green roof - heatwaves
MER	Multiple energy modes
MNF	Multipurpose flood management zones - green
MTR	Multiple transport modes
MYF	Multipurpose flood management zones - grey
NTH	Non-motorized transport
PPF	Permeable pavements
RHD	Rainwater harvesting - drought
RHF	Rainwater harvesting - flood
UBF	Urban lakes and water bodies - flooding
UBH	Urban lakes and water bodies – heatwaves
UGF	Urban vegetation, trees and parks - flooding
UGH	Urban vegetation, trees and parks - heatwaves

4.1 Classification by Attributes - Type of infrastructure

Type of infrastructure	Measure	Title
Green/Blue	BRF	Blue roof
	GFH	Green façade
	GRF	Green roof - flooding
	GRH	Green roof - heatwaves
	MNF	Multipurpose flood management zones - green
	UBF	Urban lakes and water bodies - flooding
	UBH	Urban lakes and water bodies – heatwaves
	UGF	Urban vegetation, trees and parks - flooding
	UGH	Urban vegetation, trees and parks - heatwaves
Grey	ACF	Flood adapted construction
	AHF	Flood adapted HVAC
	ALF	Flood adapted location
	AUF	Flood adapted use
	BIE	Building insulation - energy
	BIH	Building insulation - heatwaves
	BSE	Building shading - energy
	BSH	Building shading - heatwaves
	CIR	Critical infrastructure location
	CPH	Cool pavements
	CRH	Cool roof
	DER	Decentralised renewable energy systems
	EEH	Energy efficient appliances
	ETH	Electric transport
	GMR	Electrical grid monitoring & control systems
	MER	Multiple energy modes
	MTR	Multiple transport modes
	MYF	Multipurpose flood management zones - grey
	NTH	Non-motorized transport
	PPF	Permeable pavements
	RHD	Rainwater harvesting - drought
	RHF	Rainwater harvesting - flood

4.2 Classification by Attributes - Main threat addressed

Main threat addressed	Measure	Title
Drought	RHD	Rainwater harvesting - drought
Flooding	BRF	Blue roof
	GRF	Green roof - flooding
	UBF	Urban lakes and water bodies - flooding
	UGF	Urban vegetation, trees and parks - flooding
	ACF	Flood adapted construction
	AHF	Flood adapted HVAC
	ALF	Flood adapted location
	AUF	Flood adapted use
	CIR	Critical infrastructure location
	DER	Decentralised renewable energy systems
	GMR	Electrical grid monitoring & control systems
	MER	Multiple energy modes
	MNF	Multipurpose flood management zones - green
	MTR	Multiple transport modes
	MYF	Multipurpose flood management zones - grey
	PPF	Permeable pavements
	RHF	Rainwater harvesting - flood
Heatwaves	BIE	Building insulation - energy
	BIH	Building insulation - heatwaves
	BSE	Building shading - energy
	BSH	Building shading - heatwaves
	CPH	Cool pavements
	CRH	Cool roof
	EEH	Energy efficient appliances
	ETH	Electric transport
	GFH	Green façade
	GRH	Green roof - heatwaves
	NTH	Non-motorized transport
	UBH	Urban lakes and water bodies – heatwaves
	UGH	Urban vegetation, trees and parks - heatwaves

4.3 Classification by Attributes - Scale of implementation

Scale of implementation	Measure	Title
Building/Site	ACF	Flood adapted construction
	AHF	Flood adapted HVAC
	AUF	Flood adapted use
	BIE	Building insulation - energy
	BIH	Building insulation - heatwaves
	BRF	Blue roof
	BSE	Building shading - energy
	BSH	Building shading - heatwaves
	CRH	Cool roof
	EEH	Energy efficient appliances
	GFH	Green façade
	GRF	Green roof - flooding
	GRH	Green roof - heatwaves
	RHD	Rainwater harvesting - drought
Neighbourhood/District	CPH	Cool pavements
	MNF	Multipurpose flood management zones - green
	MYF	Multipurpose flood management zones - grey
	PPF	Permeable pavements
	UBF	Urban lakes and water bodies - flooding
	UBH	Urban lakes and water bodies – heatwaves
	UGF	Urban vegetation, trees and parks - flooding
	UGH	Urban vegetation, trees and parks - heatwaves
City/Region (Catchment)	ALF	Flood adapted location
	CIR	Critical infrastructure location
	DER	Decentralised renewable energy systems
	ETH	Electric transport
	GMR	Electrical grid monitoring & control systems
	MER	Multiple energy modes
	MTR	Multiple transport modes
	NTH	Non-motorized transport
	RHF	Rainwater harvesting - flood

4.4 Classification by Action Cluster

Action Cluster	Measure	Title
Multipurpose spaces		
	MNF	Multipurpose flood management zones - green
	MYF	Multipurpose flood management zones - grey
	UBF	Urban lakes and water bodies - flooding
	UBH	Urban lakes and water bodies – heatwaves
	UGF	Urban vegetation, trees and parks - flooding
	UGH	Urban vegetation, trees and parks - heatwaves
Reduced energy consumption		
	BIE	Building insulation - energy
	BSE	Building shading - energy
	EEH	Energy efficient appliances
	ETH	Electric transport
	NTH	Non-motorized transport
Resilient infrastructure networks		
Transportation	ETH	Electric transport
	MTR	Multiple transport modes
	NTH	Non-motorized transport
Energy system	DER	Decentralised renewable energy systems
	GMR	Electrical grid monitoring & control systems
	MER	Multiple energy modes
Flood adaptation		
Sustainable Urban Drainage Systems (SUDS)	BRF	Blue roof
	GRF	Green roof - flooding
	MNF	Mixed-use flood management zones - green
	PPF	Permeable pavements
	RHF	Rainwater harvesting - flood
	UBF	Urban lakes and water bodies - flooding
	UGF	Urban vegetation, trees and parks - flooding
Flood adapted planning	ACF	Flood adapted construction
	AHF	Flood adapted HVAC

Action Cluster	Measure	Title
	ALF	Flood adapted location
	AUF	Flood adapted use
	CIR	Critical infrastructure location
	UBF	Urban lakes and water bodies - flooding
UHI reduction		
Reduce anthropogenic heat sources	BIE	Building insulation - energy
	BSE	Building shading - energy
	EEH	Energy efficient appliances
	ETH	Electric transport
	NTH	Non-motorized transport
Reduce absorption & accumulation of solar heat	BIH	Building insulation - heatwaves
	BSH	Building shading - heatwaves
	CRH	Cool roof
	GFH	Green façade
	GRH	Green roof - heatwaves
	UBH	Urban lakes and water bodies – heatwaves
	UGH	Urban vegetation, trees and parks - heatwaves
Reduce airborne particulates	DER	Decentralised renewable energy systems
	ETH	Electric transport
	GFH	Green façade
	GRH	Green roof - heatwaves
	NTH	Non-motorized transport
	UGH	Urban vegetation, trees and parks - heatwaves
Increase evaporation and evapotranspiration	BRF	Blue roof
	GFH	Green façade
	GRH	Green roof - heatwaves
	UBH	Urban lakes and water bodies – heatwaves
	UGH	Urban vegetation, trees and parks - heatwaves

