TNA TECHNOLOGY NEEDS ASSESSMENT

Climate technologies in an urban context

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Technology Needs Assessments

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Technical editing: Daniel Puig (UNEP DTU Partnership, Copenhagen, Denmark), Léa Jehl Le Manceau (UNEP DTU Partnership, Copenhagen, Denmark) and Lucy Ellen Gregersen (UNEP DTU Partnership, Copenhagen, Denmark)

Language editing: Robert Parkin

Design/layout: Kowsky

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UNEP DTU Partnership
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Preface

Urban areas are home to an increasingly large share of the world's population. As a result, a growing proportion of global greenhouse gas emissions are stemming from activities located in cities and towns, where many of the adverse impacts of global warming are being felt most strongly. Not surprisingly, then, local governments ought to play a major role with regard to both the mitigation of and adaptation to climate change.

However, local government efforts to manage global warming are constrained by a multiplicity of factors. Chief among these are sub-optimal governance arrangements, whereby local governments have only a limited say in decisions about prioritizing actions to manage climate change, the approaches chosen to conduct these actions, and the funding allocated to do so.

Despite this, for some actions to manage climate change local governments are closer to the decision-making process. Bus-rapid transport systems and heatwave-related early warning and preparedness campaigns are cases in point. Indeed, when it comes to these types of action, local-governments may need to take the initiative. Doing so requires an understanding of the main options at their disposal.

This document outlines the options that local governments can use in their efforts to manage climate change. It covers both mitigation and adaptation actions, and makes recommendations that are applicable in most contexts, the effectiveness of which has been well-established.

These recommendations are framed around the notion of "technologies", understood in a broad sense – that is, covering machinery and other physical artefacts and changes in the behaviour of individuals, including the way communities and their institutions organize themselves.

This approach has been borrowed from the so-called Technology Needs Assessment project, which this document supports. This project, a major initiative funded by the Global Environment Facility, is being implemented by the United Nations Environment Programme and the UNEP DTU Partnership.

The intended primary audience for this document consists of government officials in developing countries who make decisions concerning the management of climate change in urban areas. Secondary audiences for the report include technical specialists who support the primary audience, whether they sit in government or work independently as consultants.

It is hoped that this document will be of use to its various target audiences. Feedback on the usefulness of the advice provided in it will be most welcome.

Acknowledgements

Authors and reviewers:

Chapter 1: Introduction
Author: Léa Jehl Le Manceau (UNEP DTU Partnership, Copenhagen, Denmark)
Reviewer: Sara Trærup (UNEP DTU Partnership, Copenhagen, Denmark)

Chapter 2: Buildings
Author: Clara Camarasa (UNEP DTU Partnership, Copenhagen, Denmark)
Reviewers: Juan Pablo Jiménez Navarro (European Commission's Joint Research Centre, Petten, The Netherlands) and Faidra Filippidou (European Commission's Joint Research Centre, Petten, The Netherlands)

Chapter 3: Transport
Authors: Subash Dhar (UNEP DTU Partnership, Copenhagen, Denmark) and Talat Munshi (UNEP DTU Partnership, Copenhagen, Denmark)
Reviewers: Sonia Yeh (Chalmers University, Göteborg, Sweden) and Minal Pathak (Ahmedabad University, Ahmedabad, Gujarat, India)

Chapter 4: Solid waste management
Author: Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)
Reviewers: Daniel Ternald (United Nations Environment Programme, Osaka, Japan) and Ricardo Gabbay De Souza (São Paulo State University, São Paulo, Brazil)

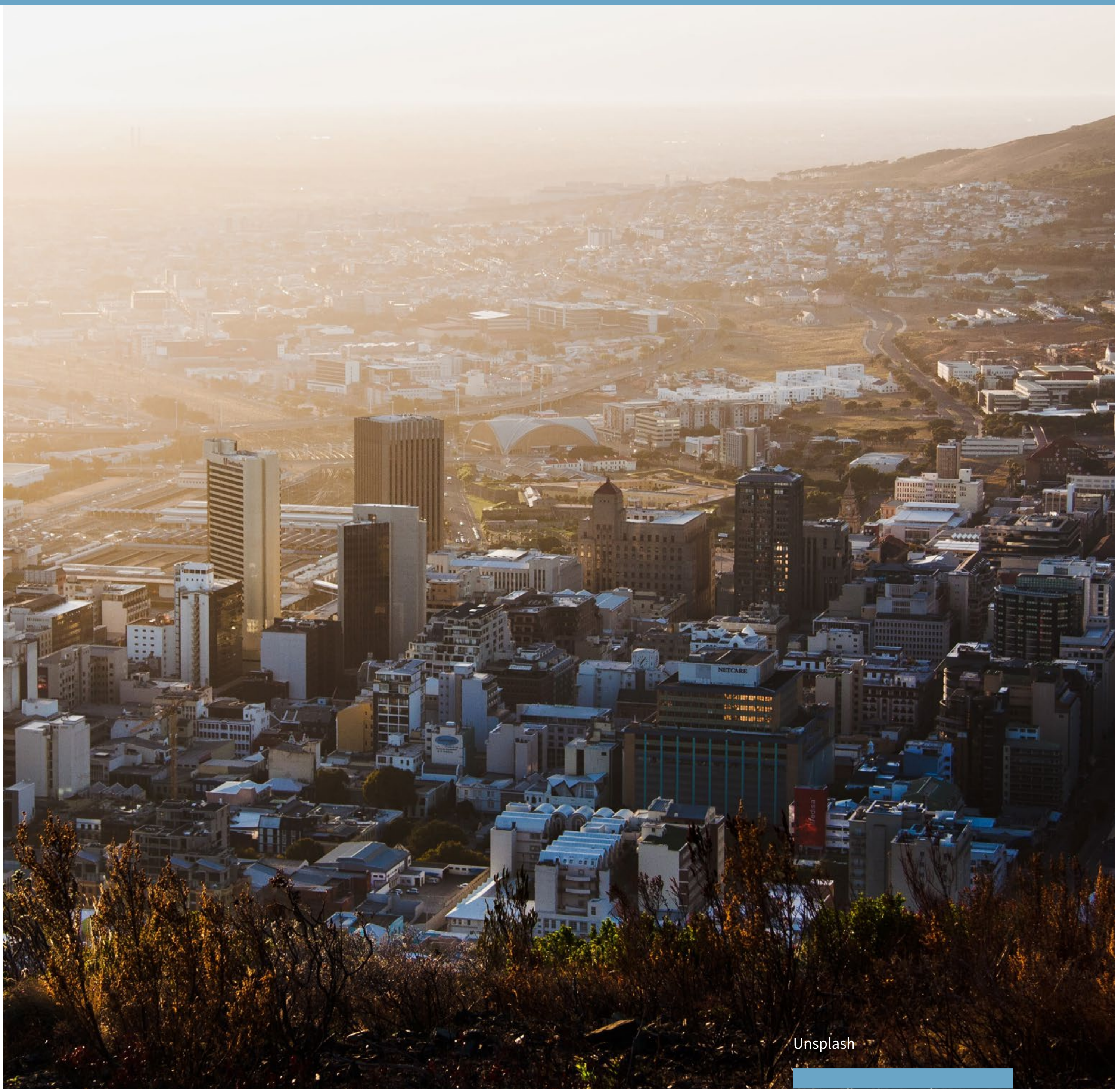
Chapter 5: Drought
Authors: Delia Sánchez Trancón (Organisation for Economic Co-operation and Development, Paris, France) and Harry Smythe (Organisation for Economic Co-operation and Development, Paris, France)
Reviewers: Brooke Demchuk (Organisation for Economic Co-operation and Development, Paris, France), Helen Laubenstein (Organisation for Economic Co-operation and Development, Paris, France), Marta Arbinolo (Organisation for Economic Co-operation and Development, Paris, France), Mikaela Rambali (Organisation for Economic Co-operation and Development, Paris, France), Simon Buckle (Organisation for Economic Co-operation and Development, Paris, France), Stephanie Lyons (Organisation for Economic Co-operation and Development, Paris, France), Taehoon Kim (Organisation for Economic Co-operation and Development, Paris, France), Xavier Leflaive (Organisation for Economic Co-operation and Development, Paris, France), Mónica García Quesada (International Water Resources Association, Paris, France) and Sung-Phil Jang (International Water Resources Association, Paris, France)

Chapter 6: Floods
Authors: James Miller (United Kingdom Centre for Ecology and Hydrology, Wallingford, United Kingdom) and Gianni Vesuviano (United Kingdom Centre for Ecology and Hydrology, Wallingford, United Kingdom)
Reviewer: Adeline Perroux (RWE, Swindon, United Kingdom)

Chapter 7: Heatwaves
Authors: Gerardo Sánchez Martínez (UNEP DTU Partnership, Copenhagen, Denmark), Julio Díaz Jiménez (Carlos III Health Institute, Madrid, Spain) and Cristina Linares Gil (Carlos III Health Institute, Madrid, Spain)
Reviewers: Mary Sheehan (Johns Hopkins University, Baltimore, USA) and Maya Negev (Haifa University, Haifa, Israel)

Contents

1. Introduction



Unsplash

“The battle for life on earth will be won or lost in cities.”

Ahmed Djoghlaf, Executive Secretary of the Convention on Biological Diversity under the United Nations Environment Programme (UNEP) until 2012.

Enhancing the development, transfer and uptake of technology is a key pillar of the international response to climate change. With funding from the Global Environment Facility and working through the UNEP DTU Partnership, the United Nations Environment programme supports developing countries in preparing their Technology Needs Assessments and Technology Action Plans within the global Technology Needs Assessment project. Since 2009, a hundred developing countries have joined the project, twenty-four in the Latin America and Caribbean region, thirty-seven in the African region, and thirty-nine in the Asia-Pacific region.

The objective of the Technology Needs Assessment project is to assess and articulate countries’ technology needs in relation to climate change adaptation and mitigation. Technology Needs Assessments provide information about the potential, ability and scale of climate technologies, and they can play a unique role in the formulation and implementation of Nationally Determined Contributions. They are a highly practical tool that provides an effective and solid foundation upon which developing countries can both scale up and implement action on climate technologies. Countries can therefore pursue both the targets they agreed under the Paris Agreement and their national Sustainable Development Goals.

Developed under and for the Global Technology Needs Assessment project, this guidebook focuses on climate change in urban contexts and outlines options that local governments can use in their efforts to manage climate change. It covers both mitigation and adaptation actions, and provides recommendations that are applicable in most contexts. Cities, including their governments, residents, communities and commercial and industrial actors, are indeed essential to building a sustainable future, and their active participation is critical to defining and implementing a system-wide technology transition locally, nationally and globally.

The United Nations estimates that the world’s population will grow from its current 7.7 billion to 8.5 billion by 2030. Across regions, this growth will be unevenly distributed (Table 1): whereas Africa’s population will grow fastest in the period to 2030, Asia will continue to have most of the world’s people. Europe will be the only continent to lose population, albeit only slightly.

By 2030, about three-fifths of the global population will be living in urban areas, twice as many as in 1950. Today, the Americas and Europe are the world's most urbanized regions; only Africa's population remains mostly rural, albeit by a small margin (Table 2).

Table 2. Urban population projections

Region	Urban population (percentage of total population)			
	1950	2000	2020	2030
Africa	14.3	35.0	43.5	48.4
Asia	17.5	37.5	51.1	56.7
Europe	51.7	71.1	74.9	77.5
Latin America and the Caribbean	41.3	75.5	81.2	83.6
Northern America	63.9	79.1	82.6	84.7
Oceania	62.5	68.3	68.2	68.9
World	29.6	46.7	56.2	60.4

Source: United Nations, Department of Economic and Social Affairs, Population Division (2018). World Urbanization Prospects: The 2018 Revision, Online Edition.

By 2030, the world will have 43 megacities, each hosting more than ten million inhabitants. However, the distribution of these megacities will be uneven: most of them will be found in developing regions, mainly in the poorest countries. At present the ten fastest growing cities are located in Asia (with the exception of Lagos in Nigeria). Close to half of the world's urban population resides in small cities with fewer than 500,000 inhabitants, while one in eight people live in 33 megacities. (1)

Cities are home to major consumption and production activities, making them large consumers of energy and major greenhouse gas emitters (2). The building and transport sectors constitute key greenhouse-gas emitting sectors in urban areas. Cities account for 40 percent of final energy consumption (3) and will generate more than 60 per cent of the world's greenhouse gas emissions by 2030. (4)

Cities are also increasingly facing major challenges from climate change impacts, including heatwaves, pluvial and river flooding, coastal flooding and coastal erosion, droughts and water scarcity, vector-borne diseases, wildfires and windstorms. (5)

In this context, cities have a rich opportunity to accelerate positive change by planning their spatial structures and reducing their ecological footprints. With growing population rates, and in the world's increasingly connected economy, the choices that cities make around energy, transportation and building standards have impacts beyond their boundaries. As such, cities can offer options for smarter choices within the energy, housing, transport, food, green space, water and waste sectors, among others. Around the world, cities are already taking independent action, often with innovative solutions, thus pushing governments to follow. (6)

Community-managed public spaces in Nairobi, Kenya (7)
Kibera is the largest slum in Nairobi and is located alongside the Ngong River. Kibera is home to more than 300,000 people and this slum is characterized by poor drainage and sanitation systems. The slum also has precarious housing and limited public space, with few city services reaching the neighbourhood. Due to climate change, the slum has experienced large storms and heavy rains. In addition, the slum faces flooding, sewage overflows and mudslides, with up to 40% of homes in the neighbourhood regularly experiencing flooding.

In 2006, the non-for-profit Kounkuey Design Initiative was launched in the slum with the goal to improve the drainage and sanitation systems. This initiative relies on participatory and step-by-step upgrades of existing infrastructure. Working with community-based organizations, the initiative created a network of public spaces where both built and natural infrastructure, including areas of restored riverbank. This helps protecting the community from floods and reduces pollution across the country's watershed. As such, co-created and managed by local residents, Kounkuey Design Initiative provides the slum's community with more than just flood controls.

This guidebook describes key mitigation and adaptation technologies that are of direct relevance in the urban context. Our goal is to provide city-level decision-makers with information about the technological options they have in mitigating greenhouse-gas emissions and adapting their cities to the impacts of climate change to which the world is already committed. Below is an overview of the sectors that are documented throughout the guidebook.

Adaptation

Drought. During the 21st century, climate change is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, thus intensifying the competition for water in cities. Technologies covered: smart water systems, blue-green infrastructure and sanitation, with in-situ reuse of reclaimed water.

Heatwaves. The increase exposure to high temperatures engendered by climate change can compromise the body's ability to regulate temperature, potentially resulting in a wide range of illnesses, including heat cramps, heat exhaustion, heatstroke and hyperthermia. Technologies covered: district cooling and cool roofs.

Floods. The changing climate is intensifying the hydrological cycle, driving more frequent and intense storms that lead to deeper and more prolonged flooding. Technologies covered: green roofs, retention and infiltration basin sustainable drainage systems, and flood-resilient buildings.

Mitigation

Transportation. The urban transport sector accounts for a significantly large and growing share of global greenhouse gas emissions, but urban transport also contributes substantially to other environmental and social problems, notably local air and noise pollution, road congestion and safety. Technologies covered: transit-oriented development, smart mobility and battery electric vehicles.

Buildings. In cities, buildings are foundational items, as they sustain all the city's key functions, from housing to services to communications. Nevertheless, buildings constitute the single largest contributor to global greenhouse gas emissions, accounting for a third of all energy-related carbon dioxide emissions globally. Technologies covered: great walls and green roofs, efficient heating ventilation and air conditioning systems, and photovoltaic panels.

Solid waste management. The municipal solid waste-management sector represents a major challenge for developing countries due to significant environmental and socioeconomic issues involving rapid urbanization, inappropriate practices and the existence of the informal waste sector. Technologies covered: integrated waste management, waste recycling and composting.

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2. Buildings

Unsplash

Buildings are foundational items of urban development, as they sustain all the key functions of a city, from housing to services to communications (1). What is more, today's urban areas transform and distribute energy, sustain biodiversity, and provide well-being to city dwellers (2). As such, buildings have become, more than ever before, the lifeblood of the world's fast-growing urban fabric (3).

Nevertheless, buildings currently face a number of challenges. First, buildings are the single largest contributor to global greenhouse gas emissions (4), accounting for a third of all energy-related carbon dioxide emissions globally (5). Second, building construction accounts for the greatest share of natural resource use globally. Urbanisation drives the loss of productive land, which affects both managed systems, notably agriculture, and natural systems (6). Third, solid and liquid wastes discharged from buildings, particularly for cooling purposes, cause local pollution (7). Fourth, building materials can increase temperatures in urban areas, especially where green spaces are scarce, thus creating the so-called urban heat-island effect, which has negative impacts on human health (chapter 7). Fifth, in many buildings indoor air quality is poor as a result of indoor biomass combustion and deficient ventilation, which increases the risk of illnesses such as asthma, pneumonia, tuberculosis, and premature death (8). Sixth, buildings are vulnerable to the effects of climate change (9), as a growing share of the building stock experiences reduced lifetimes (or the increased risk of collapse) due to adverse weather conditions exacerbated by climate change, such as extreme heatwaves, droughts, fires, and flooding (10).

Solutions to these problems are to be found in the way buildings are planned, built and managed. Indeed, buildings afford the greatest opportunity for delivering long-term, cost-effective greenhouse-gas emission reductions: if implemented today, existing technologies would make it possible to reduce up to 60 percent of the energy buildings will use by 2050 (11). Similarly, indoor and outdoor building pollution can be substantially reduced through readily available efficient heating, ventilation, air conditioning, and cooling systems, thus avoiding millions of chronic diseases and premature deaths each year (12). Passive cooling interventions such as shading, natural ventilation and heat sinks can also alleviate the urban heat-island effect (Chapter 7). Automated design and prefabrication can help reduce natural resource use while increasing the efficiency of the building sector's value chain.

Upgrading the building stock can lead to additional benefits beyond those associated with human and environmental health. From a macro-economic point of view, investments in upgrades to existing buildings can contribute up to 15 percent of national gross domestic product and 10 percent of employment worldwide. Work productivity can also increase through effective building design and improving the indoor air quality of workspaces (8). In light of the above, efforts to reduce global warming greenhouse-gas emissions from buildings represent not only a necessity but also an opportunity to boost economic growth and social development. Against this background, the objective of this chapter is to describe buildings' technological potential in respect of climate change adaptation and mitigation in urban contexts. To this end, key approaches to climate-conscious buildings are described along with potential technology solutions, highlighting some of the synergies with other components of the urban system (i.e., health, waste, transport, droughts and floods).

2.1. Overview of technology options

Buildings are complex systems in the form of still structures (13). The “optimal” composition of the system can vary significantly across regions and building uses. Nonetheless, efforts to identify such optimal compositions should in all cases treat a building as a unity – and in turn as part of the larger urban system – rather than a set of technologies or components. In fact, to obtain the necessary impact, a holistic approach will be needed that considers a bundle of these solutions along the whole lifespan of the building, including master planning, life-cycle assessment and integrated building design. In keeping up with this principle, this chapter describes solutions that help manage building energy use in urban contexts. Although the focus is on options that are relevant to developing countries, deciding optimal technology bundles will of necessity be region- and need-specific.

Broadly, mitigation typologies for buildings can be clustered into the following groups:

- Passive design strategies
- Nature-based solutions
- Energy-efficient building systems
- Behavioural energy consumption patterns
- Onsite renewable energy generation

Passive design strategies. In buildings, passive design refers to the use of natural elements to reduce or even completely remove the need for mechanical cooling, heating, ventilation and lighting (14). One example of passive design is the optimisation of spatial planning and orientation to control solar gains and maximise daylight intake, or employing the building structure and fabric to facilitate natural ventilation strategies. A second example is the use of thermal mass to reduce internal peak temperatures (15). In traditional architecture practices, this involves using natural materials to improve the cooling and/or heating properties of the building. In Baja California, for instance, traditional houses are built of adobe, a heat-absorbing material that, due to its high heat capacity, stores heat during the day and releases it at night, thus regulating indoor temperatures (16). In the Philippines, thatched buildings enable abundant ventilation and protection from the heat (17). In cold countries like Sweden, traditional architecture uses an airtight building envelope that avoids infiltration, as well as few and small windows, except on the south side, to increase solar intake while reducing heat loss (18).

Nature-based solutions. The phrase ‘nature-based solutions’ refers to building design options that mimic nature and/or rely on natural materials to reduce building energy use. In the urban contexts, nature-based solutions help sequester carbon dioxide, balance local and global carbon cycles, and protect biodiversity (19). They can do this through so-called ‘green and blue infrastructure;, respectively, tree, parks and hedgerows, among other vegetable-based elements, and rivers, canals and wetlands, among other water-based elements (20). Nature-based solutions are also relevant in the context of drought, for example (chapter 5).

Nature-based solutions for buildings can include (but are not limited to) green walls and green roofs, street trees and other green urban infrastructure that can be applied in both residential and commercial buildings. Other examples of nature-based solutions in building construction are timber and wood framing structures, wood for building envelopes and flooring, straw or hempcrete walls, insulating wood fibre-based sheathing, and cellulose-fibre insulation.

Energy-efficient building systems. Globally, the energy consumed for space heating and cooling accounts for up to 40 and 61 percent of the total energy demand in commercial and residential buildings respectively (21,22). Compared to older buildings, newly constructed buildings typically use more energy per square meter due to their energy-intensive air-conditioning and/or heating systems (17). The building elements that are most relevant to increasing the efficiency with which energy is used in a building include, but are not limited, to (26) the building’s envelope (namely, its roof, outer and foundation walls, and its windows); heating, ventilation and air-conditioning systems (mainly, heat pumps, water heating and cooling systems, convectors and coils, and energy storage); appliances, such as those found in most households; and lighting (mainly through LED lamps and smart metering systems).

The proper sizing, installation and maintenance of efficient heating ventilation and air conditioning systems can reduce energy demand (23,24). For instance, in the Unites States recent studies have shown that best practices in building maintenance and operations reduce energy use by 10 to 20 percent across all climate zones. In contrast, poor maintenance practices can increase energy use by 30 to 60 percent (25).

Behavioural energy consumption patterns. Building energy use can be reduced by managing the building occupants’ active and passive use of space, systems and other amenities that influence, among others, the energy used for space and water heating (27). These patterns include window opening, the use of solar shading and blinds, adjusting heating ventilation and air conditioning set points, and the use of hot water. There is ample evidence that, if not managed, behavioural energy consumption patterns increase the demand for energy (28). Therefore, through educational programmes targeting the behavioural aspects of building energy consumption, building energy use can be reduced significantly.

On-site renewable energy-powered electricity generation. Renewable energy-powered electricity-generating technologies can be placed on buildings (consider, for example, a set of photovoltaic solar panels on a rooftop). By providing alternative sources of electricity and heat, potentially in combination with energy storage technologies, reliance on these so-called distributed electricity-generating options can complement electricity supplied from the main grid (29). These technologies are especially relevant in the context of efforts to provide electricity to rural areas in developing countries. Kenya, for instance, is the world leader in the number of solar power systems installed per capita (30).

2.2. Selected technologies

The following paragraphs describe three technologies: green walls and green roofs; efficient heating, ventilation and air-conditioning systems; and photovoltaic panels. The selection is based on three considerations. First, in relation to the required investment, these technologies have the potential to achieve large energy savings in buildings. Second, all three technologies are relevant to urban contexts in developing countries. Third, these three technologies have been identified as having the greatest impact.

2.2.1. Green walls and green roofs

Scope of the technology

In the context of buildings, green walls and roofs are among the most relevant nature-based solutions, mainly due to their ability to reduce building energy demand and the carbon sequestration capacity of the plants and substrates they uphold (31). Green walls and roofs are especially suitable for consolidated urban areas, where the space available for new green infrastructure is limited or non-existent (32).

Although their capabilities vary depending on the natural species selected, it is estimated that green surfaces can provide annual emissions reductions of the order of 0.5 kilograms of carbon dioxide per square metre (33). Likewise, a number of quantitative studies have demonstrated the impact of lowering urban temperatures and increasing humidity when the building envelope is covered with vegetation. This is particularly relevant in warm and dry regions, where green walls and roofs help reduce temperatures, thus limiting the use of ventilation and air-conditioning systems, preventing urban heat-island effects, and contributing to managing droughts (chapter 5). Similarly, humid climates can also benefit from green surfaces, especially when both walls and roofs are covered with vegetation (34).

Ancillary benefits of green roofs and walls

The benefits of a green envelope go way beyond reducing emissions and balancing urban temperatures. Indeed, green roofs and walls are reported to increase the well-being of urban residents, while contributing to ecological stewardship and safeguarding biodiversity. Further, they enhance the aesthetic value of the urban landscape, improve building performance, increase real estate values, and promote recreational building use (35–37).

The potential benefits of green roofs and walls in terms of quality of life and well-being can be achieved in a number of ways. One is through air purification, because a suitable choice of urban vegetation will be able to collect fine dust and improve air quality (38), thus helping prevent respiratory disorders (39). In addition, contact with nature has been shown to contribute to humans' physical well-being (for example, by reducing blood pressure, heart rate and muscle tension, and by producing stress hormones) (40). Finally, when they are accessible to the building's occupants, green roofs can create a space for physical activities, thus preventing sedentary lifestyles and related diseases, notably obesity (39).

In terms of costs, the installation and maintenance of green roofs and walls might incur higher initial costs than most conventional building cladding systems. However, when environmental and social benefits are monetized during the building's life-cycle, green roofs and walls become economically attractive (41,42).

Barriers to adoption

The uptake of green roofs and walls faces several barriers (Table 1), which are more prominent in developing countries. Across regions, the lack of finance is a pervasive barrier, which arises mainly as a result of the limited public awareness about the cost-benefit ratios of nature-based solutions (43). Limited coordination across institutions and a certain inertia in management approaches represent further barriers to the uptake of green roofs and walls (44), as different public departments and/or institutions operate on the basis of distinct visions, goals and legal structures (45). Arguably, identifying appropriate indicators and metrics to quantify the socio-economic and/or environmental effectiveness of green surfaces would help break down these barriers (20).

Table 1. Selected barriers to green roofs and walls

Category	Barrier
Economic and financial	(Perceived) high initial capital investment
	Lack of available financial resources
	Lack of knowledge of financial incentives
Market conditions	Property ownership, split incentives and bureaucracy
	Risk aversion and resistance to change
	Lack of public awareness and support
	Few local reference examples
	"Siloed" thinking and institutional arrangements
Legal and regulatory	Lack of support policy and legal frameworks
	Lack of political will and long-term commitment
Human capacity	Lack of skilled knowledge brokers and training programs
	Lack of design standards and guidance for maintenance and monitoring
Technical	Functionality and performance uncertainties

Source: Own elaboration. Clara Camarasa (UNEP DTU Partnership, Copenhagen, Denmark) adapted from Sarabi S, Han Q, Romme AGL, de Vries B, Valkenburg R, den Ouden E. (45)

Enablers to adoption

Due to the fragmented nature of the construction industry's value chain, no single stakeholder holds the key to the large-scale uptake of green roofs and walls. Rather, there is normally a whole cohort of such stakeholders, starting with architects. Architects are responsible for the conception of a building's envelope, and therefore for the integration of nature-based solutions in the building's design plans. An architect's local knowledge can help ensure that green roofs and walls suit the local context, increasing the likelihood that these nature-based solutions will be accepted and ultimately successful. Building owners, on the other hand, must create a demand and promote the appropriate use and maintenance of green roofs and walls to ensure continuity. To establish this demand, conducive regulatory frameworks are needed in the form of building codes, standards and/or guidelines. Furthermore, national and local governments should increase awareness of the benefits of green roofs and walls, as well as sharing know-how on their implementation. In some jurisdictions, financial instruments, such as tax incentives, may be needed to support the upscaling of these solutions.

Trade-offs

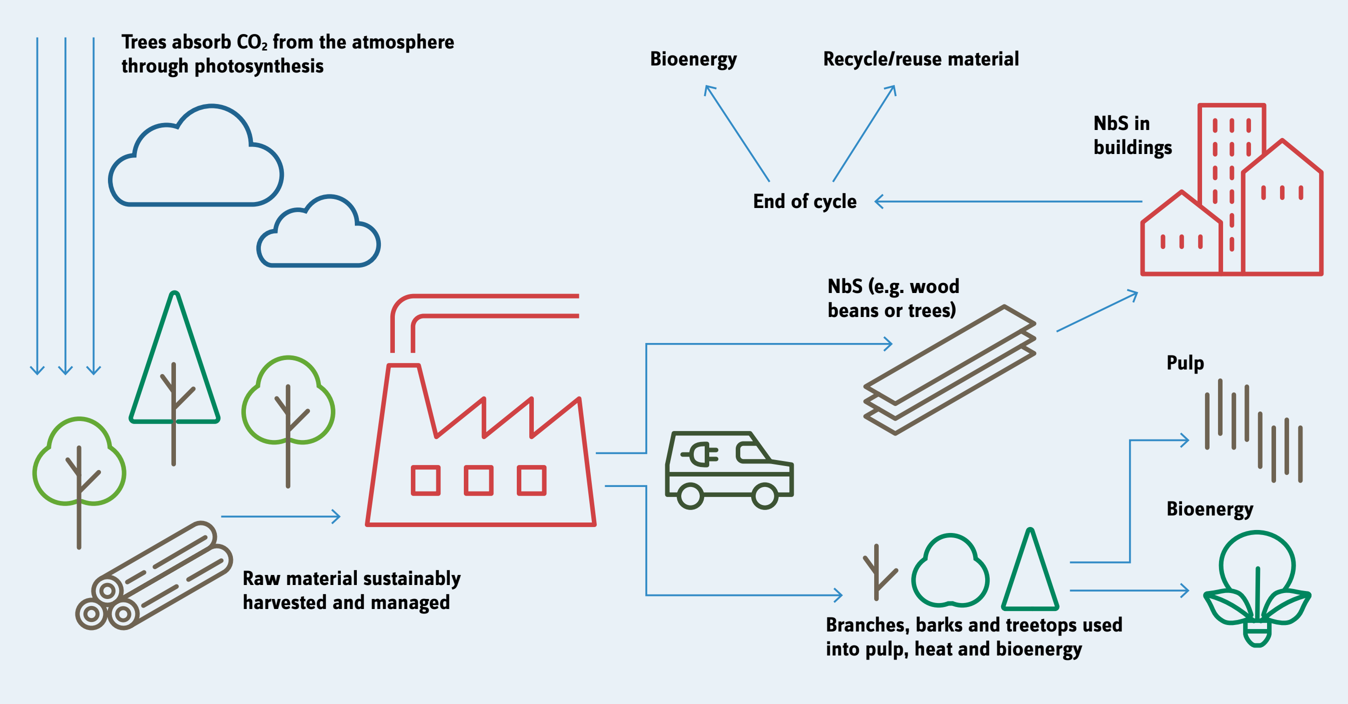
Unintended negative impacts can arise if species with low biodiversity values are promoted, as they can displace natural species, thus altering ecosystem balances (20). Likewise, it is important to avoid planting allergenic species. Otherwise, the respiratory benefits might become negative impacts. A further potential trade-off concerns the broader cradle-to-grave impacts of the products and processes involved in the manufacture and installation of green roofs and walls. As for any building material or construction practice, these products and processes result in environmental (and social) footprints in the form of the energy and materials used and recycling and disposal requirements, among other issues (46). If this footprint is not duly assessed (Figure 1), green roof system components (for example, the substrate and the water-proofing membrane) may cause more emissions during their life-cycle than they actually capture (33). Green roofs may also require additional maintenance compared to conventional or cool ones, as well as irrigation, which may be a problem in water-scarce contexts. Conversely, a positive impact can be achieved when the whole lifespan of the building solution is taken into consideration.

2.2.2. Efficient heating ventilation and air conditioning systems

Scope of the technology

Worldwide, building energy use represents a significant share of final energy demand. In developing countries, improved energy access and a greater use of energy-consuming devices has led to heightened energy use in buildings (4,47). Efficient heating, ventilation and air-conditioning systems for buildings have the potential to reduce carbon-dioxide emissions by up to two giga-tonnes globally and save 710 million tonnes of oil equivalent of energy by 2050 as compared to non-energy-efficient systems (48).

Figure 1. Life-cycle of carbon sequestration in buildings for nature-based solutions in buildings



Source: Own elaboration. Clara Camarasa (UNEP DTU Partnership, Copenhagen, Denmark), 2021.

Mitigation benefits

Beyond the decrease in energy demand and associated greenhouse-gas emissions, efficient heating, ventilation and air-conditioning systems offer a wide array of additional benefits. First, compared to traditional systems, efficient systems last much longer and require less maintenance. Second, levels of hazardous gases are reduced, notably carbon monoxide, carbon dioxide, sulphur dioxide, nitrogen oxides, ozone, radon and volatile organic compounds, for which efficient systems offer comparatively higher indoor-air quality. For instance, volatile organic compounds or unbalanced levels of carbon dioxide can cause headaches, dry coughs, dizziness, nausea, tiredness, and eye, nose, and throat irritations. Third, when combined with building automation and control systems, efficient heating, ventilation and air-conditioning systems can be used to detect potential threats associated with natural accidents, human error or terrorism, as well as chemical, biological, radiological, and explosive incidents that cause major structural damage to the building or its infrastructure.

Barriers to adoption

There are several barriers to the more wide-spread deployment of efficient heating, ventilation and air-conditioning systems. These barriers relate to economic and financial considerations, market conditions, legal, regulatory and institutional capacities, human capacities, and awareness and information (Table 2).

Enablers to adoption

A rising demand for technologically advanced heating, ventilation and air-conditioning systems is expected to drive the market growth of these technologies. Demand-side actors such as owners of private and public buildings are often identified as the main decision-makers in the adoption of this technology. However, recent studies demonstrate

Table 2. Selection of barriers to heating, ventilation and air-conditioning systems

Category	Barrier
Economic and financial	Perceived high initial capital investment
	Long payback times due to low energy prices
	Perceived financial disincentives: perception of investment as costly and risky, and split economic interests among stakeholders due to fragmented value chain
	Limited knowledge about investment horizons, risks, and life spans
Market conditions	Fragmented building-sector value chain
	Limited awareness of available technical capacity and potential ancillary benefits
	Technology lock-ins
	Lack of interest in future energy-sector issues
Legal and regulatory	Lack of regulation against rent-seeking behavior
	Inappropriate or lack of a regulatory framework (e.g., building codes and standards)
Institutional and organizational	Limited institutional capacity
	Limited management and organizational skills
	Lack of interconnection regulations and grid access limitations
Human capacity	Unskilled technical personnel
	Lack of inadequate technical capacity
Information and awareness	Fragmented or lack of information
	Lack of awareness of the technical capacity and benefits

Source: Own elaboration. Clara Camarasa (UNEP DTU Partnership, Copenhagen, Denmark)

that they are not the only decision-makers involved in the technology selection: engineers, installers and construction companies also have a high level of interest and influence in this process (49). Nonetheless, a conducive policy environment is needed for these groups to be able to promote efficient heating, ventilation and air-conditioning systems. Therefore, public authorities ought to reform regulatory frameworks, develop educational and awareness-raising programmes, and introduce appropriate financial incentives.

Trade-offs

The proper sizing of efficient heating, ventilation and air-conditioning equipment is one of the most important processes in terms of appropriate energy use in a building. An oversized unit can lead to energy waste, high costs over time and uncomfortable inner temperatures, all of which are the opposite of what these systems intend to achieve (50). To avoid these unintended negative impacts, it is important to conduct thorough assessments of the capacity required, given the needs and use of the building. Another important aspect to consider is the building's use. In order to be effective, heating, ventilation and air-conditioning systems require periodic maintenance to improve their lifespan and efficiency. Maintenance should be combined with adequate occupant behaviour practices on energy use to ensure sustained reductions in energy consumption (51,52).

2.2.3. Photovoltaic panels

Scope of the technology

Small-scale solar photovoltaic panels – typically placed on rooftops – are key components of net-zero energy-building strategies (53). Solar photovoltaic panels transform sunlight into direct-current energy. Through an inverter, direct-current energy is converted into alternate current energy.

Mitigation benefits

Rapid technological developments and related cost reductions have made solar photovoltaic systems, and therefore electricity, more accessible in places where they used to be absent. In developing countries, two features of these systems have helped increase their uptake. First, most developing countries are located at latitudes with high solar irradiance. Second, solar photovoltaic systems are relatively affordable and suitable for both homes and energy communities (54).

The advantages of solar photovoltaic panels extend far beyond the buildings' energy use. When placed on a grid-connected roof, they produce electricity at the site of consumption, thus avoiding losses during grid transmission and helping utilities meet broader demand by feeding surplus electricity into the grid. Selling excess electricity back to the grid provides revenues that should be taken into account in making financial decisions over whether or not to install solar photovoltaic systems on a building. Not least, the widespread development of solar panels that green buildings are favouring has helped the solar energy industry create jobs around the world: in Bangladesh, for instance, home solar systems have generated 115,000 direct jobs and 50,000 more downstream (2). Furthermore, the deployment of solar photovoltaic systems goes hand in hand with the growth of the electric vehicles industry (55,56). Thanks to the relentless advances in energy storage, energy-sharing between buildings and electric vehicles is becoming a reality. Indeed, in the near future, building designs are likely to include (private) charging stations for electric vehicles (chapter 3).

Barriers to adoption

At present, solar photovoltaic panels provide less than two percent of the world's electricity, but modelling shows that they could contribute 4.9 Gigatonnes of carbon dioxide emissions reductions in 2050, representing 21 percent of the overall energy-sector emissions reductions needed to meet the Paris Agreement's climate goals (57).

Despite the growth in solar photovoltaic system-powered electricity generation and emissions reduction potential, financial barriers, notably high capital costs, long payback times and risks, still hinder their adoption, particularly in developing countries

(58). Indeed, lacking policy inducements, solar photovoltaic systems are not profitable in some contexts.

Enablers to adoption

Empirical evidence across various regions reveals that government incentives to strengthen the solar photovoltaic market in frontrunner countries is having a positive impact on developing countries. Governments can be key enablers of this technology in a number of ways. To bridge the higher upfront costs compared to fossil-fuel based technologies, governments are relying on direct capital subsidies, tax incentives, storage incentives and/or incentives for electric vehicles. They can also leverage market barriers by creating synergies among enablers.

Trade-offs

The operation of solar photovoltaic systems presents few environmental shortcomings. Conversely, the manufacture of these systems produces hazardous substances (notably arsenic and cadmium), water pollution, and emissions of air pollutants (59,60). Counterbalancing these negative effects requires actions across the whole value chain. Technology developers are working to reduce or avoid the unintended negative impacts mentioned above. In parallel with this, solar photovoltaic system installations should be properly planned, notably with regard to their siting, and they should be maintained adequately so as to keep them in service for as long as technically possible. Finally, end-of-life recycling and disposal procedures should be in place locally.

2.3. Key policy-related issues

Regulations for energy efficiency in buildings in developing countries, especially in rapidly developing economies such as India and China, are designed to improve comfort and reduce the sharp increase in building energy use. However, the efficiency standards included in building codes rarely represent the optimum for efficiency, and builders and designers rarely have an incentive to exceed the standards set out in the codes or to come closer to that optimum because higher standards mean lower profits. For this reason, more stringent energy-efficiency requirements should be introduced for new buildings.

Another important policy consideration in relation to climate-mitigation policies in buildings is related to the fact that these typically cover the interest of specific stakeholder groups in the building value chain. Due to the fragmented nature of the construction industry's value chain, so-called split incentives, where the party that has the power to introduce change has no incentive to do so, hinder the adoption of stringent climate change-mitigation technologies.

Green walls and green roofs. Building regulations can support increasing installations of green walls and green roofs by considering or representing them in building codes and standards. Currently, building codes across the world are largely anthropocentric, hence nature-based solutions such as green building elements are typically not featured (61). For building regulations to effectively support green walls and green roofs, natural species need first to be recognised as necessary within a shared urban habitat before being integrated into urban activities across all building-development processes. This will require both awareness-raising of the need for their preservation and a stronger understanding of local natural ecosystems and how these can be integrated into building design.

Efficient heating, ventilation and cooling systems. There are a number of policy-related aspects to consider in relation to energy-efficient heating, ventilation and cooling systems. First, there should be a policy of introducing energy consumption limits in large buildings. Second, with reference to indoor air quality, a reference indoor air renovation rate should be devised and pollutant concentrations inside buildings should be limited. Third, in terms of a system's units design, the system's installed power should be limited and a number of energy-efficiency requirements introduced for the design of new systems. Another important aspect concerns maintenance of the systems: periodic energy audits, including inspections of boilers and air conditioning systems, should be mandated. In addition to the foregoing, regulations on thermal the behaviour of buildings should define the requirements for buildings without heating ventilation and air conditioning systems (for example, wall and floor insulation, types of glass coverings and surfaces, limiting heat loss and controlling excessive solar gains). Furthermore, regulations should set limits for the energy requirements for air-conditioning and hot water production, making it compulsory to install solar energy systems and favouring the use of other sources of renewable energy (62).

Photovoltaic systems. In order to incentivise the adoption of photovoltaic systems, self-consumption schemes should be as comprehensive and as simple as possible. Consumers and "prosumers" (that is, electricity consumers that produce some of their electricity needs from their own power plants, use the distribution network to inject excess production, and withdraw electricity when self-production is not sufficient to meet their own needs) should be provided with all the necessary information to calculate the incomes and costs that are relevant to the distributed generation. Self-consumption schemes with or without decentralized storage should be permitted and enforced by renewable energy laws or other applicable legislation addressing all relevant stakeholders, from utilities to prosumers. In addition, tariff design should be flexible and adjusted in a timely fashion to allow additional customer classes and effective billing and reporting systems to be established (63). To enable this, policy instruments should create rate structures or incentive programs so that system owners can be compensated for the variety of benefits and services provided by energy storage associated with distributed solar energy.

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3. Transport

Unsplash

In 2019, before the COVID-19 global health pandemic altered production and consumption patterns, the transport sector accounted for around 24 per cent of energy-related carbon dioxide emissions worldwide (1). Out of this, road transport accounts for three-quarters of emissions and urban transport accounted for halft of these emissions (2). Not least, urban transport results in additional negative social and environmental impacts, such as local air pollution (through emissions of nitrogen oxides and fine particulate matter, among other health-impairing substances), noise pollution, road congestion, and risks to safety (3). Compared to reducing greenhouse-gas emissions, managing these additional social and environmental impacts are of more direct concern to urban decision-makers. Local air pollution in many developing-country cities is a case in point.

In this chapter, we focus on technologies and practices to reduce greenhouse-gas emissions from urban passenger transport. Decarbonizing transport involves (i) behaviour and lifestyle changes and (ii) new and cleaner technologies and fuels (4).

3.1. Overview of technology options

Technologies and practices for urban transport that are relevant for mitigation are often categorized according to the so-called "avoid, shift and improve" framework, with which a combination of interrelated mitigation options in the context of transport services can be examined (5). The 'avoid, shift and improve' framework envisages the reduction of greenhouse-gas emissions through i) avoiding travel as far as possible, ii) shifting unavoidable demand to more efficient modes of transport, and iii) reducing the greenhouse-gas intensity of the technologies used to meet the demand for travel (4). Table 1 lists key strategies to achieve the three goals above, indicating technologies and practices that can be used to operationalize each strategy.[1]

3.2. Selected technologies

In the following sections, we document three technologies that can be implemented easily because they revolve around mature practices. Each of these technologies covers one element of the avoid-shift-improve framework. Although each of the three selected approaches can be considered in isolation from the other two, they complement one another well. For each technology, we describe its scope, its alternatives, the barriers to and enablers of its implementation, and its applicability in a developing-country context.

3.2.1. Transit-oriented development

Scope of the technology

Worldwide, transit-oriented development is one of the most widely recognized urban-planning concepts. Essentially, transit-oriented development involves a transit corridor (typically, a rail or bus station) that is within walking distance of a dense, pedestrian-friendly network of residential, business and leisure spaces (Box 1). As such,

1
It is worth noting that the categorisation is not fixed. Indeed, a strategy listed under "Avoid" may also be appropriate in the context of "Shift". For example, whereas dense and mixed-use urban design can help reduce trip lengths, it also help make a city more public transport-friendly.

Table 1. Avoid–Shift–Improve related strategies

ASI Lever and Objective	Strategy	Technology and Practices
Avoid long and unnecessary motor-vehicle trips	Dense and mixed-use urban design	Renovation of historic districts and downtown areas
		Transit-Oriented Development
		Integration of land-use and transport planning
	Use of information technologies to reduce trips	Tele-work, virtual meetings through improved connectivity and internet access
Shift individual motorization towards public transport, cycling and walking	Improved facilities for cycling and walking	Recovery of invaded sidewalks and public spaces
		Rehabilitation of waterfront sidewalks with adequate design, urbanism and furniture
		Cycle ways and cycle lanes, safe cycle parking
	Improved public transport systems	Road-based (BRT, Buses, Trackless Trams)
		Integrated Systems (Ticketing, Planning)
		Rail based (Metro, Trams)
		Cable cars
	Smart mobility	Car sharing & Ride Hailing
		Autonomous vehicles
		Intelligent Transport Systems
	Disincentives on individual motor vehicle use	Taxes on fuels and registration
		Administrative restrictions (using plate numbers)
		Road pricing (Urban tolls, Congestion Pricing)
Improve technologies and transport-management systems	Increase share of clean and low-carbon fuels	Biofuels, Compressed Natural Gas (CNG) and Synthetic Fuels (Power to X)
	Increase share of clean and low-carbon vehicles for road-based transport	Hybrids & Plug in Hybrid
		Battery Electric Vehicles (Buses, Cars, 3 Wheelers, 2 Wheelers)
		Fuel-Cell Hydrogen Vehicles
	Improved management	Technical inspection programs, including air pollutant controls
		Traffic control networks, centralized dispatch and control of transit services

Source: mainly adapted from Hidalgo and Huizenga (5) and updated by authors for emerging trends in the last seven years

Note: The entries in bold correspond to the technologies (or groups of technologies in the case of "smart mobility") described in the reminder of this chapter.

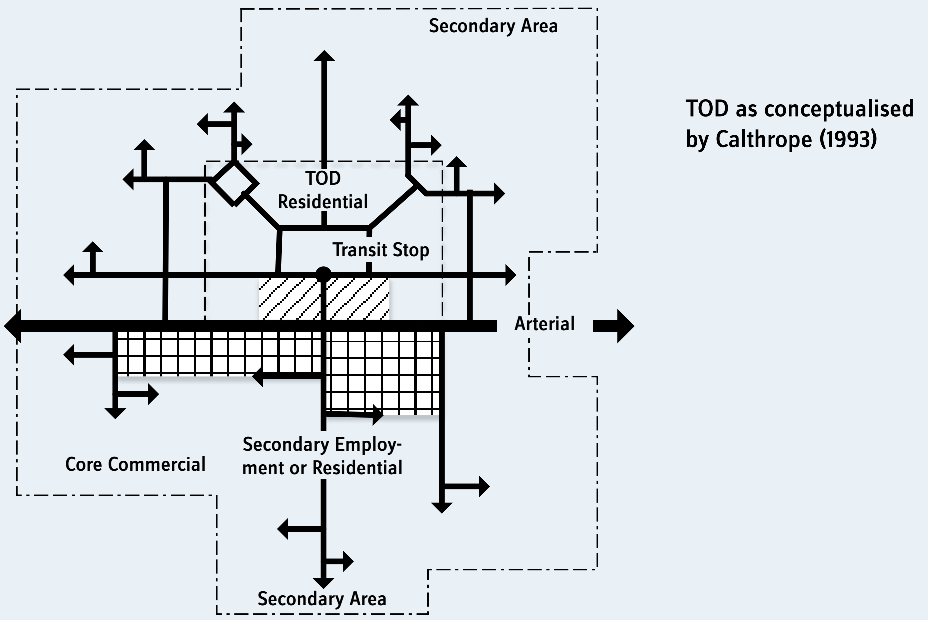
transit-oriented development discourages car use and promotes public transport, walking and cycling.

The evolution of transit-oriented development
In 1952, Stockholm's local authorities adopted the urban development approach that later became known as "transit-oriented development". The approach involved communities that were within walking distance of a Tunnelbana station, Stockholm's underground rail network. These communities had both access to key services and high-density residential spaces (6).

However, transit-oriented development as a concept only became prominent in 1989, with the adoption of the so-called Bay Area rapid transit system in San Francisco. This was a system in which land-use mixtures and densities were suggested as a way of increasing transit ridership. Figure 01 shows its conceptual design (7), whereby transit-oriented development is designed to create a mixed-use community within an average of ten-minute walking distance from a transit stop and core commercial area.

Over the years, the modern concept of transit-oriented development has remained unchanged: "careful coordination of urban structure around the public transport network and public transport nodes (stations and interchanges) in particular" (6). In another, more specific definition, transit-oriented development is described as "land-use and transportation planning that makes cycling, walking, and transit uses convenient and desirable, and that maximises the efficiency of existing public transit services by focusing development around public stations, stops, and exchanges" (8).

Figure 1. Transit-Oriented Development (7, 10)



Source: Own elaboration. Subash Dhar (UNEP DTU Partnership, Copenhagen, Denmark) and Talat Munshi (UNEP DTU Partnership, Copenhagen, Denmark) adapted from Calthrope (1993) (drawing not to scale)

Depending upon the context or location, transit-oriented development will revolve around different types of nodes. For example, the node may be a core centre (that is, a primary centre for economic and cultural activities), a local centre (that is, a secondary of neighbourhood centre for economic and cultural activities) or a destination (9) (10).

Denser and more mixed land-use development patterns can result in a good mix of activities (land uses) with convenient walking distances, making it quicker to reach destinations using non-motorized modes of transport. By reducing the need to use cars it frees up space which can be used for public transport, non-motorized transport or for other land use purposes (11). Moreover, it reduces the pressure on land by increasing land consumption with infill and introducing high-density mixed-use development, thus reducing the need to build on the urban fringes (12). Transit-oriented development minimizes fuel consumption, air pollution and transport-related greenhouse gas emissions by reducing dependence on motorized transport.

Transit-oriented development also results in compact cities if it is used as a citywide strategy and not a standalone project on a selected transit corridor. Thus, transit-oriented development reduces the cost burden on municipalities, as they are not required to provide and manage additional infrastructure for the sprawling cities (13, 14). The other benefits also include gains in gross domestic product, resulting from increases in employment and land values.

Mitigation benefits

Creutzig et al. (15), in their study, estimated the mitigation potential of urban planning to be about 25 percent in 2050 compared to a business as usual scenario. City-based assessments, however, are more optimistic (Table 2) indicating that transit-oriented development projects result in considerable greenhouse-gas emissions reductions.

Table 2. Mitigation benefits of the technologies in multiple cities

City	Reference	Mitigation benefits
Rajkot	Munshi, Shah (16	Transit oriented development strategies implemented in Rajkot can reduce carbon-dioxide emissions by 47 percent in 2030 compared with the business as usual scenario.
Curitiba	Jin (16)	Daily per capita carbon-dioxide emissions from transport in Curitiba are 220 grams per person and day which is very low compared to country's average of 2,600 grams per person per day[a].
Bogota	Hook, Kost et al (18)	Saved 69,000 tons of carbon-dioxide emissions from the 42 km bus rapid transit phase II network.
Mexico City	Hook, Kost et al (18)	Savings associated with the 20 km long MetroBus in Mexico City, are estimated at up to 26,000 tons of carbon-dioxide per year
Jakarta	Hook, Kost et al (18)	Carbon-dioxide savings of bus rapid transit are 3.15 to 3.26 million tons per year

[a] *Source: EA. World Energy Outlook 2017. Paris: International Energy Agency; 2017*

In most countries, especially developing countries, access to public tranpsort is often seen as benefiting the urban poor. However Transit-oriented development plans have been been challanged on the grounds that they can cause gentrification and displacement (19). If Transit-oriented development is implement without limiting the access for private automobiles, these type of development can actually intensify (because of the density) the number of private automobiles used in the areas and worsen the air quality (20). Thus cities must use transit-oriented development to encourage transit and discourage the use of private automobiles.

Trade-offs and linkages with other sectors

Transit-oriented development is an urban design concept that complements other measures to decarbonize transport. It also involves changing the cityscape and defines the investment that orients the urban form that supports public transportation, thus encouraging residents, jobs and shopping to congregate around transit nodes. It is well known that land-use changes take a long time to materialize. Therefore, although transit-oriented development has apparent benefits, the carbon dioxide savings will occur at a much slower rate than investments in other transport technologies, such as non-motorized transport infrastructure and electric vehicle infrastructure.

The carbon-dioxide benefits associated with transit-oriented development also depend upon the capacity of the transit corridor. For example, transit-oriented development around a bus-rapid transport line will have lower density and less holding capacity than a transit-oriented development around a metro line. Further reductions linked to a bus-rapid transport system will depend on the fuel used and bus efficiency. If electric-drive vehicles are used, the carbon intensity of electricity will determine the eventual carbon dioxide savings. However, as stated earlier, public transport systems cannot function as independent entities. Modern-day smart cities draw links between other green transport technologies, urban planning etc., in planning transit-oriented development (17).

Barriers to adoption

Transit-oriented development is an urban planning concept that involves upfront costs, which are huge in most cases and involve constructing properties, transport infrastructure and other associated amenities. The total costs associated with implementing such projects differ from case to case, and depend upon the cost of infrastructure construction in the country concerned. In India's Dwarka transit-oriented development project[2] in Delhi, the cost is estimated at around 167 million USD. The project is expected to recover its costs (including the cost of debt financing) and return an equity internal rate of return of 3 percent over the 35 years of the project (assuming inflation of 5 percent per annum). The cost of providing a transit-oriented development in London ranges from 250 million USD (bus-rapid transit) to 1.02 billion (light-rail transit); it is estimated that the benefit to cost ratio of the bus-rapid transit option is (1.6) $1.6 benefits for every $1.0 spent, and 0.8 for the light-rail transit option.[3]

Brownfield[4] transit-oriented development can be challenging to implement compared to greenfield development. In brownfield transit-oriented development, the current

2
https://www.smartvizag.in/wp-content/uploads/2017/12/Transit-oriented_Redevelopment_of_the_Dwaraka_Bus_Station_Feasibility_Study_Final_Report.pdf

3
https://d3n8a8pro7vhmx.cloudfront.net/shiftlondon/pages/129/attachments/original/1464886814/Shift-Final-Business-Case.pdf?1464886814

4
Brownfield development involves transit-oriented development in an already built-up area where a transit project is envisaged or under implementation.

development has to give way to the new transit-oriented development, if development is to occur. Therefore, in addition to redevelopment costs, one has to consider the added costs involved in relocating the existing residents, jobs and shops to a new location. Many cities in the developing world use added floor area and development rights to cover the cost of redeveloping and developing transit-oriented development areas. However, this approach can increase rents and property prices, pricing out middle- and low-income residents. Studies have also found that most high-income residents are captive car riders, suggesting that there is a risk of transit-oriented development mechanisms serving the real estate market rather than the chosen goal of increasing transit use, especially in the developing world.

Enabling policies also have to circumvent the avoid-shift-improve framework introduced earlier. Many countries do not have any provision for micro-level planning. Thus urban planning norms might have to be amended to allow for station area plans. The development control regulation will also need to change to allow for the design, densities, diversity and constrained parking and access of private automobiles envisaged in transit-oriented development.

Relevance for developing countries

Many developing countries are augmenting their public transport infrastructure[5]. Despite the barriers mentioned above and the long gestation period, transit-oriented development has apparent benefits, which is also the reason why cities have turned towards transit-oriented development. For example, in India, thirteen cities have plans for transit-oriented development, and NIUA estimates there is transit-oriented development in eighteen Indian cities. (18) In the developing world, these are the most rapidly sprawling cities, which must re-engineer and optimize their use of space to keep developing. In many developed countries, transit-oriented development is also used to redevelop declining urban areas. The environmental benefits of transit-oriented development are also a driver in cities where air pollution is a major problem. Thus transit-oriented development is most important for its contribution to urban growth and development and its benefits to the environment.

3.2.2. Smart Mobility

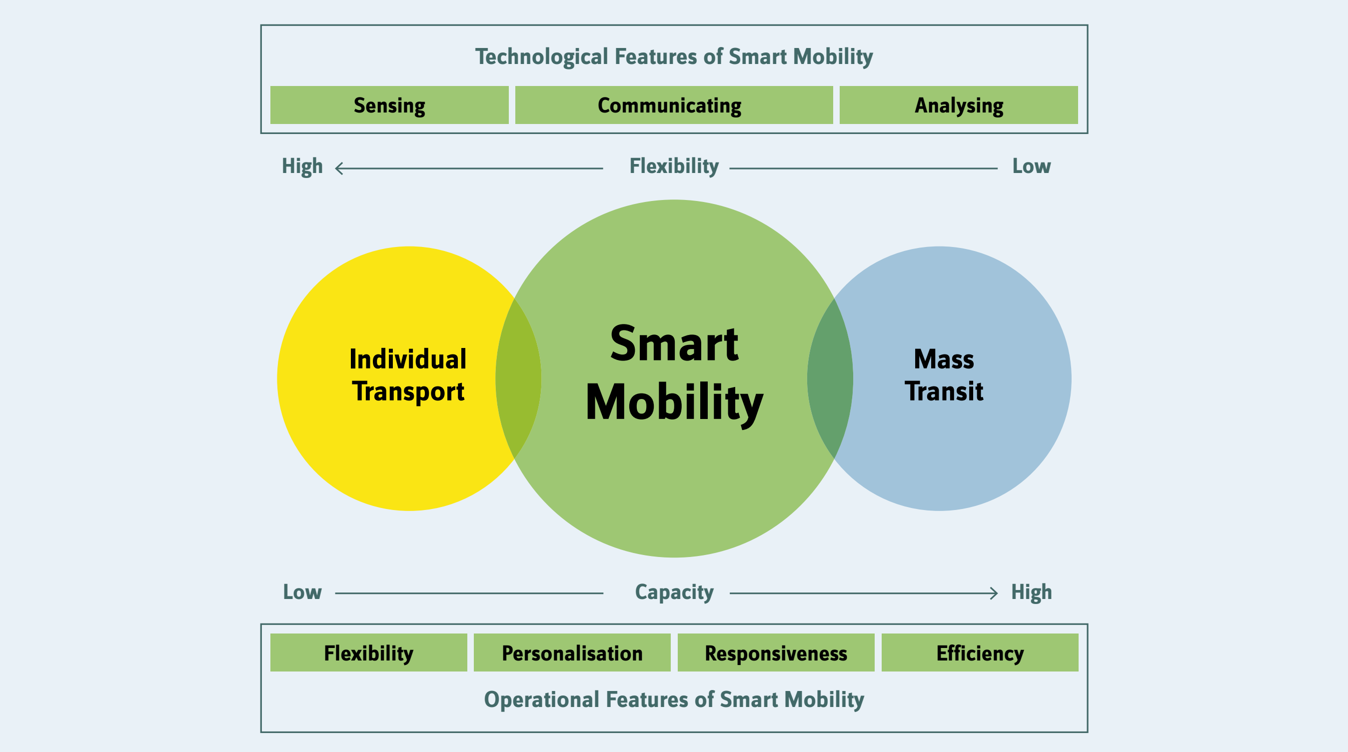
Scope of the technology

The process and practices whereby information and communication technology and other hi-technology innovations are adopted by transport are generally referred to as smart mobility (Noy and Givoni, 2018). Smart mobility solutions focus issues related to safety, transport management and the environment, including decarbonizing transport.

Mobility solutions are primarily viewed as either individual or collective (mass transit). Individual solutions offer a high degree of flexibility to users, although with low efficiency. Conversely, collective solutions have low flexibility and high efficiency (Figure 2).

5
Today 177 cities have bus-rapid transport systems, most of which are being implemented in Latin America (fifty-seven) or Asia (forty-five). In Africa, so fa only five cities have bus-rapid transport systems, although many more plan having them. It is important for the sustainable development of cities with bus-rapid transport systems (and many other cities with metro systems) that development around transit stations is carefully planned.

Figure 2. Smart mobility and its features



Source: Borysov, Azevedo et al. (19)

Disruptive technologies like smart-phones, high-speed mobile internet and the prevalence of sensors have allowed an interplay of solutions that have helped customize and design both individual and collective mobility solutions to suit individual travel needs. The number of smart mobility solutions is diverse and broad, ranging from on-demand mobility solutions (for example, car-sharing or bike-sharing) to integrated solutions (such as mobility as a service, or apps for informed multimodal trip-planning) (19).

The three main areas that have opened the smart mobility era are sensors, information and communication technology, and computer science developments (data science and artificial intelligence in particular). These three areas define mobility "smartness", which can be formulated as "sensing—communicating—analysing".

A modern car has sixty to a hundred sensors onboard (19), which help monitor all information, starting from the hardware function like fuel consumption and engine performance to assisting the driver with navigation and driving functions (cameras, advanced driver assistance etc.). Modern transport infrastructure also has sensors everywhere, which are used for intelligent monitoring of the traffic system (inductive loops, cameras, radar sensors), and parking management, among other uses.

Advances in information and communication technologies and fast internet speeds have meant constant connectivity between users and service providers, through smartphones or wearable devices. Users have been able to acquire real-time traffic information and connect with on-demand services like Uber, Lyft and others, which have transformed mobility. The high speed of mobile connectivity has also improved the connectivity a vehicle can have with other vehicles, humans, other devices, infrastructure (transport/grid) and networks. These possibilities have considerably improved the technical options and resulted in projects like the platooning of trucks in autonomous fleets. Strengthened vehicle communications have also improved safety.

The amount of data that sensors and communication devices produce has led to research on data analytics and machine learning. The vast amounts of data analysed using machine-learning algorithms have paved the way for many analytical processes, including analyses of user behaviour, predicting transport demand, supply optimization, anomaly detection, autonomous driving and driving assistance, etc. Artificial neural networks (deep learning) have paved the way for fully autonomous driving. It is expected that autonomous driving will produce savings in operating costs and make its operations safe for humans and environmentally friendly.