5 Inventory of climate change adaptation measures

Measure	**ACF**	
Title	**Flood adapted construction**	
Description	Construction of structures should be adapted to expected vulnerabilities	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Flood vulnerable spaces should be built or retrofitted with waterproof materials and fittings, constructed to flood while retaining structural integrity, or raised above flood levels	
Performance indicator	# of structures within flood zones % adapted structures within flood zones	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Kreibich, H, Seifert, I, Thieken, AH, Lindquist, E, Wagner, K & Merz, B 2011, 'Recent changes in flood preparedness of private households and businesses in Germany', Regional Environmental Change, vol. 11, no. 1, pp. 59–71. Kreibich, H, Thieken, AH, Petrow, T, Müller, M & Merz, B 2005, 'Flood loss reduction of private households due to building precautionary measures – lessons learned from the Elbe flood in August 2002', Natural Hazards and Earth System Sciences (NHESS), vol. 5, no. 1, pp. 117–126. Kron, A 2007, '10. Flood Damage Estimation and Flood Risk Mapping', in A Vassilopoulos, R Ashley, C Zevenbergen, E Pasche & S Garvin (eds), Advances in Urban Flood Management, Taylor & Francis, 213-235. Merz, B, Kreibich, H & Lall, U 2013, 'Multi-variate flood damage assessment: a tree-based data-mining approach', Natural Hazards and Earth System Sciences (NHESS), vol. 13, no. 1, pp. 53–64. Thieken, AH, Kreibich, H, Müller, M & Merz, B 2007, 'Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002', Hydrological Sciences Journal, vol. 52, no. 5, pp. 1016–1037.	

Measure	**AHF**	
Title	**Flood adapted HVAC**	
Description	HVAC adapted to expected vulnerabilities	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	HVAC adapted to expected vulnerabilities (moved to safe or protected area) - heating oil use should be discontinued	
Performance indicator	# of HVAC units within flood zones % adapted units within flood zones Quantity (liters, kg) of hazardous materials (e.g. heating oil) within flood zone	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Kreibich, H, Seifert, I, Thieken, AH, Lindquist, E, Wagner, K & Merz, B 2011, 'Recent changes in flood preparedness of private households and businesses in Germany', Regional Environmental Change, vol. 11, no. 1, pp. 59–71. Kreibich, H, Thieken, AH, Petrow, T, Müller, M & Merz, B 2005, 'Flood loss reduction of private households due to building precautionary measures – lessons learned from the Elbe flood in August 2002', Natural Hazards and Earth System Sciences (NHESS), vol. 5, no. 1, pp. 117–126. Kron, A 2007, '10. Flood Damage Estimation and Flood Risk Mapping', in A Vassilopoulos, R Ashley, C Zevenbergen, E Pasche & S Garvin (eds), Advances in Urban Flood Management, Taylor & Francis, 213-235. Merz, B, Kreibich, H & Lall, U 2013, 'Multi-variate flood damage assessment: a tree-based data-mining approach', Natural Hazards and Earth System Sciences (NHESS), vol. 13, no. 1, pp. 53–64. Thieken, AH, Kreibich, H, Müller, M & Merz, B 2007, 'Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002', Hydrological Sciences Journal, vol. 52, no. 5, pp. 1016–1037.	

Measure	**ALF**	
Title	**Flood adapted location**	
Description	Structures not located in vulnerable zones	
Type of infrastructure	Grey	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Structures should be located outside of zones vulnerable to flooding (or other hazards) - existing structures should be relocated, upgraded, or removed	
Performance indicator	# of people served by single service source % of people served by single service source	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Cater, F 2014, 'N.J. Braces For Future Disasters By Fleeing, And Fortifying, The Coast', NPR.org, 26 September, National Public Radio (NPR) cities project. Conrad, DR, McNitt, B & Stout, M 1998, Higher Ground: A Report on Voluntary Property Buyouts in the Nation's Floodplains, National Wildlife Federation (NWF), Washington, DC. Hamilton, J 2014, 'A Coastal Paradise Confronts Its Watery Future', NPR.org, 18 September, National Public Radio (NPR) cities project. Mandarano, L 2010, 'Sustainable land-use planning: revitalising a flood prone office park', Journal of Environmental Planning and Management, vol. 53, no. 2, pp. 183–196.	

Measure	**AUF**	
Title	**Flood adapted use**	
Description	Use of structures should be adapted to expected vulnerabilities	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Habitation not allowed in vulnerable spaces (e.g. basements in flood zones). Sensitive services not allowed in vulnerable spaces	
Performance indicator	# of people inhabiting flood zones % of people inhabiting flood zones	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Kreibich, H, Seifert, I, Thieken, AH, Lindquist, E, Wagner, K & Merz, B 2011, 'Recent changes in flood preparedness of private households and businesses in Germany', Regional Environmental Change, vol. 11, no. 1, pp. 59–71. Kreibich, H, Thieken, AH, Petrow, T, Müller, M & Merz, B 2005, 'Flood loss reduction of private households due to building precautionary measures – lessons learned from the Elbe flood in August 2002', Natural Hazards and Earth System Sciences (NHESS), vol. 5, no. 1, pp. 117–126. Kron, A 2007, '10. Flood Damage Estimation and Flood Risk Mapping', in A Vassilopoulos, R Ashley, C Zevenbergen, E Pasche & S Garvin (eds), Advances in Urban Flood Management, Taylor & Francis, 213-235. Merz, B, Kreibich, H & Lall, U 2013, 'Multi-variate flood damage assessment: a tree-based data-mining approach', Natural Hazards and Earth System Sciences (NHESS), vol. 13, no. 1, pp. 53–64. Thieken, AH, Kreibich, H, Müller, M & Merz, B 2007, 'Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002', Hydrological Sciences Journal, vol. 52, no. 5, pp. 1016–1037.	

<table>
<tr><td>Measure</td><td colspan="2">BIE</td></tr>
<tr><td>Title</td><td colspan="2">Building insulation - energy</td></tr>
<tr><td>Description</td><td colspan="2">Reduced mechanical cooling, reduced anthropogenic heat sources</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Grey</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/Site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Properly insulating and ventilating buildings reduces energy transfer rates - requiring less mechanical cooling, less energy consumption, and less heat emitted to the environment</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in surface temperature
[(control-insulated)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☐ Albedo (α)
☐ Vegetative fraction (λp)
☐ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☐ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☐ Rapidity, responsiveness
☐ Redundancy, modularity
☐ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Kikegawa, Y, Genchi, Y, Kondo, H & Hanaki, K 2006, ‘Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building’s energy-consumption for air-conditioning’, Applied Energy, vol. 83, no. 6, pp. 649–668.
Oikonomou, E, Davies, M, Mavrogianni, A, Biddulph, P, Wilkinson, P & Kolokotroni, M 2012, ‘Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London’, Building and Environment, vol. 57, pp. 223–238.
Sadineni, SB, Madala, S & Boehm, RF 2011, ‘Passive building energy savings: A review of building envelope components’, Renewable and Sustainable Energy Reviews, vol. 15, no. 8, pp. 3617–3631.
Santamouris, M 2014, ‘On the energy impact of urban heat island and global warming on buildings’, Energy and Buildings, vol. 82, pp. 100–113.
Shrestha, SS, Biswas, K & Desjarlais, AO 2014, ‘A protocol for lifetime energy and environmental impact assessment of building insulation materials’, Environmental Impact Assessment Review, vol. 46, pp. 25–31.</td></tr>
</table>

Measure	**BIH**	
Title	**Building insulation - heatwaves**	
Description	Reduced solar thermal gains to buildings	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Heatwaves	
Expected outcome	Properly insulated and ventilated buildings absorb, store, and reemit less energy	
Performance indicator	% reduction in surface emissivity [(control-insulated)/control)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☒ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☐ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Kikegawa, Y, Genchi, Y, Kondo, H & Hanaki, K 2006, 'Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning', Applied Energy, vol. 83, no. 6, pp. 649–668. Oikonomou, E, Davies, M, Mavrogianni, A, Biddulph, P, Wilkinson, P & Kolokotroni, M 2012, 'Modelling the relative importance of the urban heat island and the thermal quality of dwellings for overheating in London', Building and Environment, vol. 57, pp. 223–238. Sadineni, SB, Madala, S & Boehm, RF 2011, 'Passive building energy savings: A review of building envelope components', Renewable and Sustainable Energy Reviews, vol. 15, no. 8, pp. 3617–3631. Santamouris, M 2014, 'On the energy impact of urban heat island and global warming on buildings', Energy and Buildings, vol. 82, pp. 100–113. Shrestha, SS, Biswas, K & Desjarlais, AO 2014, 'A protocol for lifetime energy and environmental impact assessment of building insulation materials', Environmental Impact Assessment Review, vol. 46, pp. 25–31.	

Measure	**BRF**	
Title	**Blue roof**	
Description	Roofs including dams or trays to detain water, and controlled flow discharge	
Type of infrastructure	Green/Blue	
Scale of implementation	Building/Site	
Main threat addressed	Flooding (fluvial and pluvial)	
Expected outcome	Temporal buffer for water runoff: 80+% peak flow reduction (McLaughlin et al. 2014, p 1003)	
Performance indicator	% precipitation detained/retained [(precipitation−runoff)/precipitation)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☒ Emissivity (ε) ☒ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Beatley, T 2014, Blue urbanism: exploring connections between cities and oceans, Island Press, Washington, DC. Beyerlein, D, Brascher, J & White, S 2005, 'HSPF-Based WWHM: A tool for stormwater design using flow duration criteria', Proceedings of Watershed Management 2005 - Managing Watersheds for Human and Natural Impacts: Engineering, Ecological, and Economic Challenges, ASCE, Williamsburg, VA, pp. 1191–1201. Cass, J, Bendernagel, L, Mehrotra, S, Thompson, D & Pendharkar, N 2012, 'Case Study of an Integrated Blue and Green Roof System on a 100-Year Old Structure', Proceedings of the Water Environment Federation, vol. 2012, no. 5, pp. 966–974. DEP 2007, Jamaica Bay Watershed Protection Plan, New York City (NYC) Department of Environmental Protection (DEP), New York, NY. Katiyar, N, Rangarajan, S, Stein, J & Leo, W 2012, 'Performance Evaluation of Blue Roofs to Mitigate CSO Impacts', Proceedings of the Water Environment Federation, vol. 2012, no. 4, pp. 632–642. McLaughlin, J, Jones, M, Leo, W, Newman, T & Stein, J 2014, 'Green Infrastructure to Reduce Stormwater Runoff in New York City: Post-Construction Monitoring over Multiple Years and Lessons Learned', ICSI 2014: Creating Infrastructure for a Sustainable World, ASCE, Long Beach, CA, pp. 1001–1009.	

Measure	**BSE**	
Title	**Building shading - energy**	
Description	Passive cooling from external shading with cool surfaces	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Heatwaves	
Expected outcome	Properly shading buildings reduces internal and external temperatures - requiring less mechanical cooling, less energy consumption, and less heat emitted to the environment	
Performance indicator	% reduction in surface temperature [(control-shaded)/control)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☒ Emissivity (ε) ☒ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☐ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Arnesen, H, Kolås, T & Matusiak, B 2011, A guide to daylighting and solar shading systems at high latitude, ZEB Project report, The Research Centre on Zero emission Buildings (ZEB), Trondheim, Norway.. Littlefair, P, Ortiz, J & Das Bhaumik, C 2010, 'A simulation of solar shading control on UK office energy use', Building Research & Information, vol. 38, no. 6, pp. 638–646. Nielsen, MV, Svendsen, S & Jensen, LB 2011, 'Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight', Solar Energy, vol. 85, no. 5, pp. 757–768. Palmero-Marrero, AI & Oliveira, AC 2010, 'Effect of louver shading devices on building energy requirements', Applied Energy, vol. 87, no. 6, pp. 2040–2049. Sun, L, Lu, L & Yang, H 2012, 'Optimum design of shading-type building-integrated photovoltaic claddings with different surface azimuth angles', Applied Energy, vol. 90, no. 1, pp. 233–240. Tzempelikos, A & Athienitis, AK 2007, 'The impact of shading design and control on building cooling and lighting demand', Solar Energy, vol. 81, no. 3, pp. 369–382.	

<table>
<tr><td>Measure</td><td colspan="2">BSH</td></tr>
<tr><td>Title</td><td colspan="2">Building shading - heatwaves</td></tr>
<tr><td>Description</td><td colspan="2">Passive cooling from external shading with cool surfaces</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Grey</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/Site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Properly shading buildings and external spaces with reflective surfaces reduces solar thermal gains, materials absorb, store, and reemit less heat</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in surface temperature
[(control-shaded)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☐ Vegetative fraction (λp)
☐ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
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Palmero-Marrero, AI & Oliveira, AC 2010, ‘Effect of louver shading devices on building energy requirements’, Applied Energy, vol. 87, no. 6, pp. 2040–2049.
Sun, L, Lu, L & Yang, H 2012, ‘Optimum design of shading-type building-integrated photovoltaic claddings with different surface azimuth angles’, Applied Energy, vol. 90, no. 1, pp. 233–240.
Tzempelikos, A & Athienitis, AK 2007, ‘The impact of shading design and control on building cooling and lighting demand’, Solar Energy, vol. 81, no. 3, pp. 369–382..</td></tr>
</table>

Measure	**CIR**	
Title	**Critical infrastructure location**	
Description	Critical infrastructure located outside of vulnerable zones	
Type of infrastructure	Grey	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Critical infrastructure located outside of zones vulnerable to flooding (or other hazards)	
Performance indicator	# of people served by single service source % of people served by single service source	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Cater, F 2014, 'N.J. Braces For Future Disasters By Fleeing, And Fortifying, The Coast', NPR.org, 26 September, National Public Radio (NPR) cities project. Conrad, DR, McNitt, B & Stout, M 1998, Higher Ground: A Report on Voluntary Property Buyouts in the Nation's Floodplains, National Wildlife Federation (NWF), Washington, DC. Hamilton, J 2014, 'A Coastal Paradise Confronts Its Watery Future', NPR.org, 18 September, National Public Radio (NPR) cities project. Mandarano, L 2010, 'Sustainable land-use planning: revitalising a flood prone office park', Journal of Environmental Planning and Management, vol. 53, no. 2, pp. 183–196.	