Rapidly changing technologies have led to a lot of disruptive mobility trends with entirely new business models. First and foremost is the emergence of a lot of start-ups in shared mobility, ranging from micro-mobility solutions (bicycles, scooters) to long-range mobility solutions (Car2go, blablacar, etc.).

Mitigation benefits

Since the space for smart mobility solutions is wide-ranging, from on-demand mobility (car and bike-sharing) to integrated mobility planning that can improve public transportation efficiency, it is not easy to provide a single assessment. Shared mobility solutions have shown promise in reducing carbon dioxide emissions (20). However, the extent of the savings will depend upon the context: for example, the benefits of trips made in a shared car will be far less if the same trip is made using public transport. Life-cycle analysis of car-sharing has revealed reductions in greenhouse gas emmisions of between 33 percent and 70 percent (21). However, it has been argued that these reduction estimates have ignored the rebound effect due to increased travel. Indeed, a study of Über users in the United States showed that the vehicle kilometres they travel are growing, not declining (22).

The enormous improvements in communication systems has led to the introduction of new kinds of vehicles into automobile markets, including autonomous vehicles and connected vehicles. As stated earlier, connected vehicles use several communication technologies to communicate with the driver, other cars on the road, roadside infrastructure and the cloud. Autonomous vehicles are vehicles where at least some safety-critical control function occurs without human intervention. Eco-driving is associated with automated acceleration and braking technologies used by both connected and autonomous vehicles. In theoretical models, such technologies have revealed a potential to reduce fuel consumption by between 10 and 20 percent depending upon the driver and the context (23-25). Chen, Gonder (26) estimated the benefits to be much higher, at between 30 and 45 percent. As stated earlier, technology has improved the potential to create autonomous platoons of vehicles, which are expected to increase fuel savings by reducing air resistance; platooning benefits are likely to be between 3 percent and 25 percent (27). Because autonomous vehicles are expected to reduce crashes and improve overall road safety, the safety equipment that currently consumes a lot of the vehicle's weight will no longer be required. Reductions in the weight of the vehicles will also reduce fuel consumption. Anderson, Nidhi (25) estimate that fuel consumption can be reduced by between 4 and 7 percent if the vehicle weight is reduced by 25 percent.

An indirect effect on the environment is improved routing efficiency: a study (28) found that fuel consumption could be reduced by 12 percent when algorithms used to model route selection to reduce emissions were used. The most expected benefit of connected and autonomous vehicles will be a reduction in traffic congestion. Such vehicles make it possible to increase the road capacity and decrease congestion levels. A decrease in traffic congestion could reduce fuel consumption by between 15 percen and 60 percent depending upon the penetration levels of autonomous vehicles (29, 30).

Trade-offs and linkages with other sectors

When smart mobility solutions are applied, they are mostly a component of other transport solutions that have been added to improve their overall efficiency. These solutions do not replace other transport technologies in their essentials but, as stated above, are used to improve overall efficiency by replacing human intervention with smart solutions. Cities that use smart mobility solutions must consider the upfront costs of technology and the skills and knowledge requirements to run smart mobility operations. As the application of smart technologies to mobility is still at the nascent stage, the evidence presented in the section above is insufficient, despite which it definitely points in a positive direction regarding emissions reductions.

Smart mobility solutions rely heavily on technology for solutions. Thus, given the very high reliance on digital technology solutions, smart mobility solutions face increased cyber-security risks. Cybercriminals have been able to attack information and operating technology to disrupt the transport services (31, 32), for example, in Baltimore (33) and San Francisco (34), and with the massive hack of Uber data (35). These examples indicate that smart mobility solutions must be symbiotic with other transport actions like transit-oriented development, thus adding an angle of cybersecurity.

Barriers to adoption

Smart and innovative mobility solutions face challenges when addressing the so-called 'disadvantaged section' of transport users: young adults (36), the retired (37) and the poor (36). Urban residents who find it difficult to install smart applications must access smart mobility solutions and afford the rising fares, otherwise becoming excluded and being denied equitable access to employment, education and other services.

The greatest driver of small mobility solutions is the need for information that reduces the uncertainty element in multimodal solutions, optimizes transport solutions, and searches for green and environmentally friendly solutions. As stated above, there are risks in implementing these solutions, but security is also improving over time. Solutions will also have to be user-friendly for all sections of the population and not increase micro-mobility and public transport fares, which would generally happen with the broader adoption of technology.

Relevance for developing countries

Smart technologies with smart apps will provide an enabling environment for users of the public transport system, integrating systems with other transport infrastructure and providing demand-based services (38). Many developing countries have low financial resources, so public transportation infrastructure in many such countries is insufficient to take care of the demand for mobility. The main challenge is the amount of investment required to create a public transport infrastructure for metros and bus-rapid transport systems, for example. The gap in demand is typically catered for by para-transit modes which do not always follow a fixed route or timetable. These para-transit modes vary across countries (e.g., rickshaws in India, tuk-tuk in Thailand, matatu in Kenya) and are mainly run by private operators. Smart mobility solutions can ideally be combined with para-transit modes to improve information flows between operators and customers. Although the informality of the whole operation can be a challenge, there are already cases that give a lot of hope. For example, Ola and Über in India now include auto-rickshaws on their sharing platforms, allowing users access to para-transit modes. This development also opens up opportunities for using para-transit as shared modes of transport, leading to a plethora of opportunities for developing countries.

3.2.3. Battery Electric Vehicles

Scope of the technology

Battery electric vehicles use chemical energy stored in batteries as their power source. The batteries are used to run electric motors to propel the vehicles. As a concept, battery electric vehicles predate the internal combustion engine. However, they have grown in importance over the last decade, this being directly related to the decline in the cost of electric batteries from more than 1000 USD per Kwh for a battery pack in 2010 (39) to around 170 USD per Kwh in 2018 (40) and to even below 100 USD per Kwh in 2020 (41).

The internal combustion engine has dominated road transportation for more than a century and has enjoyed a cost advantage compared to other alternative technologies like battery electric vehicles, hybrids, plug-in hybrids and fuel-cell hydrogen electric vehicles. The reduction of battery costs in the last decade has been dramatic, which has meant that the total cost of battery electric vehicles and hybrids is now closer to conventional vehicles running on the internal combustion engine (42), especially for light-duty vehicles.

In 2019, around fifteen countries had a battery electric vehicle market share (share of new vehicles sold) of more than 1 percent for light-duty vehicles (43), though most are developed countries. Electric two-wheelers have been a great success in China, and the several Asian countries that have a large two-wheeler population have become a potential market. China has also been at the forefront of introducing electric buses, which many cities worldwide are opting for. The prospects for electric vehicles have dramatically improved due to strong policy support in many countries, including financial incentives, duty exemptions and mandates for phasing out diesel cars (44). In this scenario, electric vehicles are bound to become a dominant technology for personal and public transport in cities in the coming decades. They are also emerging as a preferred technology for shared mobility. There is an interest in fuel-cell hydrogen electric vehicles as a prospect for future (Box 2). However, at present, energy costs represent a barrier.

Fuel cell hydrogen electric vehicles

Fuel-cell hydrogen electric vehicles are an option besides battery electric vehicles, and may be a future option for heavy-duty vehicles. However, the main barrier is the cost and the energy needed to produce the hydrogen. It is energy-intensive to produce hydrogen using renewable energy: producing 1 kg of hydrogen requires 40 kWh of renewable energy (45), while 1 kg of hydrogen can propel an light-duty vehicles 100 km (46). In comparison, a battery electric light-duty vehicle will require only 22 Kwh of energy for 100 km (47). The high cost of hydrogen production is an obstacle to fuel-cell hydrogen electric vehicles. Therefore in the short term, battery electric vehicles look like the more cost-effective option.

Mitigation Benefits

Battery electric vehicles are considered a silver bullet for decarbonizing road transport. However, this will depend on the electricity used for charging and battery production. Life-cycle studies for light-duty vehicles have shown that battery electric vehicles produced and also operated on low carbon electricity would yield a carbon dioxide footprint of only 33 g of carbon dioxide -eq/vkm for a compact-size car (48, 49) compared to around 135 g of carbon dioxide -eq/vkm for an efficient light-duty vehicle in 2030 (50). Efficient internal combustion and hybrid engines running on fossil fuels cannot go below 130 g of carbon dioxide -eq/vkm for light-duty vehicless. However, if we consider that battery electric vehicles are produced using coal-based electricity, the life-cycle carbon dioxide emissions could even exceed 300 g of carbon dioxide -eq/vkm(49). Therefore decarbonizing electricity for battery production and charging is crucial.

In the case of buses operating within cities, battery electric vehicles have much lower carbon dioxide emissions than all the alternative drive-train technologies (internal combustion engines, hybrids, plug-in hybrids and fuel cell) (51), a much better picture compared to light-duty vehicles.

Modelling studies for developing countries show that battery electric vehicles can reduce carbon dioxide emissions. Dhar et al. 2017 find that well-to-wheel carbon dioxide emissions are lower in India’s transport sector with the large-scale diffusion of battery electric vehicles even when the grid has the same carbon dioxide intensity as the baseline scenario.

However, battery electric vehicles can help decarbonize electricity since using vehicle to grid technology battery electric vehicles can do smart charging and supply electricity back to the grid (52). Such charging technologies can help integrate renewables more fully in the grid, including rooftop solar in buildings (like onsite renewable generation or district cooling and heating systems in the buildings chapter). In Denmark, vehicle to grid technology has been demonstrated and both grid-based and decentralized renewables integrated on top of the building (52).

Trade-offs and linkages with other sectors

Even a rapid rollout of battery electric vehicles within light-duty vehicles will leave a large stock of vehicles driven by internal combustion engines in use for the next thirty years (53). If these vehicles continue to use fossil fuels, they will produce substantial carbon dioxide emissions. Therefore, synthetic fuels with a much lower life-cycle of carbon dioxide emissions than fossil fuels provide a path for decarbonizing the existing engine technologies. Synthetic fuels can be produced in a gaseous form or as a liquid from hydrogen and captured carbon dioxide. They can reduce local pollution when combined with conventional fuels, e.g. diesel: blending 20 vol. percent of (poly) oxymethylene dimethyl ethers, a synthetic fuel, with diesel in a diesel engine leads to 50 percent lower particulate-matter emissions (54) and the reduction of nitrogen oxide emissions (55). However, the high cost of hydrogen production is a damper for synthetic fuels since it accounts for around 63 percent of the cost. The cost of synthetic fuels was estimated at between 5 and 7 euros per litre of diesel equivalent in 2015 and is expected to fall to 1-3 euros per litre in 2050 due to a reduction in the price of renewable electricity, thus increasing the scale of production and the learning effects (56).

Different battery technologies are used in vehicles; however, lithium-ion batteries have become established as the first choice for automotive applications. The cumulative capacity of such batteries in automotive applications was around 60 GWh in 2018 (40). For lithium-ion batteries used for automotive applications in 2018, the material demand was about 11 kilotonnes (kt) of lithium, 15 kt of cobalt, 11 kt of manganese and 34 kt of nickel (53). By 2030, when the market share of electric vehicles is predicted to be 30 percent, this demand will increase thirty times for lithium and around 25 times for cobalt. Dependence on lithium is a cause of concern (57). Besides the problem of dependence on precious materials, disposal of lithium-ion batteries is also an issue since currently there is limited recycling of them (58).

Barriers to adoption

Battery electric vehicles are characterized by their high capital costs and low operating costs. Therefore, their upfront costs are a significant barrier. Battery electric vehicles are more efficient than conventional vehicles, though this advantage can be offset by low fossil-fuel prices. Therefore fossil-fuel subsidies act as a significant barrier to battery electric vehicles. The lack of information about such vehicles and anxieties about their safety and driving range are other significant barriers (53).

In countries where battery electric vehicles have gone beyond 1 percent market share, financial incentives and tax waivers (43) have played an important role in removing the barrier of high capital costs. In developing countries where governments do not have the fiscal space to provide incentives, it might help to link incentives to adopt battery electric vehicles to increased taxes on fossil fuel-fuelled vehicles.

Adopting battery electric vehicles also requires easy access to safe charging at an affordable price (59). Thus, the lack of easy and safe access to charging acts as a barrier to such vehicles. Charging can be done on-street, in public parking lots, etc. or using private chargers at home or in office parking spaces. Global trends show that the bulk of charging infrastructure consists of private slow chargers, with around seven million chargers in existence by the end of 2019 (43). Public charging infrastructure shows a mix of slow and fast chargers, but with fast chargers gaining on slow chargers. Creating a charging infrastructure requires coordination between electric utilities, automakers, landowners and policy-makers. Charging infrastructure in apartment blocks and offices would require reserving spaces for battery electric vehicle and an electricity tariff structure from utilities that is affordable.

Several countries are implementing friendly policies for battery electric vehicles. However, to attract private players to set up shop, policy stability is also essential. A lower driving range and a longer time for recharging have been ongoing challenges to battery electric vehicles, and therefore it is quite vital to create public charging infrastructure (53, 60).

Developing countries also need to think about battery disposal. Here, it might be necessary to ensure that lithium-ion batteries are recycled as effectively as lead acid batteries by making the sellers of batteries and electric vehicles responsible for the safe collection of batteries as well (58). Lithium-ion batteries used for automotive applications can be repurposed for stationary applications, can provide storage at 90 percent lower cost, and have the potential to contribute 60 percent of grid storage capacity (58).

Relevance for developing countries

Developing-country cities are hotspots of air pollution, and modelling studies show that battery electric vehicles can reduce local pollution quickly (61). Interest in such vehicles has therefore increased in these countries. China has achieved the large-scale adoption of battery electric vehicles through stringent emissions regulations, higher taxes on older and more polluting cars, and the provision of extensive charging infrastructure (43). Since several developing countries depend on oil imports, battery electric vehicles offer a way to reduce fossil fuel imports and thereby save precious foreign exchange. Battery electric vehicles with fewer components are relatively easier to manufacture, compared to vehicles that run on an internal combustion engine.

Developing countries typically have inadequate public transportation systems that lead to overcrowding and poor user experience. Battery electric vehicles when augmenting existing bus fleets can help improve the overall capacity, reduce overcrowding and hence improve user experience and help move people away from private modes of transport. In combination with transit-oriented development initiatives, this can enhance the image of transit projects in cities.

However, battery electric vehicles can put a strain on the electric grid where there is limited capacity. Such vehicles can be promoted in countries for uses that provide the greatest co-benefits in terms of air quality, mobility, energy security and job creation.

Furthermore, strategies promoting battery electric vehicles should be coordinated with electrification plans and with improving the share of renewable sources of energy in electricity generation.

3.3. Key policy-related issues

The necessary enabling conditions for the three selected technologies have been discussed under each technology separately. However, there are some common policies that cities and national governments need to undertake to introduce low-carbon and sustainable transport in cities.

Fuel taxation and subsidies. In many countries fossil fuels are subsidized, making individual modes of transport more affordable. However, this also makes it challenging to promote public transportation and alternative fuel and vehicle technologies. Therefore it is important to phase out any fossil-fuel subsidies.

Parking policies. Space in cities is quite expensive, and in the absence of any parking policies, precious public spaces are quickly taken over by parking for private vehicles. Therefore parking policies to decide on space allocations and the pricing of parking are essential.

Taxation of vehicles. Stronger environmental regulations in developed countries sometimes create an incentive to export older and more polluting vehicles to developing countries. Therefore, it is essential to have vehicle taxation policies in developing countries that are related to the vehicle's age and emissions characteristics.

Roadworthiness and scrappage policies. Vehicles must not be unsafe or very polluting. To ensure this, it is good practice to undertake periodic vehicle checks. Furthermore, a scrappage policy can be introduced to pay consumers a certain amount to scrap their vehicles. A scrappage policy will also allow track to be kept of vehicles in active use (43).

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4. Solid waste management

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The municipal solid waste management sector represents a major challenge for developing countries due to significant environmental and socioeconomic issues involving rapid urbanization, inappropriate municipal solid waste management practices, and the existence of the informal waste sector. in these countries, municipal solid waste management systems are often inefficient and operate to low standards (1, 2). Municipal solid waste management is characterized by low collection rates and the lack of appropriate waste treatment and final disposal, contributing not only to global climate change[1] and other critical environmental impacts, but also having negative economic and social effects. Most impacts related to waste management occur during the final disposal phase.

Dumping untreated solid waste on uncontrolled landfills and open sites is still the most prevalent method of waste disposal in the cities of developing countries. For example, a study analysing waste-management systems in 36 urban areas in 22 developing countries revealed the common use of open dumps without leachate treatment, treatment gases or any other necessary infrastructure. In addition, in 61 percent of the cities analysed open burning of waste by households was extensively practised (3). Uncontrolled waste-disposal practices can lead to the spread of vector-borne diseases, and the disposal of waste containing hazardous materials can be harmful to workers in the waste sector, nearby communities, and the environment. Environmental impacts in the municipal solid waste management sector include, but are not limited to, global warming, acidification, eutrophication, and human and eco-toxicity.

These are only some of the impacts that waste-management practices can have on cities. In the following section we will go further into the municipal solid waste management systems of developing countries and their stakeholders, and provide an overview of the current municipal solid waste management technologies and approaches that are available.

Typically, municipal solid waste management systems in developing countries are run by both the formal and informal sectors. Nevertheless, the stakeholders and their role are similar, despite the existence of possibly different contexts. There is a wide range of stakeholders involved in municipal solid waste management systems, and their different roles depend on the step in the waste management value chain in which they are acting (generators, waste management operators, law and policy-makers, etc.). Also, there is sometimes a blurred line between the two sectors, the same stakeholders possibly being responsible for both informal and formal roles and activities in the system.

National governments are mostly responsible for establishing national waste-management policies, strategies ensuring that local governments have the necessary enforcement capacity, and the resources for effective solid-waste management. Municipalities and other local authorities are responsible for the provision of solid-waste collection and disposal services. In addition, local governments are typically responsible for implementing waste-management legislation and regulations. If there is cooperation with the formal private sector, local governments regulate and control the appropriate

1
In 2012, the municipal solid waste management sector accounted for around 5 percent of global greenhouse gas emissions, primarily driven by disposal in open dumps and landfills without landfill-gas collection systems (1).

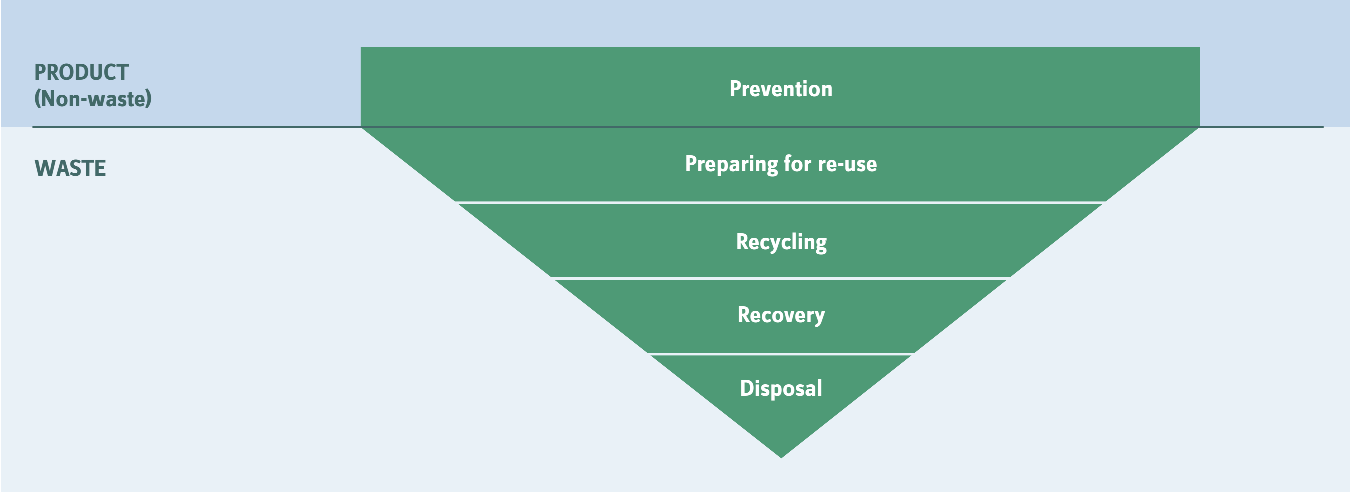
provision of waste management services by means of formal private companies, registered entities with an organized labour force and some capital investment, and covering a wide range of enterprise types. Their main motivation is to generate profits on their investments in waste services (collection, transfer, treatment, recycling and disposal).

The lack of municipal solid waste management services creates a need for alternative ways of handling and disposing of the waste, causing the development of informal waste activities (called 'informal sector' or IS) in developing countries. The informal private sector comes into play when formal waste management services are not provided, perhaps in rural areas or areas that are difficult to access, or when there is lack of financial capacity or willingness to pay for waste-collection fees. The informal sector commonly consists of individuals, groups and small enterprises that typically operate in inadequate and uncontrolled conditions and belong to socially disadvantaged individuals or groups working in informal recycling (e.g. children, women, and the elderly) (5). Frequently, the informal sector carries out waste separation and recycling, thus also reducing greenhouse gas emissions and other environmental impacts by reducing the volume of waste disposed of in landfills while at the same time creating local added value through the recycling market and informal jobs. However, despite these positive impacts, informal waste-management activities are also associated with negative social and economic conditions, such as poverty, inappropriate occupational and health-related working conditions, exploitation, discrimination, child labour, social rejection, and a lack of education (5).

Households and commercial establishments are waste-generators and waste-management service-users. Their waste composition and characteristics tend to be very similar and to be treated as municipal solid waste. Sometimes they could be involved in the city's source-segregation activities. Other possible stakeholders present in waste management systems are non-governmental organizations and external support agencies, both of which aim at supporting and facilitating the implementation of more sustainable waste management practices. This support can be provided by, for example, capacity-building, financial assistance to formalized waste workers, technical assistance for implementing separate collections, technology transfers, etc. (6).

The boundary between formal and informal stakeholders is not always clear. Recyclable materials are recovered by informal waste-workers who sell them to formal recycling companies. Municipal employees who load waste into municipal trucks (municipal waste-collection crews) may also separate recyclables as they load and sell what they find unofficially to informal sector dealers. Co-operatives consisting of informal-sector workers may undertake some formal work under contract to a municipal authority while also being involved in informal recycling (7). The next section will describe the most common working and interaction mechanisms between the two sides, as well as the waste-management technologies and approaches that link them.

Figure 1. Waste hierarchy



Source: European Waste Framework Directive, 2008

4.1. Overview of technology options

There are different options for tackling diverse issues related to municipal solid waste management that are problematic for developing countries, ranging from strategic and management-oriented options to purely technical solutions. Often, both sorts of scheme should be combined in order to optimize their results. Currently, countries in general are formulating their national goals and targets and development road-maps for the sector around resource efficiency based on waste-minimization principles. A key pillar of these is the so-called "waste hierarchy", which targets waste prevention/reduction, reuse and recycling (and the intermediate steps that link them), recovery and disposal (see Figure 1). This concept outlines an order of preference within waste-management practices. There are different variations of the waste-management hierarchy (3Rs, 5Rs, 9Rs) (8, 9, 10), but they are all very similar and are focussed on preventing waste generation as the topmost and most important aspect of the hierarchy. The Waste Hierarchy considers waste reduction and waste prevention to be the most sustainable waste management practice, as it is very critical to decoupling waste generation from economic growth (11). Waste reuse is ranked as the second best option, this being followed by waste-recycling, recovery, and disposal. Landfilling and further final disposal practices are the least sustainable options and are therefore placed at the bottom of the hierarchy.

While the waste hierarchy focuses on resource efficiency and waste minimization as the main goals, there are other waste management approaches that incorporate it as a key pillar but that also contemplate waste management more holistically. They give importance not only to the efficiency of materials and energy flows, but also to country context, with multiple actors participating in municipal solid waste management systems and the particularities of their interactions towards sustainability. Among of these approaches are:

- **Integrated waste management**, which adopts the waste hierarchy as a cornerstone, but also focuses on stakeholder participation, the integration of political and social factors, and other interrelated processes in the waste system (6).

- **Participatory waste management** pays more attention to the social aspects of waste management than integrated waste management. This approach aims to achieve solidarity within stakeholders in waste management systems and strongly supports the social and economic integration and empowerment of the informal waste sector.

In terms of the greenhouse gas mitigation potential of each waste management practice, there are a number of life cycle assessment-based studies estimating the greenhouse gas emissions of different waste management practices and comparing them in terms of their mitigation potential. In this sense, waste prevention has been proved to reduce greenhouse gas emissions by reducing raw-material extraction and energy use in production activities, as well as from avoided waste treatment and disposal. Generally, greenhouse gas emissions from waste-prevention measures are lower than any other waste-management practice. A comparative study of the greenhouse gas mitigation potential of different waste-management practices in Organization of Economic Cooperation and Development countries demonstrated that source-reduction and prevention and recycling provide the highest reductions in greenhouse gas emissions per metric tonne of diverted municipal solid waste compared with baselines practices in 2030 (13).

After waste prevention and re-use, waste-recycling is the next option for cities to consider according to the waste hierarchy. In developing countries, the mitigation potential from recycling is driven by the informal sector, which also has very interesting potential in terms of greenhouse gas mitigation. Commonly, due to the informal nature of these activities and the lack of data, it is difficult to measure the avoided environmental impacts related to informal recycling. However, some experiences were able to estimate this mitigation potential: see Table 1 for some examples.

Table 1. Examples of greenhouse gas emissions reductions from informal waste-recycling

Location	Materials	Greenhouse gas emissions saved
India	Paper, plastics, metals and glass	962,000 tonnes carbon dioxide/year
Six cities in Peru, India, Egypt, Romania, Zambia and Philippines	-	28,900 - 496,700 tonnes carbon dioxide
São Paulo, Brazil	Paper and cardboard	1,443–2,720 tonnes carbon dioxide/ year
Ormoc, the Philippines	Dry recyclables	7,750 tonnes carbon dioxide/year

Source: Aparcana and Hinostroza, 2015; King and Gutberlet, 2013; Hetz el al. 2011

After waste-prevention and waste-recycling, cities have further options targeting the final steps of the waste hierarchy. The election of these technologies will depend, among other things, on the waste's physical and chemical characteristics and the amounts generated. Among of these technologies are:

- **Composting:** this is a technological and economical accessible option that simultaneously generates aggregated value to organic waste and contributes to greenhouse gas mitigation, mainly by diverting untreated organic waste from landfills and the substitution of chemical fertilizers. The latter represents greenhouse gas savings of around 8 kg carbon dioxide e/ton of composted waste (11, 6). Furthermore, compost may also act as a carbon stock (it has a high carbon-storage capacity due to its slow carbon-mineralization process). There is consensus about this role, but not about the quantification of this potential.

- **Anaerobic digestion/biodigestion:** this is used to degrade organic waste, the main inputs of this process being biogas (methane as the main component) and digestate. Biogas has a number of uses depending on the size of the biodigestor (therefore, the amount of biogas obtained) and the quality of the biogas. Usually, small-scale biogas plants convert the gas into heat and use this energy for cooking, heating, drying of grains, etc. Bigger plants with a more complex technologies can generate electricity and heat through cogeneration. Small-scale biogas plants are more frequent in developing countries, due to their easy-to-implement technology and low construction and operating costs. The greenhouse gas mitigation potential of anaerobic digestion may vary depending on the end-use of the energy (gas, electricity, heat, transport, etc.), local energy grids, technology, etc. Anaerobic Digestion projects planned for Chile and the Dominican Republic are expected to achieve greenhouse gas savings of 6 million metric tonnes of carbon dioxide/year,[2] and in twenty years an accumulated reduction of around 51 million metric tonnes of carbon dioxide (6).

- **Mechanical biological treatment:** this usually involves a first treatment phase, corresponding to the separation and sorting of recyclable materials (mechanical phase), and a second biological one, which could be anaerobic digestion or composting for the organic fraction. Due to the high construction and operating costs, mechanical biological treatment plants are more common in developed countries (11). Owing to the combination of different treatment processes (see more in Section 2), mechanical biological treatment plants have an interesting greenhouse gas mitigation potential, depending on the technology, waste composition, type of waste, local energy grid, use of final outputs, etc. However, compared to landfill, mechanical biological treatment plants may save around 90 percent of methane emissions (11). In Organization of Economic and Cooperation and Development countries, mechanical biological treatment could reduce the amount of municipal waste diverted from landfill (relative to baseline practices in 2030) from 500 to around 2,000 kg carbon dioxide e/ton (13).

2
Million metric tons of carbon dioxide.

- **Incineration:** this technology is widely applied in developed countries (80 percent of all plants at global level), but in developing countries its implementation is still low, mainly due to inadequate waste composition (water content too high), lack of adequate legal and regulatory frameworks, and high investments and operating costs (16). Moreover, when it comes to circularity and sustainable waste management, incineration would be the last option to consider, as energy recovery comes at one of the last steps in the implementation of the waste hierarchy. municipal solid waste incineration can save greenhouse gas emissions through avoided landfilling and energy recovery (electricity and heat). For each tonne of municipal solid waste incinerated in an incineration plant with combined heat and power units, the equivalent of 1,010 kg of carbon dioxide can be avoided by diverting that waste from landfill without using methane gas (16).

- **Gasification and pyrolysis:** these are treatments carried out under oxygen-controlled conditions, during which pyrolysis gas and a solid coke are formed. The heat values of pyrolysis gas typically lie between 5 and 15 MJ/m^3 from processing municipal waste. Pyrolysis technology is constantly being developed, and some countries in Europe are introducing this technology in the form of pilot plants and demonstration plants. Other countries (e.g. Japan) are using it already on a commercial basis. However, this technology still has only a small share of the overall treatment capacity when compared to incineration and is used to process selected waste materials only (17).

- **Landfill:** this is considered the last waste management option, after waste prevention, recycling and recovery. A sanitary landfill includes landfill gas and leachate capture and treatment systems. A landfill without gas utilization would emit around 1,610 Kg carbon dioxide eq/tonne municipal solid waste (16); however, if landfill gas is used for energy recovery, it can compensate emissions in favour of greenhouse gas emission reductions. Landfill gas typically contained around 50 percent of methane and can be captured and burned in combined heat and power units to generate electricity and heat. The Environmental Protection Agency reports that approximately 60 to 90 percent of the methane emitted from a landfill can be recovered and used, depending on system design and effectiveness (18).

Although waste management treatment options are already known and well-established, there is still a lack of knowledge about them and their applicability in developing countries, which is strongly linked to the lack of understanding about the main characteristics of municipal solid waste management systems and the technical conditions required to operate certain technologies under particular contexts.