Measure	**CPH**	
Title	**Cool pavements**	
Description	Paved areas partially or completely covered with lighter surfaces	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Heatwaves	
Expected outcome	Reduction in urban heat island (UHI) effect: reduced surface temperatures & energy consumption, increased service life (Akbari et al. 2001; Akbari et al. 2009; Rossi et al. 2014)	
Performance indicator	% reduction in pavement surface temperature [(control-cool)/control)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☒ Emissivity (ε) ☒ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☐ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Akbari, H, Menon, S & Rosenfeld, A 2009, 'Global cooling: increasing world-wide urban albedos to offset CO2', Climatic Change, vol. 94, no. 3-4, pp. 275–286. Akbari, H, Pomerantz, M & Taha, H 2001, 'Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas', Solar Energy, vol. 70, no. 3, pp. 295–310. Doulos, L, Santamouris, M & Livada, I 2004, 'Passive cooling of outdoor urban spaces. The role of materials', Solar Energy, vol. 77, no. 2, pp. 231–249. EPA 2008, Cool Pavements, US Environmental Protection Agency (EPA), Washington, DC. Li, H, Harvey, JT, Holland, TJ & Kayhanian, M 2013, 'The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management', Environmental Research Letters, vol. 8, no. 1, pp. 1–14. Pomerantz, M, Akbari, H, Chen, A, Taha, H & Rosenfeld, AH 1997, Paving Materials for Heat Island Mitigation, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA. Rossi, F, Pisello, AL, Nicolini, A, Filipponi, M & Palombo, M 2014, 'Analysis of retro-reflective surfaces for urban heat island mitigation: A new analytical model', Applied Energy, vol. 114, pp. 621–631.	

<table>
<tr><td>Measure</td><td colspan="2">CRH</td></tr>
<tr><td>Title</td><td colspan="2">Cool roof</td></tr>
<tr><td>Description</td><td colspan="2">Roofs partially or completely covered with lighter/reflective surfaces</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Grey</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Reduction in urban heat island (UHI) effect: reduced surface temperatures & energy consumption, increased service life (Akbari et al. 2001; Akbari et al. 2009; Rossi et al. 2014)</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in roof surface temperature
[(control-cool)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☐ Vegetative fraction (λp)
☐ Vegetative type (vtyp)</td></tr>
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Akbari, H, Pomerantz, M & Taha, H 2001, ‘Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas’, Solar Energy, vol. 70, no. 3, pp. 295–310.
Rossi, F, Pisello, AL, Nicolini, A, Filipponi, M & Palombo, M 2014, ‘Analysis of retro-reflective surfaces for urban heat island mitigation: A new analytical model’, Applied Energy, vol. 114, pp. 621–631.
Scherba, A, Sailor, DJ, Rosenstiel, TN & Wamser, CC 2011, ‘Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment’, Building and Environment, vol. 46, no. 12, pp. 2542–2551.
Sproul, J, Wan, MP, Mandel, BH & Rosenfeld, AH 2014, ‘Economic comparison of white, green, and black flat roofs in the United States’, Energy and Buildings, vol. 71, pp. 20–27.</td></tr>
</table>

Measure	**DER**	
Title	**Decentralised renewable energy systems**	
Description	Small scale energy provision from a multitude of sources depending on local conditions	
Type of infrastructure	Grey	
Scale of implementation	City/region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Reduction in reliance on one form of energy supply in the event of failure/flooding of one mode	
Performance indicator	# of path/mode options # of customers served by single mode % of energy supply served by single mode	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☒ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory	☒ Performance ☒ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☒ Robustness
Scientific references	Bouffard, F & Kirschen, DS 2008, 'Centralised and distributed electricity systems', Energy Policy, vol. 36, no. 12, pp. 4504–4508. Buldyrev, SV, Parshani, R, Paul, G, Stanley, HE & Havlin, S 2010, 'Catastrophic cascade of failures in interdependent networks', Nature, vol. 464, no. 7291, pp. 1025–1028. Farrell, AE, Zerriffi, H & Dowlatabadi, H 2004, 'Energy infrastructure and security', Annual Review of Environment and Resources, vol. 28, no. 29, pp. 421–69. Goldthau, A 2014, 'Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism', Energy Research & Social Science, vol. 1, pp. 134–140. McLellan, B, Zhang, Q, Farzaneh, H, Utama, NA & Ishihara, KN 2012, 'Resilience, Sustainability and Risk Management: A Focus on Energy', Challenges, vol. 3, no. 2, pp. 153–182. O'Brien, G & Hope, A 2010, 'Localism and energy: Negotiating approaches to embedding resilience in energy systems', Energy Policy, vol. 38, no. 12, pp. 7550–7558. Venema, HD & Rehman, IH 2007, 'Decentralized renewable energy and the climate change mitigation-adaptation nexus', Mitigation and Adaptation Strategies for Global Change, vol. 12, no. 5, pp. 875–900.	

<table>
<tr><td>Measure</td><td colspan="2">EEH</td></tr>
<tr><td>Title</td><td colspan="2">Energy efficient appliances</td></tr>
<tr><td>Description</td><td colspan="2">Appliances that provide equivalent service with less energy</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Grey</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/Site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Efficient appliances reduce energy demand, internal thermal gains, and the need for mechanical cooling - reduced urban anthropogenic heat sources</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in energy consumption
[(control-efficient)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☐ Albedo (α)
☐ Vegetative fraction (λp)
☐ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
☐ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☐ Rapidity, responsiveness
☐ Redundancy, modularity
☐ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">ASHRAE 2009, ‘Chapter 18: Nonresidential Cooling and Heating Load Calculations.’, 2009 ASHRAE Handbook-Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE), Atlanta, GA.
Goethals, K, Breesch, H & Janssens, A 2011, ‘Sensitivity analysis of predicted night cooling performance to internal convective heat transfer modelling’, Energy and Buildings, vol. 43, no. 9, pp. 2429–2441.
Komor, P 1997, ‘Space Cooling Demands from Office Plug Loads’, ASHRAE Journal, vol. 39, no. 12, pp. 41–44.
Park, H, Ruellan, M, Martaj, N, Bennacer, R & Monmasson, E 2013, ‘Generic thermal model of electrical appliances in thermal building: Application to the case of a refrigerator’, Energy and Buildings, vol. 62, pp. 335–342.
Peacock, AD, Jenkins, DP & Kane, D 2010, ‘Investigating the potential of overheating in UK dwellings as a consequence of extant climate change’, Energy Policy, vol. 38, no. 7, pp. 3277–3288.
Wilkins, C & Hosni, MH 2000, ‘Heat gain from office equipment’, ASHRAE Journal, vol. 42, no. 6, pp. 33–39.</td></tr>
</table>

Measure	ETH	
Title	**Electric transport**	
Description	Design and policy promoting electric forms of urban transport	
Type of infrastructure	Soft	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Heatwaves (including air pollution)	
Expected outcome	Reduced anthropogenic heat sources, reduced particulate and gaseous emissions in urban area (reduction in heat release from combustion through vehicle substitution)	
Performance indicator	% reduction in heat released from vehicles [(control-electric)/control)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Allen, L, Lindberg, F & Grimmond, CSB 2011, 'Global to city scale urban anthropogenic heat flux: model and variability', International Journal of Climatology, vol. 31, no. 13, pp. 1990–2005. Pigeon, G, Legain, D, Durand, P & Masson, V 2007, 'Anthropogenic heat release in an old European agglomeration (Toulouse, France)', International Journal of Climatology, vol. 27, no. 14, pp. 1969–1981. Sailor, DJ & Lu, L 2004, 'A top–down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas', Atmospheric Environment, vol. 38, no. 17, pp. 2737–2748. Saitoh, TS, Yamada, N, Ando, D & Kurata, K 2005, 'A grand design of future electric vehicle to reduce urban warming and CO2 emissions in urban area', Renewable Energy, vol. 30, no. 12, pp. 1847–1860.	

<table>
<tr><td>Measure</td><td colspan="2">GFH</td></tr>
<tr><td>Title</td><td colspan="2">Green façade</td></tr>
<tr><td>Description</td><td colspan="2">Façades partially or completely covered with vegetation</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Green/Blue</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/Site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves (including air pollution)</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Reduction in urban heat island (UHI) effect: reduction in surface and air temperatures, potential reduction in energy consumption, reduction of wind speed.</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in façade surface temperature
[(control-green)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☒ Vegetative fraction (λp)
☒ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☐ Rapidity, responsiveness
☐ Redundancy, modularity
☐ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Alexandri, E & Jones, P 2008, ‘Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates’, Building and Environment, vol. 43, no. 4, pp. 480–493.
Cheng, CY, Cheung, KKS & Chu, LM 2010, ‘Thermal performance of a vegetated cladding system on facade walls’, Building and Environment, vol. 45, no. 8, pp. 1779–1787.
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Köhler, M 2008, ‘Green facades—a view back and some visions’, Urban Ecosystems, vol. 11, no. 4, pp. 423–436.
Koyama, T, Yoshinaga, M, Hayashi, H, Maeda, K & Yamauchi, A 2013, ‘Identification of key plant traits contributing to the cooling effects of green façades using freestanding walls’, Building and Environment, vol. 66, pp. 96–103.
Pérez, G, Rincón, L, Vila, A, González, JM & Cabeza, LF 2011, ‘Green vertical systems for buildings as passive systems for energy savings’, Applied Energy, vol. 88, no. 12, pp. 4854–4859.
Wong, NH, Kwang Tan, AY, Chen, Y, Sekar, K, Tan, PY, Chan, D, Chiang, K & Wong, NC 2010, ‘Thermal evaluation of vertical greenery systems for building walls’, Building and Environment, vol. 45, no. 3, pp. 663–672.</td></tr>
</table>

Measure	**GMR**	
Title	**Electrical grid monitoring & control systems**	
Description	Micrograms and monitoring technology (SCADA) allow more rapid response to faults	
Type of infrastructure	Soft	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Rapid identification of network issues can prevent cascading effects, limit disruption, and reduce recovery time.	
Performance indicator	% reduction in recovery time % reduction in total annual power outage [# (inhabitants + businesses) x time] peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☒ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Arup, RPA & Siemens 2013a, Toolkit for Resilient Cities. Case Study: New York City Electrical Grid, Case study, Arup, Regional Plan Association (RPA), and Siemens Arup, RPA & Siemens 2013b, Toolkit for Resilient Cities. Executive Summary, Executive Summary, Arup, Regional Plan Association (RPA), and Siemens. Arup, RPA & Siemens 2013c, Toolkit for Resilient Cities. Infrastructure, Technology and Urban Planning, Arup, Regional Plan Association (RPA), and Siemens. Colson, CM, Nehrir, MH & Gunderson, RW 2011, 'Distributed multi-agent microgrids: a decentralized approach to resilient power system self-healing', *Proceedings ISRCS 2011 4rd International Symposium on Resilient Control Systems*, The Institute of Electrical and Electronics Engineers (IEEE), Boise, ID, pp. 83–88. Siemens 2012, On the road to Smart Grid: Siemens to equip eight cities in India with supervisory control technology for power distribution systems, Press release, Siemens, Nuremburg, DE, viewed 28 September, 2014, <http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2012/infrastructure-cities/smart-grid/icsg201203014.htm>.	

Measure	**GRF**	
Title	**Green roof - flooding**	
Description	Roofs partially or completely covered with vegetation	
Type of infrastructure	Green/Blue	
Scale of implementation	Building/Site	
Main threat addressed	Flooding (fluvial and pluvial)	
Expected outcome	Temporal buffer for water runoff: "intercept, retain, and evapotranspire between 34% and 69% of precipitation, with an average retention of 56%" (Gregoire et al. 2011, p 963)	
Performance indicator	% precipitation retained [(precipitation−runoff)/precipitation)]×100 peak & average (Gregoire et al. 2011, p 963)	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☒ Emissivity (ε) ☒ Albedo (α) ☒ Vegetative fraction (λp) ☒ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☒ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Berardi, U, GhaffarianHoseini, A-H & GhaffarianHoseini, A 2014, 'State-of-the-art analysis of the environmental benefits of green roofs', Applied Energy, vol. 115, pp. 411–428. Carter, T & Keeler, A 2008, 'Life-cycle cost–benefit analysis of extensive vegetated roof systems', Journal of Environmental Management, vol. 87, no. 3, pp. 350–363. Getter, KL, Rowe, DB & Andresen, JA 2007, 'Quantifying the effect of slope on extensive green roof stormwater retention', Ecological Engineering, vol. 31, no. 4, pp. 225–231. Gregoire, BG & Clausen, JC 2011, 'Effect of a modular extensive green roof on stormwater runoff and water quality', Ecological Engineering, vol. 37, no. 6, pp. 963–969. Liu, W, Chen, W & Peng, C 2014, 'Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study', Ecological Modelling, vol. 291, pp. 6–14. Mentens, J, Raes, D & Hermy, M 2006, 'Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?', Landscape and Urban Planning, vol. 77, no. 3, pp. 217–226.	