4.2. Selected technologies

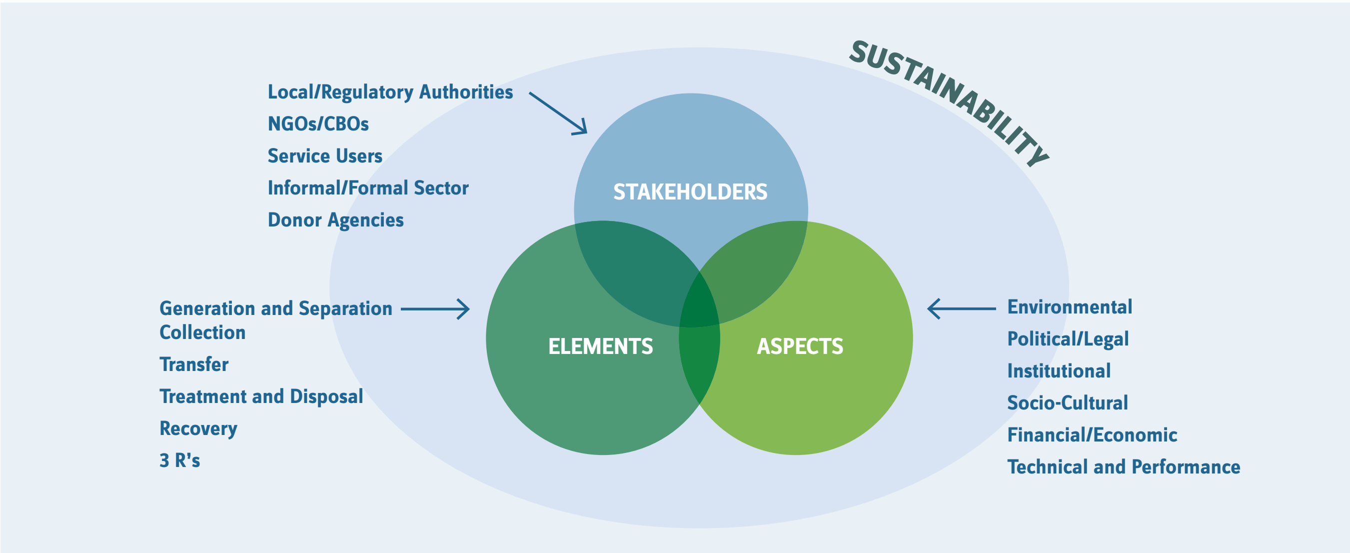
As described in the previous section, there are several waste-management options that can be selected according to particular contexts, such as waste characteristics, economic and financial restrictions, the institutional and policy-related aspects, etc.

Frequently, in order to address the particularities of each municipal solid waste management system, it is necessary to combine sustainable waste management approaches with adequate technical and operational solutions. This chapter describes waste management approaches and technology options that, when combined, can reduce the negative impacts linked to inappropriate waste management practices.

4.2.1. Integrated Waste Management and Integration of the Informal Waste Sector

The Integrated waste management approach adopts the waste hierarchy as its cornerstone by focusing on the management of material and energy flows within of the waste management system and the links outside it. Integrated waste management can be used to optimize existing systems, as well as to design and implement a new one (19). In contrast to conventional waste management systems, which mainly focus on improving the operational aspects (waste collection, transport, disposal) and increasing their efficiency, integrated waste management focuses also on stakeholder participation, waste in neighbourhoods, cities, etc. integrated solid waste management goes beyond the technical level to focus on the integration of the political and social factors, and other interrelated processes into the waste strategy (6).

Figure 2. Integrated waste management



Source: Hoornweg and Bhada-Tata, 2012

Integrated solid waste management is based on four principles: equality for all citizens regarding access to waste-management systems: ability to remove the waste safely; ability to maximize the benefits; ability to minimize the costs and optimize the use of resources; and sustainability of the system from the technical, environmental, social, economic, financial, institutional, and political perspectives. The implementation of integrated waste management involves three dimensions: 1. stakeholders, 2. waste-system elements and 3. aspects. The stakeholders are people or organizations involved in the waste-management system in both the formal and informal sectors. Waste-management elements refer to the operational dimensions of the system: waste-collection, transport, treatment and final disposal, including recycling and waste-prevention measures. The context aspects encompass the reality around a waste management system with regard to the financial, economic, environment, politico-legal, institutional arrangements, and socio-cultural aspects. This context can be changed to enable sustainability (2). The concept of integrated solid waste management considers these three dimensions to be strongly linked. Integrated solid waste management implies managing the interrelations between the contextual aspects, operational and material flow-related elements, and the stakeholders in a sustainable way. The impacts of these interactions can enable a waste management system to work or prevent it from reaching a sustainable state.

Aligned with the importance that integrated waste management gives to stakeholder involvement, including by informal actors, there have been multiple experiences in developing countries testifying to the key role of the informal waste sector and the positive economic, environmental and social impact of their inclusion within the formal waste management system. In the last few years, more and more cities in developing countries have identified the need to recognise the contribution of the informal sector and its inclusion in formal waste-management systems as an effective strategy. Governments have started to change their previous attitudes of opposition and indifference into active support (20). For this reason, in the few last years, several methods of formalization have been implemented in order to improve waste-management systems and transform them into more sustainable systems. These practical experiences have demonstrated the numerous advantages achieved through the formalisation of the informal sector (Mumbai, India; Manila, Philippines, Londrina and Diadema, Brazil; Bogota, Colombia; Cañete, Peru; among others). Among these benefits are increasing waste collection and recycling rates, poverty alleviation, reduction of health problems, job creation, women's empowerment, cost savings for the formal sector, waste valorization, and reductions in child labour and discrimination (6).

Methods of formalization are mainly based on encouraging collection and valorization activities. They aim at the recognition of informal waste workers as important stakeholders and to embrace the environmental, social and economic benefits of informal recycling activities. Many methods of formalization organize informal waste workers into more structured groups. Local authorities support formalization through recyclers' associations, micro- and small recycling enterprises and community-based organizations (1, 21). Often the cooperation scheme is based on the creation of public–private partnerships between the municipality and micro- and small recycling enterprises, collection and recycling contracts with recyclers' associations, etc. (20, 22).

Some common actions and measures are recommended to enable successful formalization, for example, favourable policies and regulations enabling the informal sector to participate in the formal waste-management system. Further recommendations are acknowledgement and acceptance by authorities of the benefits of the informal sector, political and legal recognition, stakeholder communication and collaboration in the waste-management system, and diverse technical and operational measures (access to adequate infrastructure, technical assistance, improvements to the quality of recycled materials). Aligned with that, some Brazilian cities (Diadema and Sao Paulo) have successfully implemented a more comprehensive integration approach, with more participatory elements implying ‘solid waste recovery, reuse and recycling practices with organized and empowered recycling cooperatives supported with public policies, embedded in a solidarity economy, targeting social equity and environmental sustainability’. This approach aims to implement public waste-management policies giving consideration to the environmental, social, and economic aspects. Livelihoods, income generation, human development and environmental protection are core aspects of this approach, which is based on achieving collective goals in the direction of common economic development (solidary economy), the formulation of democratic waste-management policies and participatory management (23).

Table 2 presents an overview of some of the key characteristics of integrated waste management, including formalization or integration of the informal sector, to be considered when looking at approaches or technologies for the waste sector.

Table 2. Overview of integrated waste management with formalization/integration of the informal sector

Scope of technology/ approach	Holistic approach to managing solid waste, considering material and energy flow optimization (waste hierarchy), socioeconomic context and interlinks, roles, and synergies among stakeholders.
Reasons for choosing this option	• Integrated waste management is a systemic framework focused on resource efficiency within the waste management system, in connection with other local value chains. • It works under strong consideration of the local socioeconomic context. • In conjunction with national policies, Integrated Waste Management can help to reach national waste management targets, but it is also related to sustainability (e.g. job creation, better working conditions, elimination of child labour, better education, gender equality). • Integrated waste management aims at achieving cooperation among all the stakeholders involved, creating economic and sustainability and at the same time reducing the environmental impacts.
Trade-offs	None
Barriers	• Absence of clear waste management policies and legal framework • Unclear roles and responsibilities of stakeholders • "Rejection" policies from municipal solid waste authorities and other stakeholders towards informal waste workers • Lack of environmental and social awareness of individuals especially regarding to their own responsibility as waste generators • In absence of formalization: competition with the informal sector for access to waste materials

Table 2. Overview of integrated waste management with formalization/integration of the informal sector	
Enablers	• Clear national mandate with a focus on resource efficiency and sustainability goals. • National support for cooperation among stakeholders. • Legal framework supporting the participation of the private sector (including formalized and organized waste workers) as waste management service-providers. • Creation of financing mechanisms and business incentives for small enterprises as well.

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.2. Waste recycling

As mentioned in previous sections, sustainable municipal solid waste management strategies have the so-called "waste hierarchy" as their cornerstone. An important step facilitating the effective implementation of recycling is the introduction of waste-collection schemes that allow waste generators to separate and sort different waste fractions at source. Such schemes should be designed in accordance with the local context and conditions, for example, policies and legal framework, waste composition, waste amounts, local geography, urban distribution, population, education and environmental awareness, access roads, waste collection logistics and resources, presence of an informal waste sector, and also the treatment for each type of waste material, including the recycling market and the use of materials after their recovery.

Urban cities in developed and developing countries have different socioeconomic conditions, stakeholders, waste management regulations and policies. Waste separation at the source and collection systems can follow very detailed sorting levels, e.g. sorting of different coloured glass, type of plastics, bio-wastes and other kitchen waste, as in Germany and Austria – or it could also be designed in a simpler way. An example of this is the city of Mumbai, India, where residents separate their waste into wet and dry, corresponding to biodegradable and recyclable materials. Formalized waste workers collect the waste and proceed to treat the biodegradable fraction into compost and to sell the recyclable material (24). As in this example, waste separation and collection systems can be implemented with the support of organized waste workers' associations. As mentioned in previous chapters, informal waste workers can support municipalities in implementing and operating separate waste-collection and recycling systems as part of a formalization programme. For example, they can formalize informal waste workers by hiring them as workers in the sorting section of the manual sorting plant. Informal waste workers can identify high-quality recyclable materials more quickly and more efficiently compared with less experienced workers.

The configuration of waste separation and collection systems will influence the design and purpose of recycling facilities enormously. The layout and equipment of the recycling plant will reflect the kind of waste materials that are to be handled (e.g. sourced separated by various waste materials or only a few, or no waste separated at the source), waste input and output amounts and the expected quality of the outputs. In addition to material-related operational criteria, other criteria will also play a role when deciding the kind and degree of technology of a recycling plant. We are referring to the socioeconomic and financial aspects, such as the availability of a municipal waste management budget, access to financial mechanisms, the presence of an informal waste sector, and other socioeconomic and environmental issues that should be addressed, e.g. job creation, environmental regulations, recycling targets, local recycling value chains, integration of informal workers, etc. Additionally, it will depend on cash flow, the costs structure of the recycling plant (operational expenditure versus capital expenditure over a longer period), returns on investment and other economic aspects. For example, if the informal waste sector has a strong presence, the municipal budget for waste management is low and there is a need for local job creation and strengthening local added value for recycling, a manual recycling plant could be a more suitable option.

There are always trade-offs when choosing the level of automation. Fully automated recycling plants are frequently more expensive in terms of the initial investment, but in contrast the operating costs can be less onerous because a smaller workforce is needed compared with manual recycling plants. In addition, automated recycling plants have higher sorting efficiencies. Table 3 shows referential sorting rates for manual and automated recycling plants, highlighting the efficiencies of different plants, while Table 4 presents an overview of waste-recycling characteristics to be considered, also going a little further into some of the trade-offs.

Table 3. Manual and automated sorting efficiencies according to type of material

Materials	Manual (percent (%) recovery efficiency)	Automated (percent (%) recovery efficiency)
Newspaper and corrugated	60% - 95 %	80% / 90%
Mixed glass	70 - 95%	–
Glass – selection by colour	80 - 95%	>95%
Plastic	80 - 95%	99% (PVC); >90% others
Aluminium	80 - 95%	–

Source: Dubanowitz, 2000

Table 4. Overview of waste recycling

Scope of technology/ approach	Sorting and further mechanical treatment of recyclable materials from non-hazardous municipal solid waste; waste valorization
Reasons for choosing this option	Manual: • The best option for a city with an active recycling market and an informal waste sector. This complements integrated waste management with formalization approaches • Potentially unexpansive technology, accessible for cities with modest waste management budgets • Simple technology (for manual sorting plants) • Positive social impacts (job creation) Automated: • Best option for cities with high amounts of recyclable materials • For cities with almost no informal waste sector • Needs strong market demand for recyclable materials and stable market (amounts and prices) • For cities with high waste management budget
Trade-offs	Manual: • low investment but high operational costs • Relative fast payback period (less than five years) • Easy technology, but lower sorting efficiency Automated: • High investment but low operating costs • Payback period can be long (frequently seven to ten years) • Expensive technology, but higher sorting efficiency
Barriers	• Lack of separation at the source systems makes it more difficult to obtain good-quality recyclables • If not integrated into the municipal solid waste management system, the informal waste sector can extract valuable materials even before they reach the recycling plant, making it unfeasible technically and economically, and also creating competition • Weak local recycling market (low prices, low demand) • Lack of policies and legal framework supporting recycling
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing the environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporative taxes reduction, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service providers, especially for waste collection. • Creation of quality standards for products (fertilizers, refuse derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.3. Composting

Composting is a controlled aerobic biodegradation process for treating organic waste, the aim being to avoid methane emissions linked to the unappropriated disposal of untreated organic matter. Composted inputs are typically food waste, agricultural waste, and the organic fraction of industrial and municipal wastes. Usually the end product is a very nutrient-rich organic fertilizer, which can be used instead of chemical fertilizers. Using compost as a fertilizer has a number of benefits: it reduce soil erosion, improves soil structure, facilitating water and air transport in the soil, and stabilizes pH, among other benefits. Composting is one of the most frequently applied technologies in treating organic waste in developing countries. It is an economically accessible option that at the same time generates aggregated value to organic waste. (6).

High-quality compost is produced from high-quality biodegradable input. In this sense, composting plants in developed countries work in conjunction with "waste separation at source" programmes. Waste generators are expected to sort "good quality clean" biodegradable waste (e.g. coffee and tea grounds, fruits peel, uncooked vegetables) from others that might be difficult to compost due to the longer composting time needed (mixed kitchen waste containing animal bones, food wrappings, etc.). In this way, biodegradable waste can be sorted in order to improve the balance of nutrients in the resulting compost and to reduce contamination with chemicals, plastics and other materials.

In addition to an appropriate input, composting depends on diverse operational parameters that should be kept in order to obtain a high-quality compost:

- Moisture content of the compost mixture (above 40 percent). Since food waste contains around 70 percent to 80 percent of moisture, it is necessary to add sawdust, rice husks or similar substances to reduce the moisture content. Moisture of between 50 percent and 60 percent has been reported to maximize respiratory activity in the composting process (26).

- Temperature: 55 – 70°C, depending on the material input to be composted and the homogeneity of the particle size.

Table 5 provides an overview of some of the key aspects of composting to be considered when using or considering it as a waste0management technology.

Table 5. Overview of composting

Scope of technology/ approach	• Treatment and valorization of biodegradable waste • Production of organic high-quality fertilizer
Reasons for choosing this option	• Low cost and simple technology • Low investment costs. Depends on the setting, low operating costs • Versatile technology (adaptability) • Very widespread in developing countries • Possible to implement centralized and decentralized • Best option if there is an active fertilizer market locally (high local demand)
Trade-offs	• Low investment • Typically higher operational cost • Lower mitigation potential (only through diverting biodegradable waste from landfilling or dumping and replacement of fossil fuel based fertilizers)
Barriers	• Needs waste separation at source • Needs quality standards for the final fertilizer • Needs a stable market • Needs clear policies and regulations allowing composting from municipal solid waste to be commercialized as compost for agriculture
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, taxes exemptions for waste management to technologies, corporate taxes reduction, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.2.4. Anaerobic digestion

Anaerobic digestion is the decomposition of organic matter through microorganisms in the absence of free oxygen. Anaerobic digestion occurs naturally under circumstances of oxygen deprivation, but the process can be replicated under controlled conditions to produce biogas to generate energy. The fermentation thereby controlled happens in a reactor called a biodigester, which provides stable and better conditions (temperature, pH, organic matter, etc.) for the microorganisms. The main outputs of the biodigestion are biogas and solid and liquid digestate. Methane is the source of the energy content in the biogas, its content usually ranging between 50 percent and 75 percent, depending on the input of waste and the operating conditions. The heating value of biogas is about two thirds that of natural gas (5.5 to 7.5 kWh/m3) (17). Biogas has a number of uses. Usually, small-scale biogas plants in developing countries convert it into heat and use this energy for cooking, heating, drying of grains, etc. However, plants with more complex technologies can generate electricity and heat through cogeneration (6).

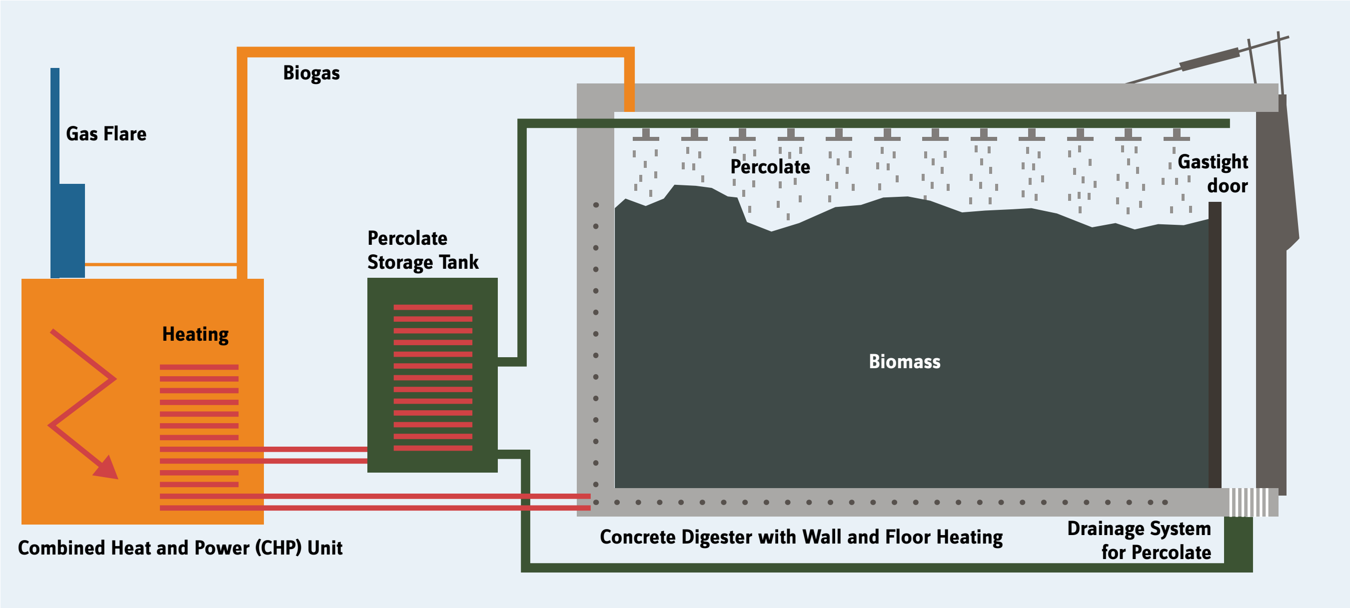
In developed countries, the organic fraction of municipal waste is treated in high-tech biogas plants. The input is source-separated in order to avoid contamination of the digestate. Large-scale biogas plants in developed countries frequently produce electricity to be sold and distributed for consumption in the national electricity grid. The heat produced during the cogeneration may be used for household heating or industrial heating. Biogas can also be cleaned and used in transport, for motor cars, gas networks, etc.

Depending on the waste input, the process flow and the main process parameters, anaerobic digestion can be categorized as:

- Psychrophilic (< 25°C), mesophilic (35-48°C) or thermophilic (> 50°C). The last is recommended when there is a risk of pathogens being produced.
- Wet fermentation or dry fermentation: waste with more than 30-40 percent dry matter (dry anaerobic digestion), waste with less than 12-15 percent dry matter (wet anaerobic digestion).
- Batch or continuous feeding: continuous feeding is common in processing liquid feedstock, such as catering waste, wastewater or industrial sludge from food-processing. Batch-feeding and batch digesters are common for solid waste input. Because most waste processed is solid waste, this is also called dry fermentation.
- One-stage and multi-stage digestion: defining the use of one or more digesters to optimize separate anaerobic digestion stages, e.g. separating the hydrolysis and acidosis from the methane-formatting phase (27).

The dry fermentation process is mostly used to treat waste inputs that are not suitable for pumping and that have a significant content of impurities that can be harmful to the stirrers and pumps in a wet fermenter. Furthermore, dry fermentation has a lower energy consumption. As a result, dry fermentation is widely used to process the organic fraction of municipal solid waste in Europe. In dry fermentation the feedstock is inoculated with digestate before each feeding cycle, and the percolate is run in circuit. The inoculum contains methanogenous bacteria, which supports the conversion of organic

Figure 3. Dry fermentation process.



Source: Qian et al., 2016

Table 6. Advantages and disadvantages of wet vs. dry fermentation

	Dry fermentation **Dry d.m. > 40 percent**	**Wet fermentation** **Wet d.m. < 15 percent**
Advantages	No need for internal mixing equipment in the reactor; strength and resistance to heavy aggregates and plastics; low loss of biodegradable organic matter in the pre-treatment; high organic loading rates; resistance to substrate concentration peaks and toxic substances; minimum and cheaper pre-treatments, reduced volume of reactors, reduced use of fresh water; minimum required heating for the reactor.	Developed technology; applicability in co-digestion with liquid waste with high organic matter content; reduced costs for pumping, mixing and pumping worldwide in the whole market: dilution of concentration of toxic substances.
Disadvantages	Less opportunity to dilute inhibitory substances and organic loads with excessive fresh water; high investment costs due to the equipment used for the treatment.	Separate phases of floating and heavy matter; abrasion of the mechanical parts due to the presence of sand and aggregate; pre-treatment of waste complex and expensive; strong sensitivity to any shocks to the presence of inhibitory substances and organic load variables; lost or organic volatile substance during pre-treatment; high investment due to equipment for the pre-treatment and for the volume of the digesters.

Source: IGWSRL (no date)

acids into methane, mainly in the digester (see Figure 3). Table 6 compares the advantages and disadvantages of wet and dry fermentation.

While biogas is frequently used to generate electricity and heat in a combined heat and power generator, the digestate can be used as fertilizer provided the waste inputs consist of source-separated, non-contaminated biodegradable waste. The solid fraction of the digestate can be dried to be used as compost, and the liquid fraction can be used as a growth stimulant for plants due to the presence of micronutrients and phytohormones. Tables 7, 8 and 9 below show some of the average indicators for biogas yields for different organic waste inputs, efficiency ratings for electricity and heat conversion by type of generator, the average electricity and heat consumption of biogas plants, and some of the general characteristics of anaerobic digestion as a waste-management technology.

4.2.5. Mechanical Biological Treatment

Mechanical biological treatment usually involves a first treatment phase, corresponding to the separation and sorting of recyclable materials (recycling plant), and a second

Table 7. Biogas and energy production for biodegradable municipal solid waste

Biodegradable waste type	Biogas yield (m^3/ton fresh)	Percent Methane	Methane yield (m^3/ton fresh)	Energy content (kWh/m^3 methane)[a]
Municipal solid waste organic fraction[b]	107	64	85	9,97
Kitchen and garden waste[c]	–	–	40 - 100	
Municipal solid waste organic fraction fresh[d]	106	–	–	
Kitchen waste[e]	80 - 120	58 - 65	–	

[a] Wirtschaftlichkeitsrechner Biogas KTBL, 2018. [b] GIZ, 2014. [c] GIZ, 2017. [d] Al Hamamre et al., 2017. [e] Austrian Umweltministerium, 2011.

Table 8. Energy conversion efficiency co-generation

Generator unit type	Gas Otto engine	Diesel engine
Electrical efficiency	34 - 42[a] 38%[b]	30–44 % 41.5%[b]
Thermal efficiency	47%[b]	42.5%[b]
Biogas plant own electricity consumption	7.6% [c] 8.1%[d]	
Biogas plant own heat consumption	28%[e]	

[a] FNR, 2016. [b] KBTL, 2018. [c] Wirtschaftlichkeitsrechner Biogas online tool, 2018. [d] Solarenergieforderverein Bayern, 2006.
[e] Wirtschaftlichkeitsrechner Biogas online tool, 2018.

Table 9. Overview of anaerobic digestion

Scope of technology/ approach	• Treatment and valorization of biodegradable waste • Energy generation (electricity and/or heat) • Production of organic high-quality fertilizer
Reasons for choosing this option	• Best option for cities with high biodegradable waste fractions and high waste flows • Anaerobic digestion is the best option for cities collecting "good quality" biodegradable waste separately from other waste streams. That would ensure high-energy production and high-quality fertilizer • High investment costs but lower operating costs • Generates up to three different valuable outputs (electricity, heat and refuse-derived fuel made from non-recyclable dry residual waste)
Trade-offs	• High investment • Low operating costs, but also low potential for job creation (workforce) • Payback period can be long (frequently seven to ten years) • More complex technology and market conditions, but it allows the economic risk to be distributed by diversifying cash flows • Higher mitigation potential (by diverting waste from landfilling, replacing fossil fuels for energy generation and replacing fossil fuel-based fertilizers)
Barriers	• Needs waste separation at the source • Needs quality standards for the final fertilizer • Needs a stable market for fertilizers and energy (e.g. national grid or private consumers) • Needs clear policies and a legal framework allowing and supporting energy generation and commercialization from waste (e.g. feed in tariffs, tax reductions, etc.)
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporate tax reductions, etc. • Long-term agreements with municipalities allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service-providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

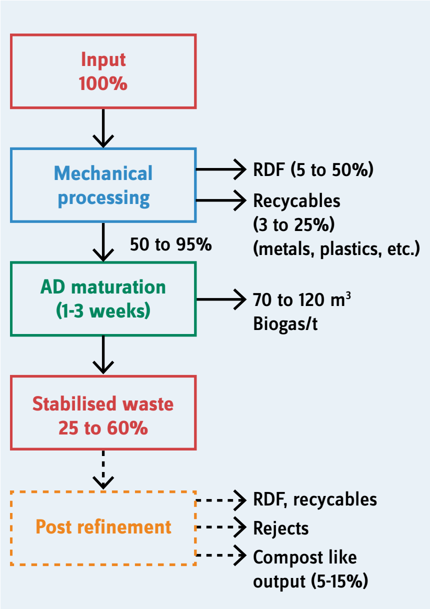
one, which could be anaerobic digestion, involving composting for the biodegradable fraction. Dry recyclable materials are sold for reutilization and the stabilized final compost-like material is landfilled or dried for its use as an alternative fuel (refuse-derived fuel or refuse-derived fuel) in incinerators or in industrial furnaces, such as cement kilns. Additionally, dry non-recyclable materials with a high calorific value (e.g. low-quality recyclables) may be also destined for energy generation as refuse-derived fuel. Due to the high construction and operating costs, mechanical biological treatment plants are mostly found in developed countries (Europe, United Kingdom and Australia) (16).

The term "refuse-derived fuel" is used to define any material that can be co-combusted and used as a secondary fuel in incineration and/or industry plants. As industrial solid waste is typically more homogeneous in its physical and chemical characteristics, industrial non-hazardous waste is frequently used as secondary/substitute fuel, e.g. waste tyres, waste oils, spent solvents, bonemeal, animal fats, sewage sludge and industrial sludge. Also homogeneous residues from industries such as plastics, textiles or the biomass industries can be used as an alternative fuel. In the context of municipal solid waste, the term "refuse-derived fuel" is used to indicate a secondary fuel derived from mixed waste fractions, different coarser grain sizes and variable physicochemical characteristics. Owing to mechanical biological treatment being able to use a combination of treatment processes and to produce different refuse-derived fuels, we will now present some of the different options:

- **Mechanical biological treatment with anaerobic digestion:** This process is ideal for generating renewable energy (e.g. electricity) for sale and distribution through the national electricity grid. Then anaerobic digestion as part of a mechanical biological treatment would represent an optimal option for waste treatment with energy recovery in a country with a favourable regulatory framework and technical conditions in place. Regarding refuse-derived fuel production, after the biodigestion, the organic fraction is dried through a composting-like process, leaving a dry, stabilized, highly mineralized organic material. This material also contains some non-recyclable dry waste, which is finally separated and used as refuse-derived fuel. Figure 2 shows the process flow of a mechanical biological treatment with Anaerobic digestion.

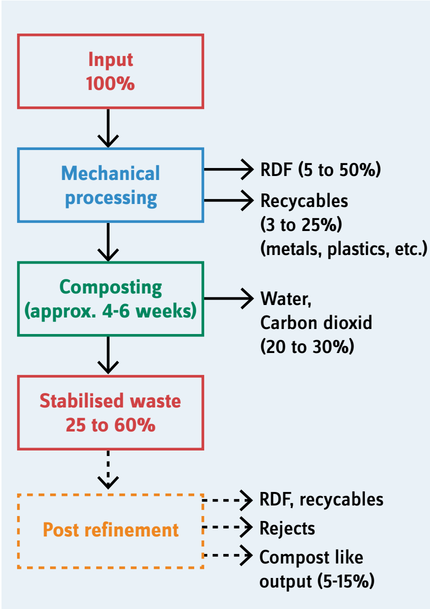
- **Mechanical biological treatment with aerobic stabilisation:** The key target of this option is mainly to treat mechanical biological treatment for further disposal, without economic dependence on other markets such us energy or refuse-derived fuel. Here, the organic fraction is stabilized, reducing the amount of biodegradable municipal waste going to landfill. Typically, the biological treatment is combined with mechanical processing to separate the refuse-derived fuel products from the waste prior to or after the biological treatment. When the refuse-derived fuel fraction is separated first, the material left after separation of the refuse-derived fuel is enriched with easily degradable components like kitchen waste and dirty paper, like tissues, which are not suitable for recycling. This material is then treated through an aerobic process (composting). This process uses some of the energy and material in the organic matter, thus generating carbon dioxide and heat. After the biological

Figure 4. Mechanical biological treatment with anaerobic digestion



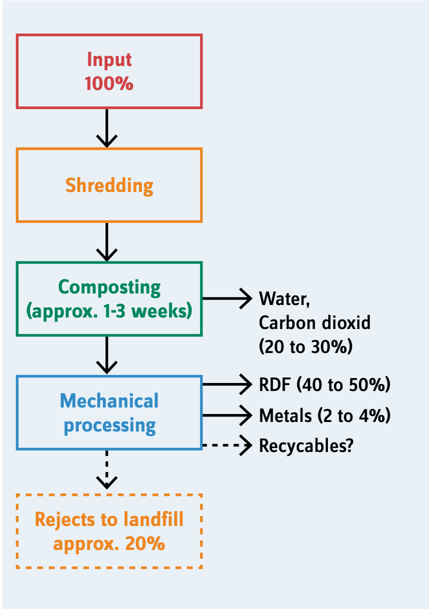
Source: 36

Figure 5. Mechanical biological treatment with stabilisation



Source: 36

Figure 6. Mechanical biological treatment with biological drying



Source: 36

hydrolysis, the waste is stabilized and ready for landfill. Further possible treatment would be a post-refinement stage, where more RDF can be separated from the stabilized compost-like material. Adding this stage depends mostly on economic feasibility more than technical issues. Figure 3 presents an example of this process, with waste streams.