<table>
<tr><td>Measure</td><td colspan="2">GRH</td></tr>
<tr><td>Title</td><td colspan="2">Green roof - heatwaves</td></tr>
<tr><td>Description</td><td colspan="2">Roofs partially or completely covered with vegetation</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Green/Blue</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Building/Site</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves (including air pollution)</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Reduction in urban heat island (UHI) effect: reduction in surface temperatures and energy consumption (Scherba et al. 2011; Peng et al. 2012; Berardi et al. 2014)</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in roof surface temperature
[(control-green)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☒ Vegetative fraction (λp)
☒ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☐ Rapidity, responsiveness
☐ Redundancy, modularity
☐ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Alexandri, E & Jones, P 2008, ‘Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates’, Building and Environment, vol. 43, no. 4, pp. 480–493.
Berardi, U, GhaffarianHoseini, A-H & GhaffarianHoseini, A 2014, ‘State-of-the-art analysis of the environmental benefits of green roofs’, Applied Energy, vol. 115, pp. 411–428.
Ouldboukhitine, S-E, Belarbi, R & Sailor, DJ 2014, ‘Experimental and numerical investigation of urban street canyons to evaluate the impact of green roof inside and outside buildings’, Applied Energy, vol. 114, pp. 273–282.
Peng, LLH & Jim, CY 2013, ‘Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation’, Energies, vol. 6, no. 2, pp. 598–618.
Scherba, A, Sailor, DJ, Rosenstiel, TN & Wamser, CC 2011, ‘Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment’, Building and Environment, vol. 46, no. 12, pp. 2542–2551.
Susca, T, Gaffin, SR & Dell’Osso, GR 2011, ‘Positive effects of vegetation: Urban heat island and green roofs’, Environmental Pollution, vol. 159, no. 8–9, pp. 2119–2126.</td></tr>
</table>

Measure	MER	
Title	**Multiple energy modes**	
Description	Diverse or redundant supply and transmission options for energy supply	
Type of infrastructure	Grey	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Reduction in reliance on one form of energy in the event of failure/flooding of one mode - private and public	
Performance indicator	# of path/mode options # of customers served by single mode % of energy supply reliant on a single mode	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory	☐ Performance ☒ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Bouffard, F & Kirschen, DS 2008, 'Centralised and distributed electricity systems', Energy Policy, vol. 36, no. 12, pp. 4504–4508. Buldyrev, SV, Parshani, R, Paul, G, Stanley, HE & Havlin, S 2010, 'Catastrophic cascade of failures in interdependent networks', Nature, vol. 464, no. 7291, pp. 1025–1028. Farrell, AE, Zerriffi, H & Dowlatabadi, H 2004, 'Energy infrastructure and security', Annual Review of Environment and Resources, vol. 28, no. 29, pp. 421–69. Goldthau, A 2014, 'Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism', Energy Research & Social Science, vol. 1, pp. 134–140. McLellan, B, Zhang, Q, Farzaneh, H, Utama, NA & Ishihara, KN 2012, 'Resilience, Sustainability and Risk Management: A Focus on Energy', Challenges, vol. 3, no. 2, pp. 153–182. O'Brien, G & Hope, A 2010, 'Localism and energy: Negotiating approaches to embedding resilience in energy systems', Energy Policy, vol. 38, no. 12, pp. 7550–7558.	

<table>
<tr><td>Measure</td><td colspan="2">MNF</td></tr>
<tr><td>Title</td><td colspan="2">Multipurpose flood management zones - green</td></tr>
<tr><td>Description</td><td colspan="2">Vegetated areas (bioswales, parks) designed to detain or retain stormwater</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Green/Blue</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Neighbourhood/District</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Flooding (fluvial and pluvial)</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Stormwater runoff buffer: Drainage of rainwater without surface runoff, increased evaporation, percolation</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% precipitation detained/retained
[(precipitation−runoff)/precipitation)]×100
peak and average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☐ Emissivity (ε)
☐ Albedo (α)
☒ Vegetative fraction (λp)
☒ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☒ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☒ Rapidity, responsiveness
☒ Redundancy, modularity
☒ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Li, H, Sharkey, L, Hunt, W & Davis, A 2009, ‘Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland’, Journal of Hydrologic Engineering, vol. 14, no. 4, pp. 407–415.
Liu, W, Chen, W & Peng, C 2014, ‘Assessing the effectiveness of green infrastructures on urban flooding reduction: A community scale study’, Ecological Modelling, vol. 291, pp. 6–14.
Stagge, JH, Davis, AP, Jamil, E & Kim, H 2012, ‘Performance of grass swales for improving water quality from highway runoff’, Water Research, vol. 46, no. 20, pp. 6731–6742.
Struck, SD, Christian, D, Sim, Y, Carter, S, Hufnagel, CL & Brescol, J 2011, ‘Applying Low Impact Development Practices to Meet Multiple Objectives: Case Studies’, in RE Beighley & MW Kilgore (eds), World Environmental and Water Resources Congress 2011: Bearing Knowledge for Sustainability, American Society of Civil Engineers (ASCE), Palm Springs, CA, pp. 608–618.
Xiao, Q & McPherson, EG 2011, ‘Performance of engineered soil and trees in a parking lot bioswale’, Urban Water Journal, vol. 8, no. 4, pp. 241–253.</td></tr>
</table>

Measure	**MTR**	
Title	**Multiple transport modes**	
Description	Multiple mode and route options for transport in urban areas	
Type of infrastructure	Soft	
Scale of implementation	City/region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Reduction in reliance on one form of transport in the event of failure/flooding of one mode - private and public	
Performance indicator	# of path/mode options # of routes served by single mode % of trips served by single mode	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☐ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Anderson, WP, Maoh, H & Burke, C 2011, 'Assessing risk and resilience for transportation infrastructure in Canada', Transportation and Innovation: The Roles of Governments, Industry and Academia, Quebec, Canada, pp. 298–312. Ip, WH & Wang, Q 2011, 'Resilience and Friability of Transportation Networks: Evaluation, Analysis and Optimization', IEEE Systems Journal, vol. 5, no. 2, pp. 189–198. Ip, WH & Wang, Q 2009, 'Resilience Evaluation Approach of Transportation Networks', International Joint Conference on Computational Sciences and Optimization, 2009. CSO 2009, pp. 618–622.	