- **Mechanical biological treatment with biological drying:** this combination seeks to make use of the energy content of the waste to produce a high-quality refuse-derived fuel, which can be burnt in industrial plant like cement kilns at a lower price than in a combustion facility or mass burn incineration. This "compost-like" process aims to remove the water content from the organic waste fraction by modifying the process and control parameters, thus enabling easier mechanical treatment subsequently. Müller and Bockreis (36) explain a typical mechanical biological treatment process with biological drying as follows: "The waste is shredded and placed in enclosed bio-drying boxes, where air is forced through the waste creating optimum conditions for microbiological activity, which will produce the heat for removing moisture from the waste (drying). The biological drying process is stopped at 15 percent to 20 percent water content, however, further drying can be performed by passing pre-heated air (produced with heat exchangers). With the drying of the waste the calorific value of the material is increased".

It is important to stress that the mass flows, efficiency of mass conversion, parameters and quality of the final refuse-derived fuel will depend strongly on the composition of the mechanical biological treatment, the input of the mechanical biological treatment plant. The values mentioned in Figures 4, 5 and 6 indicate a reference to what the conversion rates could be. Table 10 below presents an overview of some of the general characteristics of mechanical biological treatment when considering it as a waste-management technology.

Table 10. Overview of mechanical biological treatment

Scope of technology/ approach	• Combined process: sorting and mechanical treatment of recyclable materials • Energy and fertilizer production • Production of refuse-derived fuel as a secondary fuel
Reasons for choosing this option	• This is the best option for cities generating high waste amounts, but with a non-existent or incipient separation at the source system (collection of mixed waste) • Mechanical biological treatment maximizes material and energy recovery through refuse-derived fuel production, even after the biological treatment • Higher mitigation potential through the use of refuse-derived fuel as an alternative fuel in other industries • Best option for cities with high waste management budget (high investment costs) • Low operating costs
Trade-offs	• Due to higher investment, needs larger amounts of waste to be treated and therefore is not suitable for small cities • More energy consumption than other treatment options (more processes involved) • Greater potential to create more jobs (more complex layout that other treatment options) • Can work with mixed waste, but the quality of fertilizers is not appropriate for agriculture or others; most likely to be disposed of in a landfill • If the compost-like product is further used as refuse-derived fuel, the quality of the waste input should be monitored to generate good-quality refuse-derived fuel
Barriers	• Needs waste separation at source • Needs quality standards for the final refuse-derived fuel • Needs a stable market for refuse-derived fuel • Needs clear policies and a legal framework allowing the use of refuse-derived fuel from waste as alternative fuel • Needs cooperation with other industries (e.g. cement) to achieve attractive and stable market conditions
Enablers	• Waste management policies and legal framework with goals and quantitative targets for recycling, composting, anaerobic digestion, mechanical biological treatment energy from waste (also for reducing environmental impacts from waste, such as climate change) • National policies allowing the private sector to invest in waste management and to access waste materials (including formalized and organized waste workers) • Creation of economic and financial support programmes for private investors, e.g. investment funds, low interest rates, tax exemptions for waste management to technologies, corporate tax reductions, etc. • Long-term agreements with municipalities for allowing access to the waste (for private investors) • Involvement of formalized waste workers as waste management service-providers, especially for waste collection • Creation of quality standards for products (fertilizers, refuse-derived fuel)

Source: Own elaboration. Sandra Aparcana (UNEP DTU Partnership, Copenhagen, Denmark)

4.3. Key policy-related issues

Typically, municipal solid waste management systems are institutionally structured on three main levels that play different but equally important roles involving national, regional and local governments. While national government responsibilities often cover general policy or strategic decisions and the establishment of institutional and legal frameworks, regional and municipal governments are frequently in charge of their actual implementation. Regional administrations might be in charge of finances and may also be involved with the protection of regional environmental health and environmental management, or supporting municipalities through the implementation of waste-management plants. They are more likely to be involved in managing regional disposal sites, especially where regional disposal facilities are used by several towns and cities. The third governance level are the municipalities, which are typically in charge of organizing, providing and regulating municipal solid waste management services (sweeping, collection, transport, etc.), as well as implementing municipal solid waste management plans. Regarding the provision of services, cooperation with the private sector is increasing. Normally, in such cases, it is the local authorities that remain responsible for regulating and controlling the private sectors' activities.

Even though municipal solid waste management systems typically follow the structure described above, there is no doubt that they can be very different from one city to another, mainly due to their socio-economic and legal contexts. However, cities in developing countries share some common aspects or tendencies regarding their waste management problems in terms of efficiency, inappropriate waste management disposal practices, and the social, environmental and economic impacts.

These similarities allow common aspects to be identified that can be considered "key overarching enablers" for achieving sustainable municipal solid waste management systems. They could therefore be included in any waste management policy, plan or strategy:

1. Establishment of waste management policies and a legal framework (also related to waste management) with clear and measurable goals and targets, also promoting the reduction or prohibition of landfilling untreated waste. A measure like this would redirect waste materials to different treatment options. waste management targets should be measurable and legally enforced. To support their achievement and ongoing improvement, it is important to lay down legal and regulatory enforcement mechanisms. Targets should be binding, involving all relevant actors in the waste value chain, and, if possible, meeting targets should be sanctionable according to the country's regulations.

   Following that, waste management policies should incorporate the "waste hierarchy" as the key principle of all waste-management regulation and policies and others related to resource efficiency. Establishing a waste management hierarchy makes it clearer to authorities and other relevant stakeholders what the path is to higher levels of resource efficiency. A starting point could be to introduce policies to favour waste treatment and recycling. After that, waste management policies should rise higher in the waste hierarchy, towards waste prevention and upstream waste repurposing.

2. Establishing a “healthy” municipal solid waste management cost structure and budget. Frequently, waste management service fees are defined on the basis of waste generation per capita, censuses, land registries and others, and not based on the actual waste amounts generated by consumers, nor the actual waste management costs. waste management costs tend to be under-estimated, making waste services fees are lower than the costs they should cover. In addition, municipalities do not have a functioning waste-collection scheme, and there is often great mistrust on the part of the local population and a strong unwillingness to pay waste management fees. This situation could be improved by estimating the actual waste management costs and establishing of appropriate municipal solid waste management revenue streams, as well as through adjusted waste collection and disposal fees for waste service users. This should be combined with more effective ways to collect waste management fees, such as by including them in other basic services (e.g. electricity, water) and by gradually improving waste management services to increase willingness to pay.

   Another example of measures to reduce waste management costs for the municipalities could be to allocate waste-management costs to waste generators (the “polluter pays principle[3]”) in accordance with the amount of mixed waste that is generated. Applying this might successfully encourage users to separate their waste and even modify their consumption patterns towards a more efficient use of resources.

3. Appropriate formalization or integration of the informal waste sector. Policies and legal changes allowing the formalization of the informal sector are a key aspect, especially focusing on their economic and social empowerment, which would allow their successful integration into the formal waste management system (see section 2). Policies, legal frameworks and formalization strategies should start by considering the informal waste sector as a key stakeholder when it comes to achieving the waste management targets. Some experience with formalization experience has shown the readiness of informal waste workers to be formalized as long as this happens in a participatory way that fulfils their expectations and needs regarding their working conditions, income, flexibility and empowerment, among other issues (1).

4. Incentives for the private sector to invest in waste management include establishing legal, economic and fiscal incentives, as well as companies to invest in waste management services and to participate as waste management operators. Among the incentives that could be considered are value added tax exemptions, reductions in corporate taxes, attractive conditions for concessions of waste management services, guaranteeing long-term access to waste materials, tax exemptions for technology imports, access to renewable energy prices, and business models-based extended producer responsibility schemes in cooperation with municipal waste-management systems.

3
The principle that those causing pollution should meet the costs to which it gives rise (36).

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5. Drought

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Currently 4.1 billion people live in urban areas, and a quarter of the population in large cities relies on stressed water resources (1). In 2019, the average urbanisation rate was 1.8 percent (2), increasing the pressure on water resources, which are being further stressed by climate change. In urban areas, 143 million people still lack at least basic access to drinking water services, and 605 million are without access to at least basic sanitation facilities (3).

Water is the primary medium through which climate change influences the Earth's ecosystem and therefore the livelihood and well-being of societies (4). Globally, the interactions of increased temperature, increased sediment, nutrient and pollutant loadings from heavy rainfall, increased concentrations of pollutants during droughts and the disruption of treatment facilities during floods is reducing raw water quality and posing risks to drinking water quality. Climate change during the 21st century is projected to reduce renewable surface water and groundwater resources in most dry subtropical regions, thus intensifying the competition for water between sectors (5). Higher temperatures will intensify the global hydrological cycle generally (6). In dry regions, the frequency of droughts is likely to increase by the end of the 21st century. In contrast, water resources are projected to increase at higher latitudes (5).

Globally, the direct annual cost of drought is estimated at around USD 80 billion, without including indirect impacts like salinity, water quality, conflict, civil unrest, forced migration and food insecurity. Droughts are four times more costly for economies than floods (7). The financial losses associated with droughts in Europe from 1976 to 2006 were estimated at EUR 100 billion (8). The main disruptions to the economy are caused by severe restrictions and temporary interruptions to the water supply. This leads to higher operating and maintenance costs for industrial users and energy producers, loss of income, competitive disadvantages in the agricultural sector and losses in activities that depend on water, like tourism in Cape Town, South Africa, in 2017 and 2018 (9).

In 2013, the World Meteorological Organization, the United Nations Convention to Combat Desertification and the Food and Agriculture Organization organized a High-level Meeting on National Drought Policy.[1] which identified three pillars in the fight to increase resilience to drought:

- Implementing drought-monitoring and early-warning systems;
- Completing vulnerability assessments for sectors, populations, and regions vulnerable to drought;
- Implementing drought mitigation measures that limit the adverse impacts of drought and provide appropriate response measures when drought next occurs. (7)

Technologies can provide solutions for each of these pillars. Water-related innovation is a vibrant industry globally. Recently, patenting rates of water conservation and availability technologies have been higher relative to the overall rate of patenting for all (non-water) environmental technologies. This suggests an increasing demand for

1
In order to address the issue of national drought policy, the World Meteorological Organization, the Secretariat of the United Nations Convention to Combat Desertification and the Food and Agriculture Organization of the United Nations, in collaboration with a number of partners, organized a High-level Meeting on National Drought Policy in Geneva, Switzerland in 2013. The goal was to provide practical insights into useful, science-based actions to address key issues regarding drought and various strategies to cope with it (46).

improving the management of water resources and an increasing interest in innovation to address issues of water quality and quantity (10).

Innovation does not always take the form of technological breakthroughs at a high level: it also entails the production of and improvements to processes and products, which can be incremental. This type of innovation can produce "low-cost" technologies, for example, the spaghetti micro-tubes used for drip-irrigation of perennial crops, which allows farmers access to a rudimentary drip irrigation system.

This chapter presents three technical solutions for drought[2] adaptation and discusses the policy implications that need to be considered when introducing these technologies. The following section presents the selected technologies and describes how they fit within the whole range of technical solutions that are available for water-scarce cities.

5.1. Overview of technology options

Typical responses build on grey infrastructure designed to augment supply (increased storage capacity, extended mains to catch water further away from cities, or desalination plants). Such responses can add pressure to the resource and other uses, intensifying competition between cities, the environment and other users. They also can increase other water-related risks, such as flood risks, water-quality risks or risk to the resilience of ecosystems. They are only appropriate under certain conditions and limits. Cities like Cape Town or Chennai, which have essentially relied on supply augmentation measures, have proved vulnerable to extreme events. Additional short-term responses, such as banning or rationing certain uses, can come at high social or economic costs (11).

More resilient responses combine a series of measures (including the reform of water allocation regimes, management of demand), and operate at different scales. A systems approach can help determine the limitations of one-sided measures and the appropriate combination of diverse measures at the least cost for communities (11). Cities in basins characterised by drought can put in place a combination of options to avoid water scarcity. These options aim to (1) reduce overall water use, (2) reduce freshwater use by promoting the use of alternative water sources, such as reclaimed water, (3) allocate water efficiently where it is most needed, and (4) obtain additional sources of water and storage facilities.

These options are complementary to the International Water Association principles for water-wise cities focusing on a broader scale, including sustainable urban water, which covers water scarcity (12). The above options can address the technical, institutional, regulatory and economic dimensions of technological innovation.

2
A drought is defined as a prolonged period of low rainfall. Water scarcity is defined as the lack of freshwater resources to meet water demand for all uses. Water scarcity can happen without droughts, due to water pollution. In addition, drought does not have to lead to water scarcity if additional resources are available. However, a strong link exists between drought and water scarcity in the long term.

5.2. Selected technologies

The three technologies presented in the following section are technical solutions[3] to increase cities' resilience to climate change. Technical choices can only be considered appropriate where they are tailored to meet country-specific needs and contexts. New technologies operate within existing policy and institutional frameworks. Therefore, the implementation and transition of new technologies between existing and potentially required contexts are key factors in ensuring their adoption and effectiveness.

For cities located in low- and middle-income countries,[4] some technologies may not be directly affordable in terms of not only cost but also capacities. Building up innovation capabilities in low- and middle-income countries requires approaches that emphasise flows of underlying knowledge (know-how and know-why) and tacit knowledge. Policy also needs to account for context-specific technological and cultural requirements, which vary inter- and intra-nationally (13). Therefore, an 'adapt and adopt' strategy may be required to make these technologies relevant in low- and middle-income countries.

These innovations were chosen because they increase cities' resilience to drought under the current climate crisis. They are relevant and proven solutions for decision-makers across different water-scarce cities:

- **Smart water systems can be used to monitor water use, with a view to improving the management of water resources.** These systems provide multiple benefits. For instance, they provide data that can inform how water should be allocated where it is most valuable. In addition, this technology can help mitigate water scarcity by providing crucial data, such as identifying the highest water consumer or major leakage, to manage ensure and manage sustainable water usage efficiently. Finally, it increases users' awareness of water consumption and nudges consumers toward water-saving measures.

- **Blue-green infrastructures can be used to collect and store rainfall upstream of a city, thus increasing water resource availability.** They can provide affordable and sustainable solutions for increasing the water resources available for cities. They can also provide additional eco-system services, such as improving air quality and flood protection in cities. In addition, they have a decisive advantage compared with other technologies because they avoid technical lock-in and support adaptive management as risks, opportunities and social preferences evolve.

- **Distributed sanitation with in-situ reuse of reclaimed water for non-potable uses, to free up higher quality water resources.** Distributed sanitation systems increase water availability locally by transforming existing waste into a resource. This technology can have a major role for non-potable uses not requiring the highest water-quality standard for activities such as watering green spaces or cleaning buildings and vehicles.

3
Technology' is a broad concept, which includes techniques, skills, methods and processes used in the production of goods and services.

4
Economies are divided into four income-related groups: low, lower middle, upper-middle and high. Income is measured using gross national income per capita in US dollars (44)

5.2.1. Smart water systems to monitor water use: multiple benefits to allocating water where it is most valuable in a time of scarcity

Scope of the technology

Smart water systems are sensors, networks and software that allow service providers to monitor, manage and act on data relating to the part of the water cycle that is pertinent to their interests (14). They require automated data on water flows and water availability and often rely on complex mathematical modelling to derive a better understanding of river flows and improve infrastructure design (15).

Decision-makers can use the outputs of these tools to improve city resiliency by preparing the city for extreme events and improving resource use. Concerning water scarcity, smart water systems contribute to solving numerous challenges such as water access and quality, reduced demand, irrigation efficiency, decreased water losses, and reduced operating costs (e.g. energy use), as well as planning across a diversity of geographical scales.

To avoid water scarcity, cities need to plan measures based on water balance thresholds by assessing several variables simultaneously. Several countries, with Israel and Korea paving the way, have explicitly encouraged the development and deployment of smart water systems to improve water management. For example, during the water crisis in Cape Town in South Africa in 2018, the city scaled up the installation of household flow regulator devices to target households using large amounts of water (i.e. houses with large gardens, etc.), while effluent reuse schemes were stepped up to increase the amount of potable water that could be used (16).

Smart meters facilitate statistics on per-capita use and the analysis of overall water consumption. This technology supports the pro-active involvement of water users, allowing them to control the way they use water better. For example, in Boston, United States, meters registering unusual water consumption automatically warn the operator, which can in turn call the customer to check whether this unusual consumption is due to a leak or some other reason (17).

With this technology, service providers, consumers and policy-makers can fine-tune the link between water consumption on the one hand and water prices and income on the other. In addition, they can improve demand forecasting by factoring in climate variation, irrigation needs, family size and household consumption (where they have access to such data). Smart meters, coupled with flow-trace software, breaks down water consumption data by time and various types of indoor and outdoor use. This can be very helpful for service providers that are willing to refine their predictions of water demands and to improve their targeting of inefficient customers and/or appliances that should be replaced (17).

Korea’s smart water city project
The smart water city project is an example of the Korean government’s efforts to manage water resources more efficiently. It provides the water utility and the final water users with instant and reliable information on water use and on the quantity and quality of the water supplied, in particular to facilitate leakage detection and encourage the drinking of tap water. The technology provides usage and charge information through a smartphone app by analysing volume used, abnormal flow rates and leakage, based on time data acquired from digital meters (18).

A water-use variable is required to monitor water balance and thus prevent water scarcity during episodes of drought. In addition, monitoring this variable provides the data needed to reduce non-revenue water, increasing the volume available and reducing the costs for users.

In addition, Korea has nominated Busan as a National Pilot Smart City to demonstrate technological innovation, including in the water sector. Co-developed by the public utility, the master plan is the first eco-friendly waterside-complex city in Korea to apply water-specific smart technology in a smart-city business model (19).

Cost-effectiveness

The introduction of this technology can reduce non-revenue water, which decreases service-providers costs for water collection, treatment and distribution while reducing users’ water bills (18). For illustrative purposes, the following table presents the savings achieved in three locations within a network in Paju, Korea, when introducing the technology.

Location (network segment)	Leak quantity (m^3 /day)	Saved cost (million KRW/year)
GH 1-3	355.7	120
BW 1-1	397.0	134
JS 1-1	767.9	260
Total	**1520.6**	**515**

Source: K-water internal document, 2017.

This technology can support strategic prioritisation and capital allocation for maintenance activities based on the uses within a network. Service providers and authorities struggle to keep pace with the required infrastructure renewal from current revenues. To close the gap between the capital spending required and the amount of financing available, service-providers and the authorities need access to information on the evolving status of network assets. The data provided by this technology can serve as an additional variable in making decisions over prioritising asset renewal.

Trade-offs

From a service-providers' point of view, the financial cost of rolling out and operating smart water systems may not justify the benefit derived from such systems. The initial capital investment required to put a smart water system in place is higher than an automatic meter reading (two-way communication versus one-way communication). Receiving one-way information covers most the service provider's needs such as accurate billing, leakage data and non-revenue water detection.

Barriers to adoption

A regulatory framework establishing a short-term spending programme for utilities can limit investment in smart water systems due to the long payback period required. For example, in England and Wales the national regulator enforces a five-year spending programme on utilities. Smart metering has too long a payback period for this model (17).

Smart water systems are mainly used in combination with grey infrastructure, which could imply high capital costs. Korea installed a sophisticated and extensive network of large, medium and small dams, irrigation facilities and multi-regional water systems over the course of twenty years to supply water for domestic, industrial and agricultural uses, prevent floods and droughts, and generate hydro-electricity (18).

The capacity to produce, collect and share data of good quality varies from one city to another. The Organisation for Economic Cooperation and Development (OECD) survey on water governance for future cities, carried out in 2014, indicated that the key issues with data usually are (20):

- The information available is too technical;
- Data collection is incomplete and irregular;
- Data is dispersed across agencies, making it difficult to track and compare;
- Lack of data on the water balance.

Smart water systems require specific teams in charge of data analysis to carry out a water balance. Therefore, human and financial resources are needed, as well as direct collaboration with decision-makers to implement preventive measures based on the data. Data on water uses can be used to design activities targeting water savings for specific uses. However, service providers may not have the staff required to analyse and interpret data outputs. Smart water technologies place a new challenge on service providers: data has to be produced at the appropriate resolution and frequency to provide useful inputs to prevent water scarcity and optimise usage rates (21). In 2014, during California's four-year drought peak in the United States, utilities started to hire data scientists and coders to support the design of rate structures and programs that encouraged water efficiency (22).

The lack of open-source software and standardisation among smart water systems results in data issues around storage, transfer and use. Due to the lack of international standardised software and data warehousing, service-providers may need to switch software when implementing smart water systems, thus increasing the capital costs. Potential workarounds could compromise service-providers' software security.

Enablers to adoption

Water scarcity, combined with economic incentives, creates a demand for smart water systems technologies. In Israel, economic incentives designed to reduce water demand in urban areas, such as increasing block tariffs and fines for municipalities at a level of above 12 percent water loss, resulted in the development of innovative water management devices. Israel saw an increasing demand for (i) water meters that are read remotely and more accurately (including measuring small drops, so leaks would be fixed), (ii) devices to optimise the network's pressure, and (iii) computerised irrigation systems (18).

Smart water systems may be adopted as an unintended consequence of unrelated initiatives. For example, in Scotland since 2008 the competition for non-domestic customers has triggered the diffusion of smart meters, as utilities have striven to improve their performance and customer service. Advanced metering, pressure management and pipe-monitoring systems have reduced leakage with minimal physical intervention (17).

To avoid water scarcity, water balance at a higher level than the city is required. Decision-makers may be daunted by the idea of investing in a technology that can only be used to take decisions when additional data is required outside their jurisdiction. Metropolitan governance arrangements are mechanisms to pool resources and capacity across municipalities within metropolitan areas. They can help to handle interdependencies across authorities and reduce fragmentation to manage water resources and water services more efficiently.

Linkages with other sectors

Stakeholders trying to reduce overall energy consumption can use smart water systems. Smart water systems can decrease energy consumption and losses by reducing the amount of water pumped, transported, heated, or treated. Overcoming leakage requires additional energy to pump and carry water that does not reach consumers. Smart water systems can monitor online pressure and provide warnings of pressure changes or significant pressure losses in the network. With this technology, utilities can optimise the network pressure remotely to help save energy (23).

The smart water systems used for monitoring water use in the water and sanitation sector apply to industry, energy and agriculture. Utilities, users and decision-makers can use this technology in other sectors. In OECD countries, such as Spain and Israel, farmers use this technology to plan and assess drip irrigation and fertilisation for high-value crops. They monitor water consumption per crop (hence the different uses across plots and varieties) and automatize irrigation based on climatic, soil, physiology and phenotype variables.

5.2.2. Blue-green infrastructures to collect and store rainfall upstream of a city

Scope of the technology

Nature-based solutions are solutions inspired and supported by nature that are cost-effective, simultaneously provide environmental, social and economic benefits, and help build resilience to the impacts of climate change. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes through locally adapted, resource-efficient and systemic interventions (24). Nature-based solutions can be regarded as an 'umbrella concept' for other approaches, such as ecosystem-based adaptation, eco-disaster risk reduction, green infrastructure and natural climate solutions (25).

Blue-green infrastructure[5] is a type of nature-based solution that involves strategically planned networks of natural and semi-natural areas with other environmental features that are designed and managed to deliver a wide range of ecosystem services. These services include, for example, water purification, air quality improvements, heat wave reduction (chapter 7), carbon sequestration (chapter 2), and more space for recreation (25). Green-blue infrastructures refers to green-spaces and water bodies such as a network of wetlands, flood areas and retention areas.

Blue-green infrastructures can be part of the solution for dealing with droughts by increasing water availability for cities through storage, and groundwater and surface recharge, as well as helping improve water quality. Blue-green infrastructures help manage water scarcity because they can avoid technical lock-in[6] and support adaptive management as risks, opportunities and social preferences evolve. Many blue-green infrastructure technologies are mature and have been in use for centuries.

A 2019 survey by the Organisation of Economic Cooperation and Development (OECD) of implementation of its Recommendation on Water indicated that nature-based solutions feature quite prominently in water management strategies. In the national adaptation strategies and plans of Colombia, the Czech Republic, Hungary, Ireland, Slovakia and Switzerland, nature-based solutions were indicated as measures to be used against drought.

Blue-green infrastructures are also central to local water management plans and investments. For example, Eau du Grand Lyon, a French water utility, created artificial recharge ponds[7] and has entrusted a reforestation and conservation programme to the National Office of Forests to protect the natural recharge area for the wells (26). Box 'Eau du Grand Lyon' provides additional details.

This section focuses on blue-green infrastructures that collect and store rainfall upstream of a city. However, these infrastructures provide many other services of benefit to cities, notably services related to water quality and flood protection.

5
The term 'blue-green infrastructure' is used in this chapter to emphasize the diversity of technical solutions and their potential combinations within the concept. Green infrastructures, for example, include green roofs and permeable areas that can be integrated into the design of housing. Blue infrastructures, for example, are lakes, wetlands, canals and ponds.

6
Technology lock-in is a form of economic path dependence whereby the market selects a technological standard but because of network effects gets locked-in or stuck with that standard, even though market participants may be better off with an alternative (47).

7
Artificial recharge is the practice of increasing the amount of water that enters an aquifer through human-controlled means. In this case, groundwater was artificially recharged by redirecting water across the land surface through ponds.

Mexico’s drought management policies

In Mexico, nature-based solutions play an integral role in mitigating the risk of water stress and are a key component of drought management strategies (27).

Mexico’s National Water Programme (2020-2024) sets the framework for water-management investments in the country, including sustainable water management, increased access to water, technical capacities, and water security for floods and droughts. Within this framework, the car manufacturer Volkswagen collaborated with the National Commission of Natural Protected Areas in the Puebla-Tlaxcala valley to re-plant nearby deforested volcanic slopes to improve groundwater replenishment in the valley and build resilience against drought in the region. Increased water supply benefited both the nearby city of Puebla and the operations of the Volkswagen plant (28).

To monitor the effectiveness of these programmes, significant data is required. In Mexico, as in many countries, one challenge is the limited data that can be easily used to plan nature-based solutions. Performance is highly site-specific and at times complicated to assess, and a wide array of data, local information and methodologies may be needed to conduct technical feasibility assessments (27). In addition, Mexico also prepares budgets on an annual basis, which makes it difficult to secure long-term funding for monitoring.

Cost-effectiveness

Blue-green infrastructures to collect and store rainfall provide additional benefits, some of which can be quantified and monetised. These infrastructures can also increase water infiltration and reduce flooding risks to cities, while simultaneously supporting agricultural production and the functioning of ecosystems, and providing recreational and tourism benefits (29).

"Eau du Grand Lyon" water utility

The Eau du Grand Lyon water facility provides and distributes drinking water in the Grand Lyon area covering 59 municipalities with a population of 1.3 million. The Grand Lyon metropolitan area owns the land and the water infrastructure assets, decides on the investment programme and sets the water tariffs, leaving day-to-day operations and maintenance to Eau du Grand Lyon. Water comes mainly from wells in the Rhone River alluvial aquifer in the heart of the city, through riverbank filtration and managed aquifer recharge.

Eau du Grand Lyon assessed the benefits for its capital and operating costs of this natural infrastructure, compared with a grey infrastructure that would deliver similar water production capacity of 1 million m3/day. This assessment confirmed that, in this case, source protection was likely to be more cost-effective than grey infrastructure. Managing the natural infrastructure enabled the operator to keep water tariffs down through cost savings (26).

Table 1. Cost-benefit comparison of green and grey infrastructure by Eau du Grand Lyon

Costs	Existing green infrastructure	Classic grey infrastructure	Difference
Total annualized costs associated with typical coagulation and filtration plant (€ million/year)	32	52 to 74	20 to 52 € million/ year
Operating costs (€/ m^3)	0.04 (wellfields and source protection)	0.15 to 0.25 (for a treatment plant)	0.11 to 0.21 € million/year

Source: The Nature Conservancy, 2019

However, blue-green infrastructures have not been properly valued yet, limiting assessments of their economic benefits. Analytical frameworks often fail to take into account the co-benefits provided, placing them at a disadvantage when compared to grey infrastructures in economic terms. The economic analysis of blue-green infrastructures is complex and often lacks records of the achievement of past costs and benefits and robust performance data (27). For instance, blue-green infrastructures can mitigate climate change, as they capture carbon and reduce the urban 'heat island' effect. Blue-green infrastructures can gain value and function over time as soil and vegetation prosper. This makes assessing their benefits even more difficult, placing them at a disadvantage compared with grey infrastructures (25).

Trade-offs associated with 'adopting' the technology

Decision-makers face trade-offs between issues relating to water, energy and land. The main inherent trade-off for blue-green infrastructures in collecting and storing rainfall is that land cannot be used for other productive use. This is particularly an issue where land is scarce and high-value, typically in dense periurban areas. However, blue-green infrastructures provide multiple benefits, which can be aligned with the value of land. Ecosystem services can be combined with other valuable uses, such as sustainable agriculture in catchment areas. As an illustration, wetland, peatland and natural park restoration programmes are good examples of how economic activities (for example, tourist activities) can be combined with blue-green infrastructures, thus increasing the recharging of water resources upstream of cities.

Barriers to adoption

Blue-green infrastructures require space to be able to collect and store the large volumes of water that might be needed in a short period. Therefore, they are more adapted to new urban areas or rural areas upstream of cities. In existing high-density areas, these types of infrastructure are most difficult to implement because space is scarce.

Blue-green infrastructures require collaboration between the stakeholders of different sectors across local and regional scales (e.g. national flood and drought management agencies, public works or infrastructure agencies, infrastructure operators, and regional and local authorities) (27). Strong environmental and economic links connect urban and rural water users, including flows of agricultural goods, manufactured goods, people, information and ecosystem services between the two areas. Decision-makers can use the challenge of this strong economic regional interdependence as a platform to address water security. Cities can benefit from water savings and quality improvements upstream, and in turn help farmers make the best use of water by incentivising or compensating those who contribute to water security (17).

Lack of awareness and understanding about the performance of blue-green infrastructures in the longer run and gaps in technical capacity are hindering their design and implementation. This also encourages policy-makers to turn to options they are used to relying on, especially when they have to take decisions within a short time span. The difficulty of quantifying the benefits and the lack of robust performance data make it hard for blue-green infrastructures to be considered on a level playing field with grey solutions (27). Cities that are already equipped with grey infrastructures and predetermined technical pathways may struggle to adapt blue-green and grey infrastructural networks.

Blue-green infrastructures require time to deliver some of their services. In cases of drought, cities often look for short-term actions that can deliver immediate responses to crises (e.g. water trucks). Conversely, blue-green infrastructures tend to require anticipation and planning to provide water security.

Enablers to adoption

Blue-green infrastructures marketed as green investments are currently experiencing a rapid increase in demand. Public funding is an important source of finance to kick-start and cover any risks that projects may give rise to.[8] For example, the United Kingdom plans to invest around EUR 30 million through the Green Recovery Challenge Fund related to nature conservation and restoration, with a focus on tree planting and the rehabilitation of peatlands (27).