Measure	**MYF**	
Title	**Multipurpose flood management zones - grey**	
Description	Manufactured areas (e.g. parking or recreation) designed to detain or retain stormwater	
Type of infrastructure	Grey	
Scale of implementation	Neighbourhood/District	
Main threat addressed	Flooding (fluvial and pluvial)	
Expected outcome	Flood inundation buffer: Storage of stormwater in pre-planned, managed area	
Performance indicator	% precipitation detained/retained [(precipitation−runoff)/precipitation)]×100 peak and average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☒ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Han, K, Kim, Y, Kim, B, Famiglietti, JS & Sanders, BF 2014, 'Calibration of stormwater management model using flood extent data', Proceedings of the ICE - Water Management, vol. 167, no. 1, pp. 17–29. PUB 2013, Strengthening Singapore's Flood Resilience, PUB, Singapore's National Water Agency, Singapore.	

Measure	NTH	
Title	**Non-motorized transport**	
Description	Design for safe use of non-motorized transport	
Type of infrastructure	Grey	
Scale of implementation	City/region (catchment)	
Main threat addressed	Heatwaves (including air pollution)	
Expected outcome	Reduced anthropogenic heat sources, reduced particulate and gaseous emissions in urban area (reduction in motorized vehicle travel through travel substitution by non-motorized means)	
Performance indicator	% reduction in heat released from vehicles [(control-substituted)/control)]×100 peak & average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☒ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Allen, L, Lindberg, F & Grimmond, CSB 2011, 'Global to city scale urban anthropogenic heat flux: model and variability', International Journal of Climatology, vol. 31, no. 13, pp. 1990–2005. Pigeon, G, Legain, D, Durand, P & Masson, V 2007, 'Anthropogenic heat release in an old European agglomeration (Toulouse, France)', International Journal of Climatology, vol. 27, no. 14, pp. 1969–1981. Sailor, DJ & Lu, L 2004, 'A top–down methodology for developing diurnal and seasonal anthropogenic heating profiles for urban areas', Atmospheric Environment, vol. 38, no. 17, pp. 2737–2748.	

<table>
<tr><td>Measure</td><td colspan="2">PPF</td></tr>
<tr><td>Title</td><td colspan="2">Permeable pavements</td></tr>
<tr><td>Description</td><td colspan="2">Paved areas partially or completely covered with permeable surfaces</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Grey</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Neighbourhood/District</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Flooding (fluvial and pluvial)</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Stormwater runoff buffer: Drainage of rainwater without surface runoff, increased evaporation (time and quantity) (Starke et al. 2011; Li et al. 2013)</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% precipitation detained/retained/infiltrated
[(precipitation−runoff)/precipitation)]×100
peak and average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☐ Emissivity (ε)
☐ Albedo (α)
☐ Vegetative fraction (λp)
☐ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☒ Adaptability, flexibility
☐ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☒ Rapidity, responsiveness
☒ Redundancy, modularity
☒ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Brattebo, BO & Booth, DB 2003, ‘Long-term stormwater quantity and quality performance of permeable pavement systems’, Water Research, vol. 37, no. 18, pp. 4369–4376.
Li, H, Harvey, JT, Holland, TJ & Kayhanian, M 2013, ‘The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management’, Environmental Research Letters, vol. 8, no. 1, pp. 1–14.
Li, H, Kayhanian, M & Harvey, JT 2013, ‘Comparative field permeability measurement of permeable pavements using ASTM C1701 and NCAT permeameter methods’, Journal of Environmental Management, vol. 118, pp. 144–152.
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</table>

Measure	**RHF**	
Title	**Rainwater harvesting - flood**	
Description	Tanks and cisterns designed to store stormwater	
Type of infrastructure	Grey	
Scale of implementation	City/Region (catchment)	
Main threat addressed	Flooding (sea, tidal, fluvial and pluvial)	
Expected outcome	Flood inundation buffer: Storage of stormwater in pre-planned, managed area	
Performance indicator	% precipitation detained/retained [(precipitation−runoff)/precipitation)]×100 peak and average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☐ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory	☐ Performance ☒ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Burns, MJ, Fletcher, TD, Duncan, HP, Hatt, BE, Ladson, AR & Walsh, CJ 2012, 'The stormwater retention performance of rainwater tanks at the land-parcel scale', 7th International Conference on Water Sensitive Urban Design, Melbourne, AU. Inamdar, PM, Cook, S, Sharma, AK, Corby, N, O'Connor, J & Perera, BJC 2013, 'A GIS based screening tool for locating and ranking of suitable stormwater harvesting sites in urban areas', Journal of Environmental Management, vol. 128, pp. 363–370. Petrucci, G, Deroubaix, J-F, de Gouvello, B, Deutsch, J-C, Bompard, P & Tassin, B 2012, 'Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study', Urban Water Journal, vol. 9, no. 1, pp. 45–55.	

Measure	**RHD**	
Title	**Rainwater harvesting - drought**	
Description	Tanks and cisterns designed to store stormwater	
Type of infrastructure	Grey	
Scale of implementation	Building/Site	
Main threat addressed	Drought	
Expected outcome	Stormwater runoff buffer: Storage of rainwater for local use	
Performance indicator	% precipitation retained quantity precipitation retained peak and average	
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h)	☐ Emissivity (ε) ☐ Albedo (α) ☐ Vegetative fraction (λp) ☐ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☒ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory	☐ Performance ☐ Rapidity, responsiveness ☒ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Aladenola, OO & Adeboye, OB 2010, 'Assessing the Potential for Rainwater Harvesting', Water Resources Management, vol. 24, no. 10, pp. 2129–2137. Burns, MJ, Fletcher, TD, Duncan, HP, Hatt, BE, Ladson, AR & Walsh, CJ 2012, 'The stormwater retention performance of rainwater tanks at the land-parcel scale', 7th International Conference on Water Sensitive Urban Design, Melbourne, AU. Petrucci, G, Deroubaix, J-F, de Gouvello, B, Deutsch, J-C, Bompard, P & Tassin, B 2012, 'Rainwater harvesting to control stormwater runoff in suburban areas. An experimental case-study', Urban Water Journal, vol. 9, no. 1, pp. 45–55.	