Policy coherence across sectors can be a catalyst for the deployment of blue-green infrastructures. This means that a cross-sectoral and cross-governmental approach is needed. Facilitating collaboration between multiple actors can improve coherence, help create synergies, and avoid trade-offs between different policy objectives (27). For example, health programmes have shown that introducing urban green spaces reduces heat-related mortality. Green infrastructures protect from heat by reducing the urban heat island effect and providing shading (chapter 7).

8
As noted by case-study interviewees, the availability of funding for monitoring and maintenance remains an issue for project implementation. This can lead to wariness amongst landholders, as they do not want to bind themselves to potentially costly long-term maintenance or unknown expenses in the case of a project's failure (27).

Decision-makers are putting in place economic incentives to support the introduction of blue-green infrastructure by valuing resilience to droughts and the co-benefits of nature-based solutions and signalling the cost of path-dependency. Incentives promoting policies allowing municipalities to levy a rainwater tax can be a strong stimulus for blue-green infrastructures. Municipalities can levy taxes based on the impervious surface of a property that drains water into the public sewage system. This type of tax takes into account the cost of treating all the wastewater which cannot naturally percolate through the soil (30).

Decision-makers are putting in place regulations to enforce the introduction of blue-green infrastructures through spatial planning, building codes and public procurement (27). In 2011 Copenhagen put in place a Municipality Plan that requires the establishment of green roofs on new buildings with a roof slope below 30°. The implementation of green roofs is not supported financially by government, and therefore developers and owners need to bear the full implementation costs. However, developers and owners are allowed to decide freely on the size, the type of habitat developed and the type of access to the roof (31).

Linkages with other sectors

The water and sanitation and agriculture sectors both require coherent planning to maximise the benefits of blue-green infrastructures. The EU Strategy on Adaptation to Climate Change also includes nature-based solutions as one of its three cross-cutting priorities, with the goal of increasing resilience and contributing to achieving the objectives of the so-called Green Deal. It specifically references nature-based solutions in the agriculture sector for adaptation to drought (27). For example, blue-green infrastructures that store water can be a tool for increasing crop resilience to climate change, while providing water for city water networks by increasing groundwater recharge and improving soil moisture.

The planning of blue-green infrastructures is at the core of urban planning, therefore decision-makers need to adopt a holistic approach that considers all their dimensions. As presented in other chapters (3 and 7), blue-green infrastructural technologies can be used for several purposes. These technologies require more complex planning due to their links with other sectors, but they provide a wider range of outcomes than grey infrastructures.

5.2.3. Distributed sanitation with in-situ reuse of reclaimed water for non-potable uses

Scope of the technology

In distributed system models, infrastructures and critical services are located close to points of demand and resource availability and are linked by exchange networks. Services traditionally provided by a single linear system are instead delivered through a network that is tailored to a location but able to transfer resources across wider areas. Especially for water and wastewater systems, distributed systems can:

- Reduce costs and resource use, by adapting water management to the context and making the most of available resources;
- Improve service security and reduce the risk of failure, by building redundancies into the system; and
- Adapt to shifting conditions and demands, as well as responding to risk and uncertainty, by increasing the diversity and flexibility of water systems without locking utilities, customers and future governments into rigid pathways for delivering critical services (32).

Distributed systems[9] do not phase out centrally piped infrastructures: rather, both systems coexist and rely on each other to build both redundancy and resilience (17). Distributed sanitation systems include in-situ wastewater treatment produced in-situ or collected such as rainfall. The wastewater can come from one individual source, such as a building, or from multiple sources in a limited section of the network, such as residential or industrial areas. The technology can vary hugely depending on the infrastructure and purpose; however, the common elements are collection, wastewater storage, treatment, treated water storage and distribution network or point.

Distributed sanitation in Tokyo, Japan

In Tokyo, drought projections suggest an increasing frequency of severe droughts (33), indicating that the city is likely to have a high risk of water scarcity by the end of the 21st century. In 2003, Tokyo established 'Guidelines on the Promotion of Efficient Water Usage', designed to provide guidance on using water (including non-potable water and rainwater) efficiently in large-scale construction and development projects. Because of these efforts, the number of facilities installing non-potable water systems has steadily increased. As of 2012, in-building recycling systems were installed in 408 facilities, 360 facilities had industrial water systems, and 1,335 had rainwater harvesting systems.

The Tokyo Dome, Japan's first all-weather multipurpose stadium, is equipped with both underground storage tanks to collect rainwater from the roofs, and a recycling system that recycles greywater from washbasins and kitchen sinks for non-potable use. These two systems combined provide roughly half of the Tokyo Dome's total demand for water (17).

Source: Adapted from a case study developed by the Tokyo Metropolitan Government for this Organisation of Economic Cooperation and Development project. It is based on data from the Ministry of Land, Infrastructure, Transport and Tourism (2013), Heisei 25-nenban Nihon no Mizushigen (Water Resources in Japan).

9
Decentralised and distributed systems have similar scaling and characteristics. Often they have the same modular and containerized technologies. However, there is a key difference in terms of the network: distributed systems are physically or managerially linked to a larger system, while decentralised systems are disconnected from the network. failure (27).

Cost-effectiveness

When water tariffs are linked to water availability, distributed water systems can reduce customers' costs during periods of water stress. Putting the right price tag on water can be done through administrative water pricing by a central authority. However, currently agricultural water use is substantially under-priced in most countries within the Organisation of Economic Cooperation and Development (17).

Trade-offs

Energy consumption can be a trade-off. Depending on the characteristics, the total energy required to treat wastewater locally may be higher than in a unique centralised piped system. If a renewable source provides the energy required, this will limit the trade-off.

Barriers to adoption

Distributed systems can limit economies of scale. Urban water management generates economies of scale, as it is generally cheaper to operate a large treatment plant than several smaller ones. Although treatment and reuse technologies can save on the capital costs of extending central infrastructures, this may require more energy, as economies of scale apply here as well (17). The difficulties involved in selecting the right scale of implementation makes it more challenging to assess economies of scale (20).

Distributed systems reduce users' overall consumption, which limits revenue for utilities. Service providers and authorities may be reluctant to explore options that negatively affect the existing networks' revenue base unless they can identify alternative sources of revenue (17).

In the case of water shortages, distributed storage precludes allocating available resources where they are most needed (17). Treated water cannot be re-introduced into the water network, only used in-situ. Distributed sanitation currently serves non-potable uses, though during periods of water shortages human consumption is the main priority.

The lack of a regulatory framework and of any clear responsibility can create barriers to introducing this technology. Who is responsible for the service provided at the building level? Accountability is a challenge because distributed systems require the capacity to monitor and control the quality of multiple water flows at several levels. For example, the United States does not apply overarching national quality standards for water for on-site systems using alternative water sources, nor regulations to address ongoing operations and public health concerns (17).

Distributed systems can weaken existing central systems when the wealthiest consumers disengage from the central network, thus depriving the managing utility of revenues. This is an issue because distributed systems work best in combination with centrally piped infrastructures (17).

Enablers to adoption

Distributed systems provide a local solution, which can decrease water competition across sectors by providing additional resources locally. The largest nuclear power plant in the United States, in Palo Verde, Arizona, uses wastewater as the sole source for cooling. The wastewater is piped in and re-treated onsite before being used. Once it runs through the cooling system, it is transported to a pond where it evaporates. The power plant has secured 98 billion litres of wastewater a year until 2050 (34).

Water scarcity pushes users to find additional sources of water. Distributed systems provide an additional source of water locally without using the common resource by re-using already existing water instead of consuming new water from the network. Water security is therefore increased locally and at the basin scale.

The readiness of decision-makers to display local capacities or to establish the city as a 'green' reference (17) within the country or the region can be a key factor in promoting distributed systems in cities.

Linkages with other sectors

Distributed sanitation systems can be considered in housing (chapter 2) and city-planning sectors. New developing areas are the ideal location for installing these systems, which require multiple piping networks. City planners could consider this technology when planning new areas and neighbourhoods within fast growing cities, presenting a strong threat to already scarce resources.

Distributed sanitation systems can be integrated with the energy sector, especially with renewable sources of energy such as solar. The treatment needed to transform waste into resources requires additional energy locally. Therefore, when combining this technology for renewable sources of energy, it turns into a multi-solution system by mitigating climate change and improving the city's adaptation response.

Distributed sanitation systems can be used for other purposes than non-potable uses outside the water and sanitation sector. Distributed water systems may be more acceptable from a user perspective when used in other sectors such as industry or energy.

5.3. Key policy-related issues

Urban water technologies entail trade-offs between water, energy and land use. An optimal combination of innovation and existing systems requires reflecting on the externalities that are related to these three dimensions. Water, energy and land use have an equilibrium point that is associated with using the most advanced, up-to-date technology available. At a given technological state of the art, further reductions in water savings signify increases in either energy consumption (for high-tech solutions such a distributed sanitation) or land use (for low-tech solutions such as blue-green infrastructures). However, until this equilibrium point is reached, there may be significant gains in water supply, wastewater and drainage. Beyond this equilibrium, improvements in one aspect can trigger costs in others. The choice of the most desirable trade-offs depends on the specific constraints of the city context (17). It is always a political decision.

Policies are required to overcome market failures and support the diffusion, deployment and use of water-related innovations. The use of innovative technologies requires that benefits are valued and captured to finance the capital and operating expenditure. While the supply of innovation for urban resilience to droughts abounds, markets fail to deploy them at scale. Market failures result from distinctive features of these innovations. For example, the price equilibrium of blue-green infrastructures does not accurately reflect the true benefits of the eco-system service. Prevalent business models and financing mechanisms may be biased towards the status quo.

Decision-makers can create a demand for technologies through regulatory instruments such as minimum and quality standards and economic instruments (35). Until prices reflect water stress or cities face a 'day zero',[10] customers may not demand alternative technologies to reduce water use and guarantee the continuity of services. **Pricing policies reflecting water scarcities combined with awareness-raising can increase the demand for water-saving technologies**.

Regulatory frameworks can drive the diffusion of innovation, but they can also lock cities into sub-optimal technical trajectories. Technical innovation is flourishing, but the diffusion of these technologies across borders and sectors is lagging behind. Some innovations, such as smart technologies, distributed systems or blue-green technologies, are potentially disruptive. Disruptive technologies work best in combination with non-technological innovations, such as water-sensitive urban design or innovative business models for water utilities. Water-sensitive urban design refers to land-planning that takes into account the urban water cycle and water supply in order to minimise environmental degradation and improve the aesthetic and recreational appeal. Cities would benefit from having a wide latitude to explore technologies that fit contexts (17).

When introducing innovations to reduce water consumption, the financial viability of utilities may be threatened. Policy-makers and service providers will need to consider innovative business models and identify additional sources of revenue to ensure financial incentives for utilities. If correctly used, smart water systems and distributed systems can reduce water consumption, though this compromises the financial sustainability of water utilities. Nonetheless, the water sector is currently testing alternative regulatory models to guarantee financial incentives when reducing consumption, such as introducing revenue stabilisation, performance-based rate-making, distribution system improvement charges and capital expenditure riders (36). Performance-based contracts between utilities and service authorities can set targets and fees based on connection rates, non-revenue water reductions, and water or energy conservation.

10
The "day zero" term was developed during the water crisis in Cape Town, South Africa, in 2018, a reference to the day that tap water becomes unavailable due to water shortage.

The introduction of new technologies can generate new sources of revenue for water and sanitation services. Governments could consider levying taxes on those (including land and property developers) who benefit from increased water security or who generate higher costs and externalities (e.g. the owners of large impervious surfaces, such as roads or car parks) (17).

'South-South' cooperation is a pertinent and sustainable option for cities located in low- and lower middle-income countries when introducing technologies to increase water's resilience to climate change. 'South-south cooperation' refers to technical cooperation, knowledge-sharing and skills in specific areas among developing countries (37). The Water Operators Partnerships initiative is a water utility twinning programme designed to promote knowledge-sharing and build the capacity of water utilities. The programme brings together an experienced utility with a utility needing help to improve its services. For example, the public utility of Ho Chi Minh City, the largest city in Vietnam, has received support from the Metropolitan Waterworks Authority in Thailand. Through this collaboration, the Vietnamese utility increased it capacity for network improvement and distribution monitoring through better data management and analysis (38).

5.3.1. Key policy considerations for smart water systems

Government programmes for water technology incubators can result in new smart water system technologies leveraging private investment. Cities can reimburse a percentage of the installation (up to a certain amount) to mitigate the risks involved in installing innovative technologies in exchange for incubators leveraging private funds for the scaling-up phase (18). Additionally, there is an economic incentive for policy-makers, as these types of programme result in job creation for the city.

Water scarcity, combined with economic incentives, can create a market demand for smart water system technologies for domestic use. Economic incentives designed to reduce water demand in urban areas, such as increasing block tariffs and imposing fines for losing water above a certain level, can result in the deployment of innovative water-management devices (11).

5.3.2. Key policy considerations for blue-green infrastructures to store rainfall upstream of a city

Formulating policy targets for blue-green infrastructures can be an effective way of strengthening current policy support. Blue-green infrastructures are well-recognised priorities in national climate and biodiversity policies. While their integration into overarching national policies is essential, it is important that sectoral policies (infrastructure, agriculture, water, etc.) include them too, as they will ultimately drive their implementation. Taking into account the trade-offs between blue-green infrastructures and other sectoral policy objectives is important to ensure mutually reinforcing efforts. Finally, the formulation and monitoring of policy targets will be important in strengthening policy effectiveness (27).

Blue-green infrastructures need to be promoted by and co-ordinated among a wide range of actors. Many actors are involved in planning and implementing them**.** This means that a cross-sectoral and cross-governmental approach is needed. Facilitating collaboration between multiple actors can improve coherence, help create synergies and avoid trade-offs between different policy options (27).

Regulation can unleash considerable opportunities for blue-green infrastructures. Spatial planning, building codes and public procurement are key vectors for scaling them up. Given the important role of local governments in spatial planning, countries have issued national guidance and developed tools to help promote their integration into land-use plans (27).

Information is key to identifying opportunities and triggering action for blue-green infrastructures. Compiling and communicating the increasingly available information on good practices and the performance data of blue-green infrastructures through repositories, guidelines or other design tools can significantly support the scale at which blue-green infrastructures are used and taken into account within decision-making processes (27).

5.3.3. Key policy considerations for distributed water systems

Distributed water systems are not merely technical innovations: they require innovative governance. Decision-makers need to take into account issues of ownership and responsibilities for service provision, which are crucial to ensuring the sustainability of services. By increasing the number of systems, utilities, users, landowners and decision-makers need to reach agreements on how to manage them while ensuring the necessary quality standards and controls. Alternative systems can only be considered when an adequate service capacity exists for operation and maintenance and the supply of replacement components (20).

Distributed water systems require advanced regulatory frameworks, which set different water-quality standards, depending on water use and supplementary water quality controls. This requires additional capacity and financial and human resources. These systems increase monitoring by having a greater risk of mechanical failure (more types of components are required for several distributed systems than for a traditional centralised piped system). Also, being more numerous, they require a higher number of controls per authority. Regulators could solve these challenges by standardising the models under their jurisdiction and introducing smart water systems providing remote monitoring. However, as noted above, new sources of revenue from the private sector will be needed to ensure enough funding to cover additional monitoring.

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6. Floods

Unsplash

There is widespread agreement in the literature on the threats that climate change poses to our ability to adapt to the increasing risks of flooding in cities in both developed and developing countries (1) (2) (3). Intensification of the hydrological cycle through higher temperatures is driving more frequent and intense storms that are causing deeper and more prolonged flooding, posing perhaps the greatest and most observable risk that climate change presents to cities (4) (5). Further, for cities located on low-lying deltas or tidal rivers, there is the added risk of rises in sea level from climate warming bringing about coastal flooding, particularly during storm surges. Combined with the concomitant processes of urbanization and land-use change in upstream areas, coupled with erosion in coastal areas (6), increasingly rigid urban systems see their adaptability to rapid changes being diminished.

Urbanization causes densification and urban sprawl, which replaces natural soils and vegetation with impervious surfaces and natural watercourses with artificial drainage, leading to more run-off and less infiltration (7). As a result, drainage and flood management infrastructure are eventually become overwhelmed (8). Land-use changes within watershed catchments reduce the available water storage-capacity and increase flood volumes (9). Eroded coastlines have less capacity to buffer storm surges and resist coastal flooding (10). All these threats are amplified in developing countries where population growth is rapid and planning comparatively weaker. Thus, in the rapidly growing cities of West Africa, extreme flooding and population growth are pressing issues for the urban population (11) (12).

6.1. Overview of technology options

To combat the risks posed by flooding and the threat that climate change poses because of the increased frequency and severity of flooding, there exists a wide range of hardware and software technologies which can some means of adaptation enable to varying degrees and on varying scales (5). These range from the widely used application of 'grey' engineering hardware, such as flood embankments and concrete walls to contain rivers and protect developments, to 'green' engineering solutions that reduce urban run-off, from green roofs to holistic 'green' software solutions such as catchment management plans (13). In the following sections, with a view to illustrating the wide range of options in use, we present a non-exhaustive list of both green and grey hardware and software technologies that are commonly employed to manage flood risk and climate change adaptation to varying degrees. They have been grouped here into common themes, each being provided with a brief outline and discussion with respect to climate change adaptation applications.

6.1.1. Regulating run-off in urban areas through sustainable engineering

In urban areas, increasing applications of flood adaptation technology are being introduced that are defined as 'green engineering' or 'green infrastructure', rather than traditional 'grey' engineering and infrastructure. This is widely called a 'sustainable drainage system' (14) in the United Kingdom, or 'low impact development' (15) in the United States. Sustainable drainage systems include a suite of measures based on either source control of run-off, such as green roofs or variable infiltration. Such features are a central component of run-off management in any new development with a green focus and in cities incorporating design principles based around natural water management solutions (16). There is a wide diversity of sustainable drainage systems: four main groups of technologies are listed below:

- **Green roofs** are now frequently used to reduce run-off in urban areas. By installing a green vegetative layer and an underlying drainage layer that can intercept, infiltrate and store rainfall, 'green roofs' reduce the rate and volume of run-off from roof areas (17). They are increasingly being used, especially in new developments wishing to boast their 'green credentials' (18) (19).

- **Permeable hardstanding surfaces** reduce run-off from urban areas such as roads or car parks by replacing traditional impervious hardstanding materials like paving and asphalt with more permeable solutions for both vehicles and people. These include gravel, block paving with spaces for water to seep between the paving stones, or vegetated grid paving (20).

- **Infiltration sustainable drainage systems** receive run-off from impervious areas but allow the water to collect and infiltrate to soils below. These include bio-retention systems such as soakaways and rain-gardens that are not directly connected to storm drainage systems, but which temporarily collect and pond run-off to facilitate local infiltration and reduce run-off into drainage systems, with overflows to storm drainage during large events.

- **Retention sustainable drainage systems** retain run-off and slow the flow of water while also filtering and treating water quality. These include detention and infiltration basins connected to storm drainage that can significantly slow the release of urban run-off into drainage systems while in some cases also using infiltration into soils and groundwater below. These systems include either permanently wet systems, such as ponds and wetlands, or variably wet/dry systems such as swales. Such systems might also incorporate engineering such as hydro-brakes or weirs to regulate run-off volumes during storm events.

All these sustainable drainage systems are being promoted to control run-off by allowing infiltration and local water retention in storm events. They also variably manage water quality by allowing water to filter into the soil below, or introduce vegetation that can treat pollutants. They also provide an associated benefit for amenity and biodiversity within the city environment through the habitat and visual component they provide. These added benefits and their design, based around enhancing natural processes such as infiltration, filtration, retention and release, are why sustainable drainage system, are often considered nature-based solutions, despite their engineered design. 'Nature-based solutions', a wider term for green infrastructure, are being widely promoted as 'soft' sustainable socio-ecological solutions to problems facing human well-being, in contrast to grey 'hard' engineered solutions with no amenity or biodiversity benefit (21). Nature-based solutions are viewed as adaptation solutions to increasing flooding risks from climate change, but there is uncertainty over their effectiveness for managing the type of extreme events caused by climate change in cities (22). In general they are viewed as more effective for more frequent smaller events, for reducing run-off leading into storm drain systems, and for having a range of additional benefits that mitigate other climate change risks such as heat stress (23).

6.1.2. Hard engineering

Traditionally, flooding risks in urban areas have been managed using the hard/grey engineering approach using concrete, steel and mechanical systems to move and control the flow of water within and around urban areas. This approach has three main engineering components for managing flooding:

- Engineered controls upstream of urban areas reduce flood flows and manage the flow regime. Examples of these controls are large water bodies with outlet controls, such as dams, which can store significant quantities of water during storm events and release it in a controlled way when flows are lower. Such engineered controls are highly effective when dealing with large river systems with networks of dams that can store and release large volumes of water in a coordinated and controlled manner, thus reducing flooding peaks and water volumes passing through downstream areas (1).

- Engineering works within and around urban areas either to protect areas from flooding or to divert flood waters during high flow events. *Flood embankments* and *river engineering* in particular are ubiquitous, long-used engineering solutions for managing flooding in cities on large rivers by speeding up flows through urban areas through straightening and dredging channels, employing concrete to improve hydraulic efficiencies, and raising embankments to contain more flow. Such solutions are high risk, as the consequences of a failure in terms of flooded areas are huge, as has occurred in Dhaka City. Despite this, they are widely employed in developing nations (24).

- Within urban areas, *storm drainage* performs the key task of routing run-off from impervious surfaces away from developed flood-prone areas to receiving river waters. Traditionally this was combined with foul water from housing and industry, but in developed countries storm and foul water drainage are now almost always separate systems. Run-off is collected from roofs, roads and hardstanding via storm drains that collect water before it is directed by predominantly sub-surface drainage and routed into larger open channels and streams or ponds. Such systems are designed with an engineered capacity to receive run-off from calculated areas, but subsequent development can put pressure on drainage systems, leading to capacity being exceeded and surface water flooding (25).

Engineered approaches have fallen out of favour for purposes of climate change adaptation in developed countries due to the high capital and environmental costs involved and because they do not deal with the source of run-off (26). Essentially, such approaches are not sustainable and are prone to fail with ongoing urbanization and climate change, as they do not address changes to the natural flow regime caused by catchment alteration, impervious surfaces or storm water drainage (27). Furthermore, they are not easily adaptable to such changes beyond their engineered design capacity without significant costs and associated impacts.

6.1.3. Nature-based approaches to catchment water management

The majority of catchments in which urban areas are located contain a mosaic of land-uses, which, in most cases are dominated by different types of agriculture and forestry. By installing drainage ditches and altering natural vegetation, urban areas have significantly altered natural systems and water pathways in the surrounding areas. Further, around river floodplains, landowners have sought to disconnect the river to protect valuable land for farming, changing the natural shape of river channels as a consequence. The effect has been to reduce a catchment's natural capacity to infiltrate and store water during storms and to speed up the conveyance of run-off into rivers and towards downstream areas. The loss of floodplains in particular has led to a loss of natural water storage where sediment would naturally spread onto productive grasslands, as well as altering the natural geomorphology of the river system, leading to more flooding downstream.

A nature-based approach to catchment management is being adopted more widely as a more holistic whole-systems approach to managing how water is generated and conveyed within a catchment system. Three main approaches are liasted below:

- **Land management** to improve infiltration to underlying soils and reduce run-off during storms involves working with landowners to manage cropping, install features such as buffer strips and incentivize the introduction of features such as ponds and tree-planting (28). Nonetheless, more evidence is needed to evaluate the scalability of this approach (29).

- Using **natural flood management** solutions to slow down the movement of water across agricultural or forested land to reduce flooding in downstream areas. These include the use of in-stream features such as log dams to mimic the effects of fallen vegetation. They also include river restoration, whereby a river's natural form and function is restored by, for example, restoring meanders and bankside vegetation (30), while measures such as attenuation ponds and wetlands in catchments control the volume and rate of run-off into receiving watercourses.

- The third approach, widely adopted in European Union countries such as the Netherlands, is to reconnect rivers with their floodplains through **floodplain restoration** so as to allow natural flooding processes to happen (31). Removing embankments and restoring floodplains provides rivers with spaces in which to flood, enabling the storage of large volumes of water during peak flows, which are released as flows subside. This attenuates flows and reduces the flood peak in downstream areas.

These all form part of a nature-based approach which is now widely adopted and has proved effective in many countries. In the United Kingdom, the Department for Food and

Rural Affairs (Defra) started implementing this approach in the 2000s following publication of its 'Making space for water' strategy; this now forms a part of how catchments are managed to reduce flooding and improve water quality. The advantage of such approaches in the case of climate change is that they will reduce the run-off from more frequent rainfall events and reduce the reliance on unstainable engineering in downstream cities, further reducing the amount of carbon required in the engineering use of concrete and steel. However, there is uncertainty over whether more extreme events exacerbated by climatic change can be effectively mitigated by such measures. Much of the evidence at city-scale remains conceptual (for example, (31)) or literature-based (32).

6.1.4. Technological and behavioural change

Perhaps the greatest area of change in managing the risk of flooding in cities has been the growth of technologies and knowledge to inform effective preparation, response and adaptation to flooding. This link between science, technology and behaviour is being fostered by governments, particularly government agencies with responsibility for flood-risk management. They act as the agents of change to enforce new regulations informed by knowledge of such technologies and as the enablers of uptake to ensure maximum engagement and benefit. Here, we consider three main types of technology:

- **Flood estimation** provides a basis for understanding the scale and likelihood of flooding that could occur and forms the basis for engineering design and flood planning. This approach uses observed rainfall and flood-event data to estimate the magnitude of a storm or flood event for a given probability of occurrence, such as the one hundred-year storm (that is, an event that has a one percent chance of occurring in any given year). The estimates are only as good as the data, and in areas with poor hydrometric network coverage, this approach is highly uncertain. Rainfall and flood estimates can be used to inform planning directly by providing design events, which form the basis for guidance on engineering standards, such as the scale of flood protection required for embankments. Such approaches require inputs from climate change models to consider the types of flood risk that will be faced in the future.

- **Hydrologic and hydraulic models** use design storms or observed data to model the movement and spread of water during storm events in urban areas and the effects on infrastructure. These data provide the basis for flood planning by enabling detailed mapping of flood-prone areas and the design and testing of infrastructure. Such models can also use ensembles of climate-change data to consider a range of possible future flooding scenarios.

- Advances in measurement and communication technologies have brought about significant changes in **flood forecasting** and **early warning systems** that can alert people and businesses to imminent flooding. Telemetered rain-gauges and radar systems, coupled with advances in predicting weather and hydrological models, enable conditions to be forecast days in advance. This enables effective measures to be taken before flooding occurs, such as the erection of flood barriers and the deployment of sandbags, and in extreme cases the evacuation of vulnerable persons, thus building resilience to flooding.

Flooding will occur, and people and property will be affected. A growing acceptance of this fact, coupled with more frequent and extreme flooding as a result of climate change, has accelerated the technology and uptake of *flood-resilient construction.* In the face of rising premiums or unavailable insurance, people are increasingly employing property measures that can minimize the impact of flooding when it occurs (https://floodresilience.net/) and increase resilience. This includes installing flood gates or using flood-proof materials on ground floors, or in more extreme cases building houses above ground on stilts. This type of technology accepts risk and can be built to future-proof areas that may presently be at low risk, but could be at higher risk with uncertain climate change.

Technology continues to be at the forefront of adaptation measures against urban flooding risks due to the adaptability of approaches exploiting the evolving and emerging information and knowledge, while continued research and development has adopted a focus on climate change. These approaches therefore form the basis for considering future flooding risks and how they can be managed and lived with.

6.2. Selected technologies

Given the wide range of flood-management technologies employed in cities across the world, no selection can aim at being more than illustrative. This chapter presents the technologies that, in the view of the authors, when combined, provide the most direct benefit for the associated cost, and offer some of the most practical approaches to adaptation to urban flooding in developing countries under circumstances of a changing climate. These are (i) **green roofs**, (ii) **retention and infiltration basin sustainable drainage systems**, and (iii) **flood-resilient buildings**.

These technologies have been selected because the combination of green roofs and infiltration-based sustainable drainage systems can reduce the run-off from the dominant types of impervious surfaces (roofs, roads, hardstanding) that could cause localized surface water flooding by reducing the strain on existing storm drainage. The focus is on reducing flooding from within urban areas and mitigating the effects of climate change-driven flooding within existing and new developments. The focus is not on flooding from the large river systems that pass through urban areas, as this requires much wider catchment-scale changes and certainly involves hard flood-defences if urban areas are built on floodplains. Nonetheless, there is a need to adapt to the growing likelihood of flooding, particularly in areas near rivers that will become more prone to flooding with climate change as flood defences are exceeded. For this reason, we also select flood-resilient buildings as a partner approach.

This section will describe the three technologies mentioned above and will outline for each i) the scope of the technology, ii) why it was chosen, iii) the trade-offs involved, iv) the barriers to adoption, v) enablers of adoption and vi) linkages with other sectors.

6.2.1. Green roofs

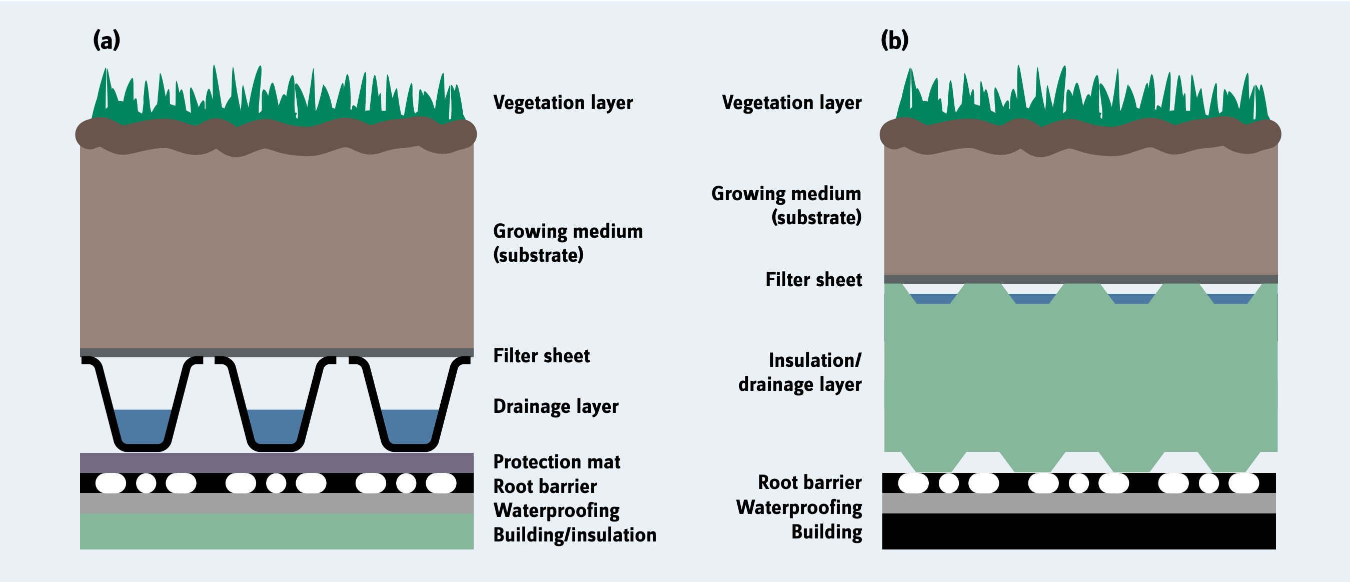
Scope of the technology

A typical modern green roof is a multi-layered system consisting from top to bottom of vegetation, a growing medium (substrate), a filter layer or sheeting, a drainage layer, a protection mat, a root barrier and waterproofing (Figure 1a). In 'inverted' roofs, the drainage layer may be combined with an insulating layer (Figure 1b).

Green roofs can help to manage urban flooding in two ways. Firstly, the total volume of roof run-off can be reduced by rainwater retention in the substrate and drainage layer, and on the vegetation. Secondly, the transformation of rainwater to run-off is delayed relative to a conventional roof because rainwater requires some time to pass through the substrate layer, even when the substrate is above field capacity. Deeper substrates result in longer delays, but even a few minutes' delay can be significant at the scale of the neighbourhood.

The two major classes of green roof, 'extensive' and 'intensive', are distinguished mainly in terms of the level of maintenance each requires, the substrate depth and composition, and the types of plants they support. The boundary between them is not formally defined, but generally consists of between 100 and 200 mm of substrate, although depths in this range are often considered 'semi-intensive' (33). Extensive green-roof substrates have ≤ 65 g/l organic content (35) and as a result best support succulents or meadow grasses that are drought-tolerant and require little maintenance. Intensive substrates have up to 90 g/l organic content (35), so they can support a wider range of plants, including small trees if the substrate depth is sufficient. This wider range of plants and less challenging growing environment requires more maintenance, the removal of invasive species and potentially irrigation. Bio-diverse roofs are generally

Figure 1. Typical non-inverted (a) and inverted (b) green roof systems



Source: Vesuviano, 2014

planted with species local to the area. The drainage layer may consist of coarse-grained materials like gravel, or may be a moulded plastic sheet, which can provide the same drainage capacity in a shallower and lighter profile. 'Mat'-type green roofs have less than roughly 50 mm of growing medium, which cannot support long-term healthy plant growth without regular fertilization and often irrigation. Because of this, some jurisdictions do not consider them to be green roofs.

Typical annual retention volumes have been established at 60 percent in a range of 6-100 percent (36), while long-term retention is a complex function of climate, substrate depth and drainage layer capacity. Retention over single rainfall events is highly variable because it also depends on the initial wetness of the green roof and the depth and intensity of the event (17). Broadly speaking, larger events have a lower percentage retention, as there is a limit to how much water a roof can store. Events in wet seasons tend to have lower percentage retention because the available storage capacity is replenished more slowly in between events, so the wetness at the beginning of an event tends to be higher.

Green roofs have been widely adopted in Europe, as well as other non-tropical northern-hemisphere countries like Canada, the United States, China and Japan. They have not yet been widely adopted in Africa, Latin America or tropical Asia, with the exception of Singapore and Hong Kong. Because of this, knowledge gaps exist in both the performance and the suitable design of green roofs in non-temperate climates (37). Nevertheless, research from Singapore (38), Hong Kong (39) and, more recently, Malaysia (40) (41) and Brazil (42) demonstrates the potential for rainwater storage and run-off delay in wet tropical climates.

Green roofs provide many benefits for both people and the environment. The benefits and abilities of green roofs vary according to the design of each roof, but include retaining stormwater, detaining (temporarily delaying) run-off, habitats for insects and birds, outdoor space for building users, space for urban agriculture, storage for carbon dioxide, absorbing airborne particulates, thermally buffering the building below, reducing the urban heat island effect, protecting the material that ensures a watertight seal with the inner structure, and improving aesthetics (34). In particular, the advantages of thermal buffering and reducing the urban heat island also lower building energy costs, providing an economic and carbon benefit that must also be considered.

One additional benefit of all green roofs over certain other nature-based solutions, like ponds, swales or basins, is that they provide flood management without taking away space that could be used for buildings, thereby maximizing green space across an urban area.

Trade-offs

Green roofs can exist in an almost-infinite range of designs. However, those that provide a wider range of benefits and/or more of a specific benefit are generally heavier and more complex, and require more maintenance than those that provide fewer benefits. From a flooding perspective, water has an approximate density of one tonne per cubic metre, so a 1,000 m2 roof that holds 40 mm of stormwater must be able to support 20 tonnes more of just water than a roof that only holds 20 mm, as well as the deeper growing medium in which the extra water is stored. The aesthetic benefits of green roofs are subjective, so any design will evoke a range of responses from different people, some of which will be negative.

From the perspective of environmental stewardship, well-designed green roofs can provide many net environmental benefits. However, some green roofs can increase concentrations of dissolved solids, organic carbon and/or nutrients in run-off, particularly green roofs that require a fertilization regime and new green roofs where very small particles are still in the process of washing out (43) (44). Downstream treatment of these solids, organic carbon and nutrients could be handled by a sustainable drainage system treatment train. Until recently, the design of many extensive roofs around the world used Alpine plant species because the similarity between Alpine environments and extensive green roofs improved plant survival (45). However, non-native species may not provide the same ecological benefits as native species.

Like other sustainable drainage systems with similar water-management effects, green roofs have maintenance requirements. However, these are not onerous, and the costs are often incurred by building owners rather than municipal councils.

Barriers to adoption

Barriers to the adoption of green roofs identified in Canada (46), Australia (47) and Hong Kong (48) fall into four clusters: lack of awareness, lack of incentives, cost (construction and maintenance) and technical issues and risks. In the Netherlands (49) additional barriers identified include difficulties in obtaining insurance for buildings with green roofs, a lack of specialist installers and 'competition' from climate mitigation technologies (like solar panels), which is a barrier faced not just by green roofs but other climate adaptation technologies too. High construction and maintenance costs were the two most significant barriers to adoption found in surveys taken in Lagos, Nigeria (50), and Kuala Lumpur, Malaysia (51). However, the experience of Malaysia suggests that these were only significant barriers for intensive green roofs, and that reporting them as barriers to green roofs in general has created an unjustified belief that extensive roofs are expensive to build and maintain.

Enablers to adoption

Enablers of adoption include legally binding requirements and incentives, financial or otherwise. Leaders in legal requirements are Linz (Austria) and Stuttgart (Germany), which have legally required green roofs on most buildings since 1985 and 1989 respectively. Both cities also began to offer financial incentives in the 1980s – Stuttgart in 1986 and Linz in 1989 – which were reduced over time as green roofs became commonplace expectations. Green roofs are now compulsory on certain buildings, usually those larger than a certain size, in many other cities, including Copenhagen (Denmark), Portland (Oregon, United States) and Tokyo (Japan). Financial incentives other than payments to cover part of the cost of the green roof include reduced stormwater drainage fees and tax credits proportional to roof area. A common incentive in the United States is the floor-area ratio bonus, which grants permission for more floor area in proportion to the area of the green roof. For example, Savannah (Georgia, United States) allows one extra floor in a building with a suitable green roof (52), while downtown Austin (Texas, United States) allows green roofs to be taken into account in granting permission for up to eight extra floors (53). Away from northern temperate regions, Singapore's Skyrise Greenery Incentive Scheme has provided up to 50 percent of the installation costs of green roofs and green walls since 2009 (54). In 2002, the government of Jingan District of Shanghai, China, began offering 10 CNY for each m^2 of green roof; this was followed in 2007 by a requirement that all new, suitable public buildings be built with a green roof (55). Also in China, Shenzhen has detailed requirements for green-roof construction, supervision and responsibilities (56).

Linkages with other sectors

Green roofs are a part of sustainable drainage system-based measures for reducing run-off in urban areas and building more flood-resilient developments. Beyond flood risk and the sectors directly involved, green roofs have many benefits for other sectors:

- Sequestering atmospheric carbon in their vegetation and binding particulates to their substrate.
- The thermal buffering effects of the green-roof system can reduce both the heating and the cooling demand of buildings.
- Can be built from waste materials, including tyres, thus reducing a building's carbon footprint.
- Reducing the urban heat island effect during heatwaves, which will be exacerbated by climate change.
- The roof can also supply water stored in the substrate for non-potable uses, including feeding green walls. This reduces local water demand and improves municipal water management.
- Providing a habitat for insects such as pollinating bees and improving urban biodiversity.

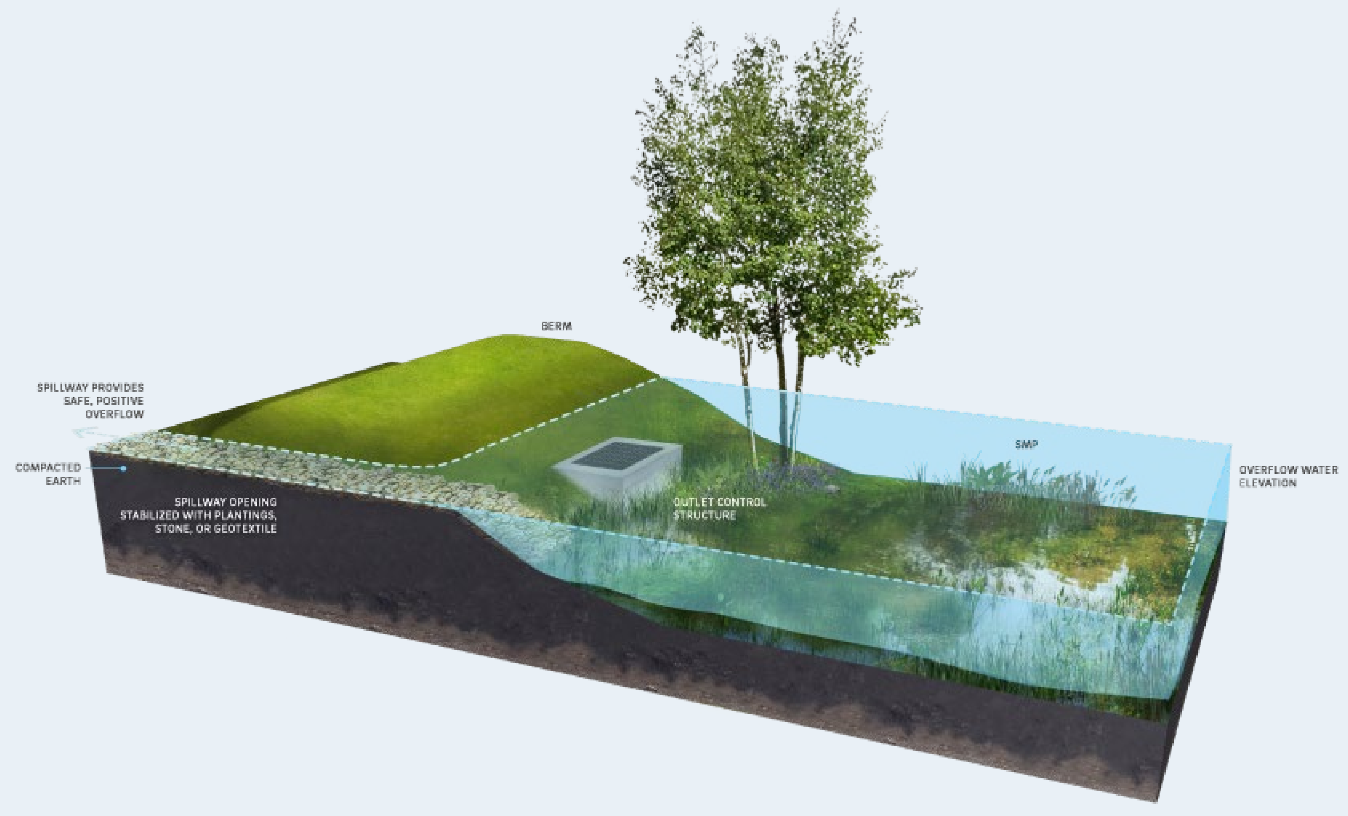
6.2.2. Retention and infiltration basin sustainable drainage systems

Scope of the technology

To mitigate the large volumes of run-off from hard surfaces in urban areas, one of the most widely applied flood technologies that mimics natural landscape systems is the use of variably wet/dry detention basins or wet ponds and wetlands that collect and store water during storms. These involve either the controlled or the natural release of stored water once the storm has passed, and in some cases infiltration to soils below.

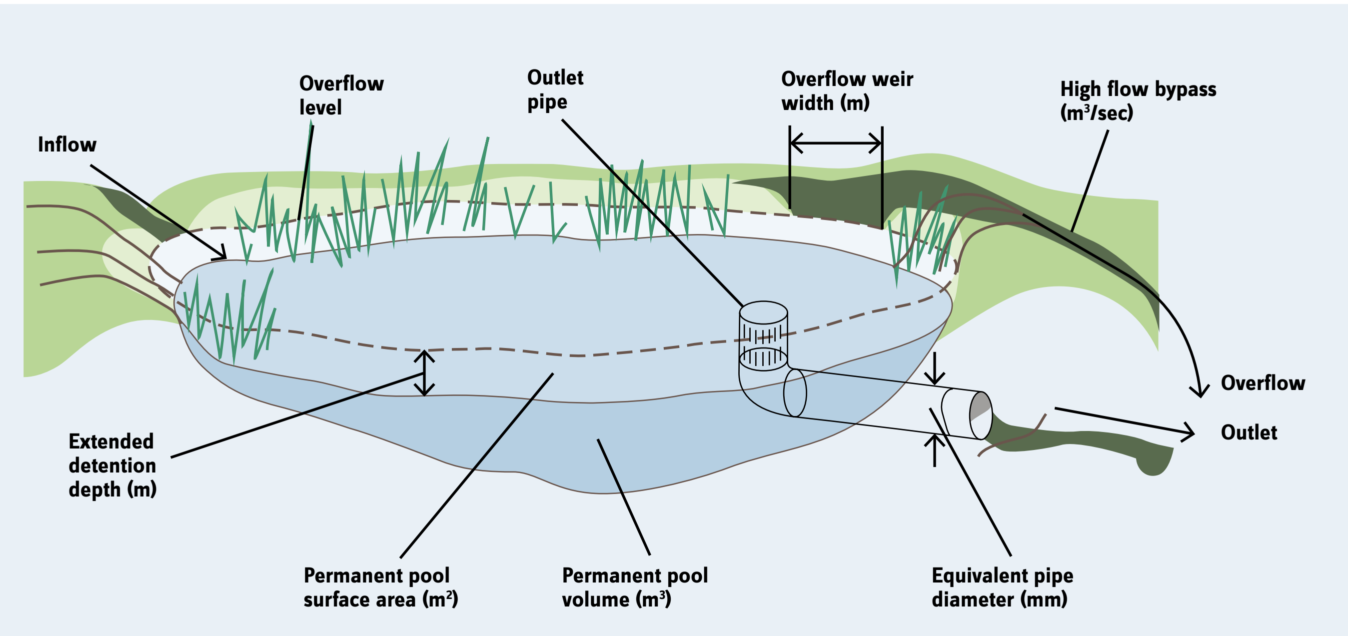
Detention basins are landscaped vegetated features within localized depressions that are typically dry most of the year, but which during and following storms can fill with run-off and become temporarily wet basins. This storage capacity reduces run-off into other areas and the storm drainage network. Detention basins can consist of vegetated depressions that offer habitat and the possibility of infiltration to soil below if the underlying soils are suitable. Such vegetated systems also offer the added benefit of

Figure 2. Detention basin



Source: *https://www.pngwing.com/en/free-png-npmiw*

Figure 3. Pond



Source: *https://www.lafayette.in.gov/2083/Green-Infrastructure* improving water quality through the removal of sediments and reducing levels of nutrients and heavy metals, particularly with increased residence times (14). There is a clear amenity value in these habitats, and even recreation benefits in the green spaces they provide. Detention basins can also consist of impermeable concrete features which offer storage but little else.

Ponds and wetlands are permanent bodies of water that offer natural run-off regulation and provide both aquatic and adjacent terrestrial habitats. The regulation capacity is a function of the storage they offer in their adjacent area and refers to how run-off from this area is controlled, usually by some form of hydraulic control such as a weir or outlet pipe. They support the growth of submerged and emergent vegetation, which offers adhesive capacity for contaminants and anaerobic decomposition, as well as slowing down flows so that sediment can settle out. Furthermore, they provide additional aesthetic, amenity and wildlife value within urban areas and are popular with developers in adding economic value (14).

The attraction and popularity of retention and infiltration sustainable drainage systems such as ponds and detention basins lies in their clear and proven multiple benefits for the environment, the developer and the residents. Compared to a hard concrete storage area, which could be cheaper and offer the same storage capacity and flood-control function, retention and infiltration sustainable drainage systems offer much more on all other levels (environment, biodiversity, carbon footprint). As a result, any such hard areas in developed cities are increasingly being converted into natural areas. Besides using sub-surface storage in concrete tanks, there are no other real alternatives that can offer the retention of large volumes of run-off from impervious areas within an urban location. Clearly, to have acceptance, particularly from local residents, sustainable drainage systems must be well managed to ensure water quality is not so degraded by pollution as to become unsightly and even dangerous to health. This requires upstream pre-treatment systems to reduce over-sedimentation and limit pollutants into the waterbody that could overwhelm their designed function. This has extra associated costs, but compared to the resulting environmental benefits and the associated costs of removing pollutants from urban systems, the long-term and downstream costs are reduced (23).

Trade-offs

Compared to conventional hard storm-water storage, natural storage systems require more design consideration. To ensure that retention and infiltration sustainable drainage systems are adopted by local residents, they must be designed together with landscape architects and not just by drainage engineers. This ensures they fit into the working landscape of the urban area and its residents and that they become a community resource.

In terms of both the materials used and the sustainability of the systems, natural retention and infiltration sustainable drainage systems really have no environmental trade-offs compared to concrete-based alternatives, except the need for upstream control of contaminants.

These types of sustainable drainage systems do require more regular maintenance than grey alternatives, as there is vegetation that requires suitable management and disposal so as not to reduce capacity or function during storm events. However, these costs are not considered to be much higher than for any public space (14). Furthermore, any works within the water will require approaches that are more considerate of the wildlife that inhabits these systems.

Barriers to adoption

The main barriers to the uptake of any sustainable drainage system is the complexity of aligning planning frameworks, engineering design, construction, maintenance, community and ownership agreements, among other issues (57). There are some local adoption and maintenance challenges that need to be considered, which hard infrastructure solely managed by a local water management agency or council does not encounter. Planning policy needs specific regulations to encourage implementation of the features of such sustainable drainage systems. Trust in the efficacy of such schemes needs to be fostered. Analyses that monetize the multiple benefits of such systems are generally not carried out because of their complexity. Lacking such analyses, sustainable drainage systems may be undervalued by stakeholders, with the result that developers and local authorities might adopt less expensive engineering approaches instead (58).

Enablers to adoption

Perhaps the greatest enabler of any new technology like sustainable drainage systems is improving the availability of clear information on its costs and benefits. Countries such as the United Kingdom have clear technical information, in the form of manuals on sustainable drainage systems (14), which have provided the basis for guidance on the implementation of such systems (57). In Europe there is a range of guidance on water-sensitive design that includes such sustainable drainage systems (for example, (59) and (20)). Examples in Africa include a range of guidance from South Africa for climates that are highly variable and different from northern latitudes (60). China leads the way in Asia by providing numerous documents to guide the national 'sponge-city' initiative approach to flood management (61), which promotes rainwater retention and sustainable use to mitigate flooding and the other water-resource issues being faced.

However, such guidance must also be delivered alongside non-statutory technical standards (for example (62)) and strong regulatory frameworks that set out the requirements for such systems and their benefits over hard engineered approaches. In the United Kingdom, the National Planning Policy Framework requires new developments to incorporate sustainable drainage systems, while within the European Union, the Water Framework Directive has been a driving force for improving the way water bodies are managed for ecology alongside other services such as flood control.

Other enablers include exemplar schemes that can demonstrate the multiple benefits of such sustainable drainage systems to different stakeholders and provide evidence of both the cost benefits and the effectiveness of flood control. Such schemes for nature-based solutions typically include sustainable drainage systems as central components and are widespread across Europe (23), as well as in Chinese cities such as Beijing and Wuhan, which have adopted the sponge-city approach.

Linkages with other sectors

These types of sustainable drainage systems in urban areas are intrinsically linked to development plans for flood-management strategies. As a result, there will be clear links to sectors involved in the management of storm drainage, as the run-off attenuation delivered by sustainable drainage systems reduces the design capacity required for receiving drainage systems. Beyond flood risk, these sustainable drainage systems have linkages with a range of other sectors:

- Wildlife charities and local communities associated with a wide range of other sectors have inherent linkages (63) with features like ponds.
- Local government sectors who manage green urban spaces to ensure multi-functional spaces that are effectively managed for different purposes.
- Ponds that offer a substantial aquatic habitat also provide waste management functions by improving water quality and sequestering and processing water pollutants. This habitat also has a direct biodiversity benefit for aquatic species and provides a terrestrial habitat for amphibians and insects.
- Infiltration sustainable drainage systems ensure less run-off and more infiltration of water to soils and aquifers below, thus improving local water management to mitigate against droughts. They also provide a local water source that can be exploited for purposes such as watering vegetation, thus reducing the strain on water supply systems.
- Water provides a localized cooling effect which can mitigate the urban heat island effect.

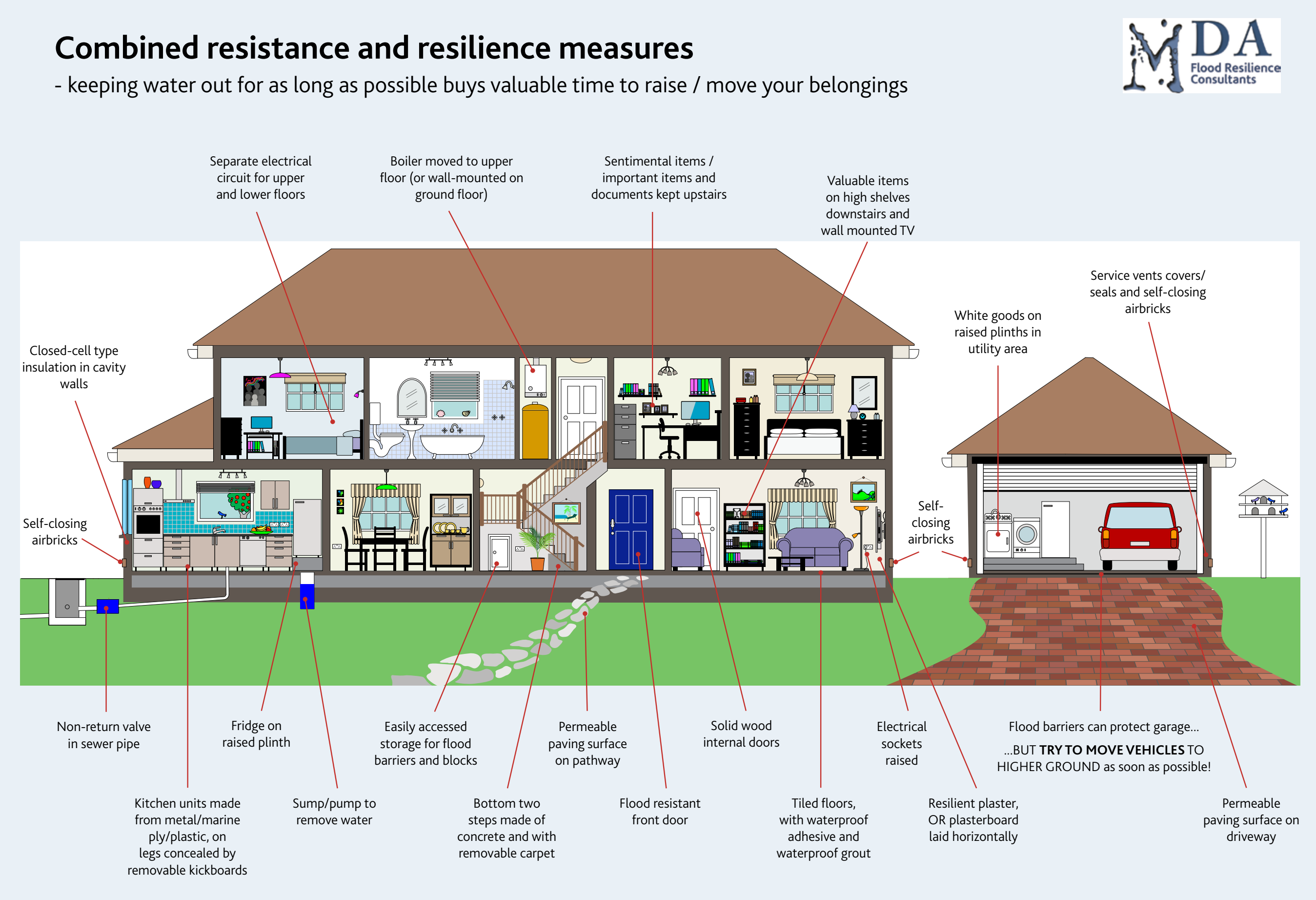
6.2.3. Flood-resilient buildings

Scope of the technology

Property flood resilience is a suite of measures that can be used to reduce the risk of damage to properties that are at risk of flooding, ranging from external to internal features targeting building materials to electrical systems (Fig. 4). The application of such methods represents an implicit acceptance that flooding will occur at some point, but that by employing such measures the damage can be reduced and the recovery can be accelerated (64). These methods are highly suitable for areas that suffer frequent flooding and where no further investment in flood defence is planned. They are also a means of ensuring resilience to projected changes in future flooding from climate change.

While the choice of physical technology is important, it has to be inserted into a framework for design and implementation that follows established guidance. There is considerable guidance on how to ensure flood resilience. This can be done prior to development, but it can also encompass retrofitted measures that mitigate flooding after it has become a problem that the property was not designed to encounter.

Figure 4. Combined resistance and resilience measures



Source: Lamond et al. 2018. Evidence review for property flood resilience phase 2. Illustration: Mary Dhonau, MDA Flood Resilience Consultants (65)

For example, the SMARTeST project provides step-by-step guidance for property owners to achieve flood resilience in their homes through six steps (Table 1), from understanding risk to identifying solutions and operation:

1. Understanding the risk means identifying the causes of flooding, be they rainfall, rivers, or even infrastructure, such as flood defence failures or overtopping. The information required to do so may come from local sources or from organizations that map flood risks.

2. Next is to plan for the risk and identify what funding might be available, e.g. raising money for a community action group or lobbying local government.

3. The property survey will provide details of how flooding might enter a property. This should cover all access points, be conducted by a trained or accredited surveyor, and take future flooding risks from climate change into account.

4. The next step is to ensure that the right products are selected. These could be external features to protect the property, such as boundary walls and flood gates that can be closed when it floods. They can also consist of internal structural measures, such as raising the floor level or using low-permeability materials. Planning where particular rooms and power points are located within properties can also ensure that the

impacts of flooding are minimized, and could even involve using the ground floor only for car-parking and temporary storage, with all accommodation above this.

5. All such equipment and design should only be installed by trained persons and a survey completed to ensure correct functioning.

6. Lastly, all flood-resilience measures in a property require maintenance to ensure their continued functioning, with suitable guidance for continued correct operation.

Table 1. The six flood-resilience steps in the SMARTeST project

STEP 1: Understanding the Risk
STEP 2: Planning – First Considerations
STEP 3: The Property Survey
STEP 4: Product Supply
STEP 5: Product Installation
STEP 6: Operation and Maintenance

Source: SMARTeST project.

There is a clear justification in designing buildings for flood resilience, as climate change will increase the probability and severity of flooding in many of the world's existing urban areas. One possibility is that an existing development that had little or no risk of flooding will gradually become at risk and that the risk will become worse, or that a new development is planned in an area with a flooding risk but no flood defences. The cost-effectiveness considerations are based on the costs of property flood-resilience measures versus the potential costs of flooding occurring and causing damage and how often this might occur. The cost benefits can be determined using expected depth-damage, that is, curves that relate a specific flood depth to expected economic damage, based on observational data from the country or region. One review of property flood-resilience measures (65) found that, although they are generally cost-effective, benefits vary depending on the degree of flood risk and the return periods involved. Overall, the review found that keeping water out of property using manually operated measures was cost-beneficial for flooding up to a return period of around fifty years (a 2 percent chance of happening in any one year), while limiting damage once inside can be beneficial at higher levels of risk, with a return period of up to two hundred years (less than 0.5 percent chance of it happening in any one year).

Trade-offs

Trade-offs in adopting property flood-resilience measures to adapt to climate change have not been explored very much in the wider literature, but among possible trade-offs are:

- Property flood-resilience measures can provide a sense of security to a property owner that may not be entirely valid in the event of a flood and that could even put the inhabitants and property at risk.
- A changing climate and changing risks might not be something that building owners are aware of. Even if they are aware, they might not have access to the data that would allow them to understand the risk. Thus, a property might have been designed as suitable for a given flood event that was formerly rare but is now regularly exceeded, bringing significant extra costs and risks.
- These measures also require a degree of maintenance, which is the responsibility of the property owner, unlike the maintenance of flood defences, which is carried out by larger agencies or government. Owners without much technical knowledge or access to guidance, tools or funding might not be able to maintain property flood-resilience measures correctly. Also, if the measures fail through poor maintenance the damage could be significant and even life-threatening.

Barriers to adoption

The type and age of the property might not enable many standard property flood-resilience measures to be employed. For example, the building may be old and have legal restrictions on what can be built, or have a fabric that is unsuitable for upgrade. Information barriers are another frequent problem hindering the uptake of measures. Guidance needs to be clear and accessible to owners, not just engineers and architects. A United Kingdom government report (66) found that, even when the options are clear and the cost benefits well defined, actually encouraging people to install property flood-resilience after a flood can be difficult because of the high upfront costs and risks related to resale, which are especially amplified if the owner has a low income.

Enablers to adoption

There are a number of ways in which the barriers to the uptake of property flood resilience can be addressed and appropriate measures enabled (67) (66):

- Stressing the co-benefits.
- Encouraging people to install property flood resilience after a flood, or prior to renovation or sale.
- Making the process of applying for financial support accessible and straightforward.
- Providing long-term, low-interest loans, combined with risk-based insurance premiums.
- Providing flood-protection certificates for properties with property flood resilience.
- Having approved property flood resilience surveyors.
- Reducing the number of property flood resilience options.
- Standardizing presentation of the pros and cons and the costs and benefits.

- Putting in place default mechanisms, such as industry standards and building regulations.
- Providing decision aids, such as comparison tools and websites.

Perhaps the best enabler is access to up-to-date and clear information and guidance on property flood-resilience options and also on codes of practice for property flood-resilience measures. Sources such as floodresilience.net and CIRIA provide access to a range of resources that covers options and guidance for both developed and developing nations.

Linkages with other sectors

Property flood-resilience measures are a direct means of decoupling some local risk from larger flood-defence schemes that are required to protect property. Such measures also improve the overall resilience of property and thus its lifespan and safety. Both factors mean that less new building stock and fewer engineered defences are required, lowering the overall carbon footprint of urban areas by reducing the fuel, concrete and steel required. This also means less waste.