<table>
<tr><td>Measure</td><td colspan="2">UBF</td></tr>
<tr><td>Title</td><td colspan="2">Urban lakes and water bodies - flooding</td></tr>
<tr><td>Description</td><td colspan="2">Urban water features designed with excess capacity to store and manage stormwater</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Green/Blue</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Neighbourhood/District</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Flooding (fluvial and pluvial)</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Stormwater runoff buffer: Drainage of rainwater without surface runoff, increased evaporation, infiltration</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% runoff intercepted
[(precipitation−runoff)/precipitation)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☒ Vegetative fraction (λp)
☒ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☐ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☐ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☒ Performance
☒ Rapidity, responsiveness
☒ Redundancy, modularity
☒ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Highfield, WE & Brody, SD 2006, ‘Price of permits: measuring the economic impacts of wetland development on flood damages in Florida’, Natural Hazards Review, vol. 7, p. 123.
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<table>
<tr><td>Measure</td><td colspan="2">UBH</td></tr>
<tr><td>Title</td><td colspan="2">Urban lakes and water bodies - heatwaves</td></tr>
<tr><td>Description</td><td colspan="2">Urban water features</td></tr>
<tr><td>Type of infrastructure</td><td colspan="2">Green/Blue</td></tr>
<tr><td>Scale of implementation</td><td colspan="2">Neighbourhood/District</td></tr>
<tr><td>Main threat addressed</td><td colspan="2">Heatwaves</td></tr>
<tr><td>Expected outcome</td><td colspan="2">Evaporation and thermal mass reduce temperatures in the vicinity</td></tr>
<tr><td>Performance indicator</td><td colspan="2">% reduction in surface temperature
[(control-blue)/control)]×100
peak & average</td></tr>
<tr><td>Affected urban surface parameters</td><td>☐ Plane area index (λp)
☐ Frontal area index (λf)
☐ Building height (h)</td><td>☒ Emissivity (ε)
☒ Albedo (α)
☒ Vegetative fraction (λp)
☒ Vegetative type (vtyp)</td></tr>
<tr><td>Resilience dimensions</td><td>☐ Adaptability, flexibility
☒ Connectivity, feedbacks, safe failure
☒ Dependence on local ecosystems
☐ Diversity
☐ Learning, memory</td><td>☐ Performance
☐ Rapidity, responsiveness
☒ Redundancy, modularity
☐ Resourcefulness
☐ Robustness</td></tr>
<tr><td>Scientific references</td><td colspan="2">Chen, Y-C, Tan, C-H, Wei, C & Su, Z-W 2014, ‘Cooling Effect of Rivers on Metropolitan Taipei Using Remote Sensing’, International Journal of Environmental Research and Public Health, vol. 11, no. 2, pp. 1195–1210.
Coutts, AM, Tapper, NJ, Beringer, J, Loughnan, M & Demuzere, M 2013, ‘Watering our cities The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context’, Progress in Physical Geography, vol. 37, no. 1, pp. 2–28.
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</table>

Measure	**UGF**
Title	**Urban vegetation, trees and parks - flooding**
Description	Urban vegetation, trees, and parks
Type of infrastructure	Green/Blue
Scale of implementation	Neighbourhood/District
Main threat addressed	Flooding (fluvial and pluvial)
Expected outcome	Interception of rainfall, temporal buffer for water runoff, increased evapotranspiration (Xiao & McPherson 2011; Inkiläinen et al. 2013)
Performance indicator	% precipitation intercepted [(precipitation−throughfall)/precipitation)]×100 (Xiao & McPherson 2011a, 2011b; Inkiläinen et al. 2013)
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h) ☒ Emissivity (ε) ☒ Albedo (α) ☒ Vegetative fraction (λp) ☒ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☒ Dependence on local ecosystems ☒ Diversity ☐ Learning, memory ☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☐ Resourcefulness ☐ Robustness
Scientific references	Inkiläinen, ENM, McHale, MR, Blank, GB, James, AL & Nikinmaa, E 2013, ‘The role of the residential urban forest in regulating throughfall: A case study in Raleigh, North Carolina, USA’, Landscape and Urban Planning, vol. 119, pp. 91–103. McPherson, G, Simpson, JR, Peper, PJ, Maco, SE & Xiao, Q 2005, ‘Municipal Forest Benefits and Costs in Five US Cities’, Journal of Forestry, vol. 103, no. 8, pp. 411–416. Soares, AL, Rego, FC, McPherson, EG, Simpson, JR, Peper, PJ & Xiao, Q 2011, ‘Benefits and costs of street trees in Lisbon, Portugal’, Urban Forestry & Urban Greening, vol. 10, no. 2, pp. 69–78. Xiao, Q & McPherson, EG 2011a, ‘Performance of engineered soil and trees in a parking lot bioswale’, Urban Water Journal, vol. 8, no. 4, pp. 241–253. Xiao, Q & McPherson, EG 2002, ‘Rainfall interception by Santa Monica’s municipal urban forest’, Urban Ecosystems, vol. 6, no. 4, pp. 291–302. Xiao, Q & McPherson, EG 2011b, ‘Rainfall interception of three trees in Oakland, California’, Urban Ecosystems, vol. 14, no. 4, pp. 755–769.

Measure	**UGH**
Title	**Urban vegetation, trees and parks - heatwaves**
Description	Urban vegetation, trees, and parks
Type of infrastructure	Green/Blue
Scale of implementation	Neighbourhood/District
Main threat addressed	Heatwaves
Expected outcome	Reduction in urban heat island (UHI) effect: reduction in surface temperatures and energy consumption (Thorsson et al. 2007; Bowler et al. 2010; Ng et al. 2012)
Performance indicator	% reduction in surface temperature [(control-green)/control)]×100 peak & average
Affected urban surface parameters	☐ Plane area index (λp) ☐ Frontal area index (λf) ☐ Building height (h) ☒ Emissivity (ε) ☒ Albedo (α) ☒ Vegetative fraction (λp) ☒ Vegetative type (vtyp)
Resilience dimensions	☒ Adaptability, flexibility ☒ Connectivity, feedbacks, safe failure ☒ Dependence on local ecosystems ☐ Diversity ☐ Learning, memory ☒ Performance ☐ Rapidity, responsiveness ☐ Redundancy, modularity ☒ Resourcefulness ☐ Robustness
Scientific references	Bowler, DE, Buyung-Ali, L, Knight, TM & Pullin, AS 2010, 'Urban greening to cool towns and cities: A systematic review of the empirical evidence', Landscape and Urban Planning, vol. 97, no. 3, pp. 147–155. Chen, Y & Wong, NH 2006, 'Thermal benefits of city parks', Energy and Buildings, vol. 38, no. 2, pp. 105–120. Donovan, GH & Butry, DT 2009, 'The value of shade: Estimating the effect of urban trees on summertime electricity use', Energy and Buildings, vol. 41, no. 6, pp. 662–668. Gill, S., Handley, J., Ennos, A. & Pauleit, S 2007, 'Adapting Cities for Climate Change: The Role of the Green Infrastructure', *Built Environment*, vol. 33, no. 1, pp. 115–133. Ng, E, Chen, L, Wang, Y & Yuan, C 2012, 'A study on the cooling effects of greening in a high-density city: An experience from Hong Kong', Building and Environment, vol. 47, pp. 256–271. Onishi, A, Cao, X, Ito, T, Shi, F & Imura, H 2010, 'Evaluating the potential for urban heat-island mitigation by greening parking lots', Urban Forestry & Urban Greening, vol. 9, no. 4, pp. 323–332. Soares, AL, Rego, FC, McPherson, EG, Simpson, JR, Peper, PJ & Xiao, Q 2011, 'Benefits and costs of street trees in Lisbon, Portugal', Urban Forestry & Urban Greening, vol. 10, no. 2, pp. 69–78. Thorsson, S, Honjo, T, Lindberg, F, Eliasson, I & Lim, E-M 2007, 'Thermal Comfort and Outdoor Activity in Japanese Urban Public Places', Environment and Behavior, vol. 39, no. 5, pp. 660–684.

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