6.3. Key policy-related issues

Policies that encourage adaptation to increasingly severe urban flooding as a result of climate change have been mentioned in the 'enablers of adoption' sections above. A common facet of such policies is that they drive forward development that is safe, reduces local flooding risks and also does not increase the flood risking elsewhere (68). The main policy-related issues fall into four main categories: incentives, disincentives, information and requirements.

Incentives and disincentives seek to encourage changes voluntarily through positive and negative consequences, without relying on mandatory requirements. Examples of incentives include the floor-area ratio bonus for green roofs and grants for the installation of property flood-resilience measures. Examples of disincentives include using tools to calculate the depth damage of properties and using this a basis for explaining the potential costs involved if property flood-resilience measures are not installed.

Information seeks voluntary changes, but without consequences. Information can be provided in the form of guidance and codes of practice. For the flood adaption technologies discussed here, guidance and codes of practice provide the necessary support for any policies based on requirements. These are essentially tools for planning and building flood-resilient urban areas. Exemplar projects such as new urban areas with sustainable drainage systems also provide a tangible showcase resource showing what sustainable drainage systems and property flood resilience systems look like and communicating their benefits. In areas where sustainable drainage systems are unknown, this provides the most accessible form of information.

There is also a growing body of guidance in the form of the sustainable drainage systems manual in the United Kingdom and the CIRIA code of practice for property flood resilience (69). These directly support policy by giving guidance to the users of these technologies and ensuring that the information is up to date and effective. There have been some studies outlining guidance for developing countries, but there are few international sources that provide region-specific advice. Examples include the South African guidelines (60) and a scoping study by the United Kingdom (70).

Requirements include national policies like the United Kingdom Floods and Water Act 2010 and international policies like the Water Framework Directive, which sets out broad ideals and goals for improving flood risk and the general direction of technologies. These can inform specific guidance on land-use planning for development and flood risk based on firm quantitative criteria such as flooding return periods. This can then be used to determine the design requirements for sustainable drainage systems and the level of climate change allowance that needs to be ensured. They can also be building regulations stipulating the type of design and materials for building property in places where there is a degree of future flood risk.

In China, where the sponge-city initiative is so prevalent, the top-down nature of government and planning means that whole cities can be directed to follow such principles that link socio-economic factors to urban-rural planning. This approach targeted sixteen pilot cities, involved large amounts of investment and resulted in nearly two thousand separate schemes being developed (61).

Key to all four categories are awareness and clarity of the potential benefits of such approaches in adaptation to flooding under climate change, set within the context of what climate change might entail with regard to future flooding risks. Obviously, legal requirements must be known and unambiguous to all relevant parties. However, this is also true of incentives, disincentives and information if the aim is to encourage as much positive change in adaptation to flooding as possible. Key to any consideration of policy is that all the technologies discussed in detail here are flood-resilient, not traditional approaches to managing flood risk. They inherently build in a system of strategic alternatives that can be combined and can provide continuous alignment of content and process with an evolving link to risk from climate change and flooding (71). The adoption of such sustainable drainage systems or property flood-resilience measures is in some way constrained by the degree of flexibility in policy-making. In addressing a Dutch Delta Programme pilot study in Dordrecht, Zevenbergen and colleagues (71) discuss the policy concept of ‘smart combination’, whereby flood protection can be replaced by prevention and preparedness measures. This approach to policy means replacing traditional approaches and considering whole system benefits alongside the most direct benefits being sought. Thus, it is not simply a matter of replacing a flood defence with green roofs, but rather of considering a combination of sustainable drainage systems and perhaps some property flood resilience to enable a more sustainable adaptation to future flood risk. This is the key policy feature of change required to enable uptake of the urban flood adaptation strategies discussed here.

Conclusions

This brief chapter on climate change adaptation technologies to mitigate future flood risks has taken three of the most widely adopted technologies in developed nations and assessed their scope, justifications, trade-offs, enablers of adoption, barriers to adoption and linkages with other sectors. The lack of examples in the wider literature suggests there has been little uptake of these types of flood-management measures in developing countries to date, making it difficult to direct readers to regional advice. The important conclusion, however, is that there is nothing unique in the technologies discussed here that would limit their suitability in other regions or climates. Likewise, they do not cost more than less green alternatives such as flood defences or constantly repairing flooded properties, especially when considered as a suite of measures for adaption to flooding.

However, the technologies discussed here would need to be adapted somewhat. Take the case of the green roof. In Burkina Faso the need for flood mitigation might not be very high at first, but the insulation and local cooling effect might be very useful. Further, the type of vegetation used in Europe would need reconsidering in a much hotter and drier climate. In Indonesia, by comparison, where there is a considerable need to reduce urban run-off, the rainfall intensities are so high that the technology would need to be adapted to receiving high volumes over short time periods to be effective. Property flood-resilience measures are adaptable to any climate, only the materials having to change to reflect local building methods. Simply moving from less durable materials such as mud and wood to concrete blocks and raising property thresholds and floor heigh, have been used in Burkina Faso to mitigate the flooding that rarely occurs in the capital Ouagadougou. Likewise, infiltration and retention basins can be adapted to local materials and climates, but aquatic habitats and biodiversity functions in hotter drier climates would be somewhat limited for such small water bodies, as they would be prone to drying out.

The risks posed by climate change for the flooding of urban communities in developing countries are considerable, as these communities are often not well protected from flooding, and there is little local or regional knowledge on the future flood risks. The type of green and adaptive technologies discussed in this chapter can provide a more local and sustainable solution to reduce local storm run-off and to adapt areas that can flood. They do not require the kind of centralized government planning and finance that would be needed for large-scale flood defences, and they all offer additional benefits to other sectors, as well as having a number of co-benefits for local communities and the environment. It is recommended that they be considered alongside the technologies introduced in this chapter and be implemented in smart combinations that best meet local needs.

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7. Heatwaves

Unsplash

Excessive heat affects the health of whole communities. Exposure to high temperatures can compromise the body's ability to regulate temperature, potentially resulting in a wide range of illnesses, including heat cramps, heat exhaustion, heatstroke, and hyperthermia (1). It also aggravates pre-existing cardiovascular and respiratory conditions, as well as causing mental health issues and domestic violence.

Some population subgroups are more exposed to and/or more vulnerable to health risks from heat than others. The main such sub-groups are the elderly, the chronically ill, people with disabilities, infants and children, pregnant women, outdoor and manual workers, athletes, and the urban poor.

Worldwide, vulnerability to heat and heatwaves is increasing (2):

- Vulnerability to heat extremes is increasing in every world region. Europe is the worst affected region, followed by the Western Pacific, South-East Asia, and Africa.
- Heat exposure is greatest in urban areas, where the majority of the population currently lives. Climate change increases exposure levels, and it is estimated that, in the near future, nearly four-fifths of the world's cities will be experiencing substantially warmer climates. For example, in 2050, Madrid's climate will resemble that of Marrakech today; Stockholm's Budapest's; London's, Barcelona's; Moscow's Sofia's; Seattle's, San Francisco's; and Tokyo's, Changsha's (3).
- Worldwide, 475 million additional days of exposure to heatwaves affecting vulnerable populations were observed in 2019, representing some 2.9 billion additional days of heatwaves experienced relative to a 1986–2005 baseline in older populations (above 65).
- Between 2000 and 2018, heat-related mortality in people above 65 increased by nearly 54 percent, reaching almost 300,000 deaths annually, most of them occurring in Japan, eastern China, northern India, and central Europe.
- Rising temperatures were responsible for in excess of 100 billion potential work hours lost globally in 2019 compared with those lost in 2000.

These trends are the result of a combination of factors, including population ageing, urbanization and climate change. This chapter focuses on climate change (Box 1).

A warming climate

As a result of anthropogenic climate change, the global mean surface air temperature has risen over the last century, leading to a worldwide increase in the frequency, intensity and duration of heatwaves (4). These trends will continue: a recent study projected that, compared to 2006, the absolute temperatures of four- to ten-day heatwaves will be between 3.4 and 6.6°C hotter in 2099 (5). With further increases in frequency, intensity and duration, heat waves are poised to become an even more significant public health risk in the medium to long term.

Tying with 2016, 2020 was the warmest on record, being fully 0.6°C warmer than the 1981-2010 reference period, and around 1.25°C above the pre-industrial period (1850-1900). Moreover, the last six years have been the warmest six on record (6).

Factors that aggravate health risks from heatwaves

The urban structure, materials, landscape and layout can all aggravate heat risks. More specifically, typical building materials and other heat-retaining surfaces, the residual heat associated with energy use, and the lack of surface humidity can increase temperatures in urban areas. Increases are more acute at night due to the scarcity of green spaces and the slow release of heat that occurs at night (7,8). This phenomenon, known as the urban heat-island effect, can result in effective differences in air temperature ranging from 3 to 12°C in large cities compared with the surrounding rural areas (8,9). The urban heat-island effect exhibits strong temporal and intra-urban variation (10,11), with higher temperatures determined by very local characteristics, such as the types of buildings and urban structure, the use of dark-coloured paving, and heat from vehicles or air conditioners.

Although outdoor temperatures and the urban heat-island effect influence indoor temperatures in buildings, indoor temperatures are also greatly affected by the shape, materials and orientation of the buildings, as well as the ventilation, shading and location of apartments within the building, among other factors. Temperatures tend to increase with elevation and proximity to the city centre, where usually there is less green space (12). Moreover, the susceptibility of a dwelling's occupants to heat and their behaviour (including occupancy patterns) also interact with the building's location and its characteristics, potentially increasing the risk of overheating (13). As a result, some cities, and within them some districts, buildings, dwellings and occupants, are systematically worse affected by hazardous heat.

In addition, the world is becoming more urban. Since 2007, more people have lived in cities than in rural areas, and over the next thirty years global population growth is expected to happen almost exclusively in the world's urban areas: by 2050, the total number of urban dwellers is forecast to grow from approximately 4.4 billion today to 6.7 billion, or two-thirds of the global population (14). The defining characteristics of urban agglomerations and of some urban populations make city dwellers more vulnerable to some of the health impacts of climate change, with heat waves being the clearest example. The combination of the tendency of urban areas to overheat, more people living in cities, population ageing and urban health-risk factors from heat is resulting in higher risks from heat for an increasing proportion of the global population. Moreover, these risks are unequally distributed, disproportionately affecting the poor, the elderly and generally the most vulnerable in society.

7.1. Overview of technology options

A wide range of technologies are available to protect urban populations from hazardous exposure to heat. Ideally, these technologies should be integrated into a heat-health action plan articulated around the elements that, in the context of the city concerned, are fundamental for effective protection against heat. These elements can be divided into (i) know-how and institutional arrangements, or orgware; (ii) devices of different types, or hardware; and (iii) processes, or software. Notwithstanding the importance of orgware, this chapter focuses on hardware and software.[1]

Moreover, the overview presented in this chapter is limited to those aspects that in most cases fall within the competencies of local or subnational governments, or where they can play a central role. For example, most often heat-wave early-warning systems are managed nationally. Although large cities have the capacity to prepare forecasts, local governments will typically be at the receiving end of heat warnings. In such situations, local governments mainly need to ensure that warnings can be received with enough lead time and adequately acted upon. Similarly, local governments are unlikely to lead efforts related to epidemiological surveillance, or other highly specialized and resource-intensive parts of heat-health action plans.[2]

Subnational and local governments are optimally positioned to take responsibility for three of the elements that would be included in a **heat-health action plan: heat-health communications and outreach, the care and protection of vulnerable groups, and the integration of heat- and climate-protection in buildings and urban planning**. The following paragraphs introduce each of these three elements.

7.1.1. Heat-risk communications

Heat risk communications refer to the development and dissemination of information and messages communicating the risks of hot weather and heatwaves and providing behavioural advice to protect oneself and others. A heat-related health-information plan must be clear about what is being communicated to whom and when.[3] Evidence-based advice must reach those who need it most, and technology can play a key role in identifying who they are and the channels by which they can effectively be reached.

The channels and technologies for reaching those vulnerable to heat have suffered a radical transformation in the last decade, quickly transitioning from face-to-face communication, phone calls and SMS, and public service advisories on radio, TV and print, to a mainly digital, web-based and mobile-focused set of technologies. National and subnational health authorities have massively adopted institutional websites, social media, e-mail and messaging Apps as their mainstream choices for the dissemination of heat protection advice (15). Although this has facilitated spreading of the information, questions remain about whether these formats and channels reach key vulnerable groups sufficiently, such as the elderly, the less tech-savvy or population groups whose members may not be proficient in the local language/s. In addition, increasingly, institutional actors are either developing, commissioning or endorsing specific mobile applications to deliver more or less "personalized" heat-protection advice to specific users.[4]

7.1.2. Protecting the vulnerable from hazardous heat

Protecting vulnerable groups and individuals requires first their identification. In addition to the individual-level identification and outreach undertaken by health-care

1
For example, orgware typically plays a key role in heat-health governance and in caring for vulnerable groups. Other related areas in which orgware is a core element of heat-health action plans are well described in the literature (82–84).

2
Nevertheless, some cities, for example in the European Union, are increasingly leading heat-health surveillance activities. Most of these are large urban areas in decentralised states.

3
Evidence based advice for protection against heat can be found at https://www.euro.who.int/en/health-topics/environment-and-health/Climate-change/publications/2011/public-health-advice-on-preventing-health-effects-of-heat.-new-and-updated-information-for-different-audiences.

4
Examples of mobile applications developed by governmental entities include Extrema (https://extrema.space/) and the application called "heat safety tool". (https://www.cdc.gov/niosh/topics/heatstress/heatapp.html?s_cid=3ni7d2XHST-Heat-App-05.2017). Several national meteorological agencies have produced similar applications.

providers and social-care professionals, systematic data analysis, including big data analytics, can be used to identify vulnerability and hot spots, both geographically and in terms of population subgroups. The use of big data in public health is growing, capitalizing on anonymized and privacy-protected sources such as high-volume electronic health records, participatory surveillance systems and mining digital traces, including social media, internet searches and mobile phone logs (16). In an urban context, heat-health analysts can use geographical information systems to cross population data from, for example, censuses or district-level household surveys, temperature measurement data, air pollution data and green space-location data, for example, measured through the so-called normalized difference vegetation index (17). If available, the mapping may include specific data on building materials and other heat-relevant urban landscape characteristics, which could be interpreted using urban climate modelling software.[5]

Technologies that help improve individual thermal comfort, which are gradually being perfected, are increasingly being used as complements to indoor cooling technologies. Personal cooling systems (for indoor or outdoor use, or both) are receiving increased attention in research, recognizing their ability to improve thermal comfort cost-effectively (18). These personalized cooling systems may include shade structures, water-based cooling, smart textiles, ventilated clothing, personal ventilation, personal humidifiers, fans, air-conditioning, and cooling clothes using air or liquids (12). Several studies have evaluated the most effective body segments for localized cooling with the aim of promoting thermal comfort and sleep (19) (20). For example, evaporative cooling has a positive cooling effect, especially in dry conditions, though its effectiveness is highly dependent on the outdoor climate.[6] However, most personal cooling systems have so far been evaluated in laboratory experiments or workplace settings only. These are not representative of vulnerable groups, whose sensitivity to heat and thermal comfort remains poorly understood.[7]

For the actual protection of vulnerable groups and individuals against hazardous exposure to heat, indoor cooling technologies, whether active, such as air-conditioning, or passive, such as natural ventilation or building modifications, remain crucial. These technologies are described in the next subsection.

7.1.3. Indoor heat reduction

The technologies for indoor heat reduction in the built environment have experienced significant development in the last decade, with both common and differentiated solutions for various settings, including dwellings, offices and other workspaces, health-care centres and other types of institution, such as long-term care centres, shelters, or prisons. Though outdoor temperature clearly influences how indoor temperatures are experienced, the latter also depend on a wide array of other factors, including building and dwelling characteristics, occupancy profiles and behavioural factors. For this reason, reducing indoor overheating can be achieved through a variety of strategies and technologies.

5
Envi-Met (38) is one such software package in common use.

6
Evaporative cooling is considered a moderately effective strategy for reducing heat exposure, having the advantage of not requiring any special installation (85).

7
A comprehensive systematic literature review focusing on the differences in temperatures of thermal comfort between younger adults and older persons found a wide range of estimates, from 0.2 to 4°C, highlighting the heterogeneity of studies and the need for further research before even considering a selection of cooling options for the elderly (86). There is therefore a need for further research on the health-protection potential of these devices for use at home and/or by vulnerable groups.

Passive cooling

A first set of technologies that can be used to reduce indoor heating involves so-called passive cooling devices and approaches (Chapter 2). These technologies can be grouped into three main blocks (21):

1. **Reducing the internal gain of heat, through:**
   - shading
   - glazing
2. **Heat transfer through the building envelope, that is, the building's shell or its outer layer, through:**
   - phase-change materials applied to wallboards, windows, roofs and ceilings[8]
   - passive cooling shelters[9]
   - heat sinks[10]
   - The building's own thermal capacity (i.e. the ability of the building to absorb heat without quickly heating up indoor spaces)
   - radiant heat barriers[11]
3. **Heat transfer between indoor and outdoor air through:**
   - natural ventilation, that is, wind-driven cross ventilation or buoyancy-driven stack ventilation
   - evaporative cooling[12]
   - ground cooling[13]

Compared to other options, passive-cooling solutions are less energy-intensive and result in fewer emissions of greenhouse gases. Furthermore, some passive cooling technologies, such as shading, some types of glazing and many natural-ventilation elements typically require minimal retrofitting and, in some instances, can be installed by the residents themselves.

Traditional architectural solutions for passive cooling may have some potential for health protection. However, they have not been systematically evaluated, and there is a clear need for more research.

It is worth noting that not all passive-cooling technologies are feasible in every setting or in every climate. For example, in many existing buildings, some passive-cooling retrofitting options, such as changes to the building's envelope, can be cumbersome, unaffordable or unfeasible for technical or other reasons. Similarly, some passive-cooling technologies are suitable for dry climates, but not for humid environments.

Active cooling

A second set of technologies that can be used to reduce indoor heating involves so-called active cooling devices and approaches. These technologies include artificial ventilation (for example, electric fans), personal cooling systems (described in the previous subsection), and air-conditioning equipment.

8
Phase-changing materials are substances that, by changing their physical state from solid to liquid, absorb or release heat. Incorporated into walls, floors and ceilings, these materials can be used for cooling or heating purposes.

9
A passive cooling shelter is a structure of pipelines sandwiched within the building framework to decrease indoor temperatures.

10
A heat sink is a cool medium to which heat is driven, such as a water body, the ground, or others.

11
Elements placed on the outside façade that block some solar radiation.

12
Evaporative cooling is the dissipation of heat via water evaporation, which can be achieved through a variety of evaporative cooler devices and techniques.

13
Cooling down a building using ground-cooled air or ground-cooled water, taking advantage of the fact that the ground tends to be cooler.

Using electric fans to reduce heat has been a widespread practice in households, workplaces and institutions for a long time. However, despite their perceived comfort, their actual protective effect on health is unclear.[14]

Conversely, the health-protection effect of air-conditioning during heat waves is well proven (22–26). In fact, air-conditioning provides a significant part of the protection against overheating in the built environment in institutions, cooling centres (private or public cool spaces that are accessible to the public during a heat wave) and homes globally. However, air-conditioning has severe drawbacks:

Inequitable access and summertime energy poverty. Those who are most vulnerable to heat often live in housing that is prone to overheating and are less able to afford the costs of air-conditioning (purchase, installation, maintenance, and crucially running costs), resulting in deep income-related inequalities (27). The running costs of air-conditioning may become unaffordable even for households that may have been able to afford the equipment and installation, thus rendering the technology ineffective (28).

Social and individual dependence on air conditioning. Spending a majority of one's time in air-conditioned environments may impair one's acclimatization to natural heat (29), create psychological dependence on air-conditioning (30), lead to systematic over-cooling (31), leave residents unprotected during grid overloads and blackouts, and destroy traditional know-how related to dealing with hot conditions, thus reducing social resilience.

Energy consumption and risk of blackouts. In locations where the use of air-conditioning devices has become general, cooling can take more than half of peak-electricity demand on hot days (32). Indeed, heat waves disrupt electric-utility operations and make electricity prices more volatile, thereby reducing the security of the electricity supply (33).

Waste heat. Most air-conditioning devices produce waste heat, which is typically expelled to surrounding areas. This waste heat exacerbates the urban heat-island effect (34).

Air pollution. In many parts of the world, the electricity used to run air-conditioning devices is generated by fossil fuel-powered technologies. In addition to global-warming carbon dioxide, these technologies emit local air pollutants, notably fine particles and nitrogen dioxide. Local air pollutants aggravate respiratory and cardiovascular disease and cause premature mortality. Moreover, air-conditioning use in combination with reduced ventilation and/or inadequate maintenance may increase indoor air pollution (12).

Greenhouse gas emissions. The use of air-conditioning devices contributes to climate change in two ways. First, many of these devices use hydrofluorocarbons, which are powerful global warming gases. Second, in areas where electricity is generated by burning fossil fuels, the increased demand for electricity associated with the use of

14
A full Cochrane review (a very high standard of scrutiny in public health) was conducted on this issue (87), concluding that existing evidence did not resolve uncertainties about the health protection potential of electric fans during heatwaves. Newer evidence has not challenged this conclusion thus far.

air-conditioning devices results in addition emissions of carbon dioxide. In the period 1990-2016, carbon dioxide emissions attributable to the use of air-conditioning devices tripled, a trend that is expected to worsen by 2050 (35).

Maladaptation. Whereas air-conditioning constitutes an adaptation strategy in that it provides protection against climate change-driven heat waves, when its use results in an increase in greenhouse-gas emissions (see above), it becomes an example of maladaptation (15). Maladaptation refers to adaptation actions that result in increased vulnerability to the risks of climate change.

7.1.4. Urban planning against heat

Taking heat exposure into account when undertaking urban planning and management can protect the population from heat risks. Protection can be achieved through three main strategies:

Changing the form and structure of the urban landscape. Though often technically or politically challenging, changing the morphology of urban settings is one of the most effective ways of improving the thermal comfort of urban dwellers. Key changes in morphology include the ratio of average building height to street width; the orientation of buildings and streets; the compactness of blocks; the location and distribution of green and empty spaces; and barriers to air and wind circulation (36,37) (38). Urban-planning strategies that prioritize internal non-motorized transportation, public transportation, pedestrian areas and green spaces against a looser conventional traffic network (39) are conducive to progressive changes in urban morphology by reclaiming public spaces for people, reducing motorized transport and promoting active mobility while increasing urban greening and reducing overheating (40).

Strategic placement of urban greening and/or water bodies. Green urban spaces protect from heat by reducing the urban heat-island effect and providing shading. Indeed, the relative abundance and size of green urban spaces is correlated with heat-related mortality. However, accurate analyses are needed to determine what types of green urban spaces can realistically be introduced into the urban fabric and what the most effective arrangements are with regard to preventing hazardous heat exposure in each location. Urban heat-risk hot-spot mapping can become a key technology to determine optimal green space types, locations, arrangements and the expected effects of urban greening interventions.[15] Remote-sensing and tele-detection, in combination with algorithms to describe potential access, use and social functions, provides an evidence base on which to take decisions regarding placement and other characteristics (41–43). Green spaces should be water-efficient and use domestic plants, with a preference for trees with wide canopies. The role of urban “blue spaces” (typically, water bodies) in reducing hazardous heat exposure at the population level is less clear than that of green spaces. The cooling effects of water bodies for cities estimated so far are modest (44) and in some studies negligible (45). Moreover, some health risks, such as drowning, injuries and vector breeding, may increase through the use of water bodies if these are inadequately managed or maintained (46). Notwithstanding these considerations, the strategic placement of water bodies could aid both in flood and drought management.

15
It is worth noting that green urban spaces provide benefits that go beyond the health benefits mentioned above. These ancillary benefits include the potential of green urban spaces for mitigation through carbon sequestration (chapter 2), the reduction of the flood-related risks and hazards that they afford (chapter 6), and their benefits in terms of moisture retention (chapter 5).

Reducing the heat absorption of urban surfaces. Changing the composition or reflectivity of urban surfaces, such as facades, pavements or roofs, can reduce heat absorption (47) (48). Using construction materials that absorb less or release more heat is an option mostly in new construction, though the regulatory and economic incentives applicable to the sector need to be aligned. Reducing the degree of soil-sealing (with artificial materials) in open spaces can reduce the build-up of heat and ultra-violet radiation from reflection. Increasing pavement reflectivity by using reflective materials or lighter colours can also yield significant reductions in the urban heat-island effect (49). Increasing reflectivity may be particularly suited to cities where significantly increasing the area of green space may not be possible. Other technologies in this category include roof gardens and facades (with special attention due to the climate adequacy and low pollen allergen of the plants), urban canopies and shading with pavilions, additional roofing, sunshades, sails, and trees with thick foliage.

7.2. Selected technologies

From this technological landscape, we select a subset of technologies that, on account of their environmental, social and economic benefits, merit particular attention in the context of adaptation to climate change in urban areas. The selected technologies meet two criteria. First, most local governments have the competencies to implement them and the institutional structures required to do so. Second, implementation of these technologies by local governments can complement or strengthen related actions taken at higher levels of governance. The selected technologies are district cooling and cool roofs.

7.2.1. District cooling

District cooling refers to a centralized network of pipes that deliver cooling (most often in the form of chilled water) from a cooling plant to a series of users. Thus, cooling becomes a commodity, like electricity or water, one that allows for centralized management in a way that is not possible with individual or building-level air-conditioning units.

Scope of the technology

With roughly two billion air-conditioning units currently in operation around the world, space cooling has become the chief driver of electricity demand in buildings. Residential air-conditioning units account for over two-thirds of the total and are very unequally distributed. Increasing income, population growth, and more frequent and extreme heatwaves are expected to spur further demand for cooling on an unprecedented scale, whereby the number of air conditioners installed could increase another two-thirds by 2030 (35). Against this background, governments worldwide are promoting district cooling. If implemented adequately and equitably, district cooling can significantly extend the health-protection effects of by air-conditioning while reducing or minimizing some of its drawbacks.

Currently, district cooling is becoming increasingly popular in various regions of the world. In the Middle East, seven million square meters of district-cooling capacity were installed in 2014 alone. Dubai, with the world's largest district-cooling network, wants district-cooling to meet two-fifths of its cooling demand by 2030, while reducing the city's power consumption for air-conditioning by half and reducing peak energy demand (50). Japan has a long tradition of district-heating and cooling, and currently some of the largest district-cooling systems are in operation in Tokyo, Osaka, Sapporo, Nagoya, Fukuoka, and Yokohama (51). District-cooling is increasingly common in the European Union, especially in Denmark, and is growing quickly in South Korea (52). In low-income countries, district-cooling is especially well developed in Port Louis, Mauritius, which boasts a seawater district-cooling system (53), and in Gujarat city, India (54). Globally, the district-cooling market is expected to reach a value of US$17.3 billion in 2024, up from just over US$11 billion in 2015, as more cities globally are expected to install district-cooling systems (50).

Key strengths of the technology

Compared with conventional air-conditioning systems, district-cooling presents the following advantages:

- More efficient use of energy, leading to over 40 percent of energy efficiency improvements and 20 percent in lifecycle cost savings as compared with the equivalent cooling capacity via individual air-conditioning units (55)
- Reduced electricity demand, in particular during peak hours, thus lessening the risk of blackouts and contributing to reducing price volatility and energy insecurity
- All else being equal, greater energy efficiency and less electricity demand means a lower carbon intensity of DCS per unit of cooling compared to individual AC units
- Less space inside the building and no facade installation
- Lower operating and maintenance costs, as well as electricity costs (56)
- Increased likelihood that cooling is powered through electricity generated from renewable sources, owing to the centralised nature of district-cooling management.

In certain situations, district-cooling systems can rely on cold water from oceans, seas, lakes, rivers and aquifers, and can also rely on waste-cooling, such as that produced in the processing of liquefied natural gas (57). District-cooling can also reduce waste heat by either releasing it outside the city or otherwise processing it centrally, thus reducing its contribution to heating urban microclimates.

In addition to helping protect human health under heat-waves, district-cooling helps reduce inequalities. Put simply, the ability to make cooling available equitably to those who need it most at a price they can afford can reduce heat-related mortality and illnesses. Furthermore, the centralized management of district-cooling reduces the central inequality components of individual air-conditioning access and operation, namely those related to summertime energy poverty. In addition, cooler homes can boost income generation in the informal sector and empower women, as observed in the Mahila Housing Trust case reported later.

In terms of the economic advantages, it is not easy to compare the operating costs of individual versus district cooling since the separate metering of cooling electricity use is uncommon, and estimates of maintenance costs and average depreciations are difficult to calculate. Pricing can also be done very differently (58), but it is likely to be heavily influenced by whether the operating authority functions as a not-for-profit organization (as mandated in many district-cooling services) or otherwise. However, from a collective perspective, a properly planned district-cooling service provides significant savings and cost-effectiveness (59), typically achieving electricity cost savings of between one-fifth and two-fifths compared to individual air-conditioning systems (60,61). Moreover, compared to large-scale deployments of individual chillers and air-conditioning units, district-cooling systems place no additional burdens on electric utilities and electricity grids.

Trade-offs

A key trade-off associated with the use of district-cooling systems is they cannot be applied anywhere but require the users' buildings to be close to each other. Indeed, district energy performance depends on centralization and scale, which is why several systems start with obligatory connections for new and/or existing projects in district energy areas. Thus, district-cooling systems are suitable for dense urban areas and have a built-in inequality element.

The centralised nature of district cooling results in a further trade-off, namely the fact that the organization running the system has a *de facto* monopoly over the concerned network and might not have the incentive to provide the best service and the best possible price (62)(58). Moreover, the possibility of acquiring a de facto monopoly on a share of the market by means of a concession may prompt rent-seeking through lobbying.

Additional trade-offs include:

- the large capital-investment cost required to develop-district cooling systems, part of which would typically be borne by the users, even though adjustments can be made to minimize the upfront costs
- a lack of redundancy given the centralized nature of the service, which means that, in cases of failure, most or even all users are affected
- the large amounts of water required, thus potentially introducing competition for the necessary resources (chapter 5)
- the waste heat transferred to local water sources may have unintended effects on local ecosystems
- implementation requires a significant policy impetus and may encounter resistance from vested interests, namely the providers of non-centralized cooling services.

Barriers to adoption

The adoption of district-cooling systems faces some of the same barriers that are common to efforts to deploy district-energy systems. Six main types of barrier can be distinguished, as outlined in the following paragraphs.

Economics and finance. District systems require high initial capital investments. Not least, only a relatively large number of concentrated settlements make the systems financially viable. Added to these considerations is the uncertainty about initial demand levels and long payback times, which make the investment less attractive.

Laws and regulations. Lack of regulation against rent-seeking behaviour is likely to stifle the development of district systems. A regulatory framework that is not conducive to investment in a centralised system has the same effect.

Institutions and organisational capacity. District systems require a degree of coordination across government agencies, as well as between national and local authorities. Not least, advanced organizational skills are also needed.

Human capacity. The design and planning of district systems requires skilled technical personnel, which is not always available locally. The same is the case when it comes to installation and management.

Information and awareness. Limited awareness of the technology is likely to stifle demand. In turn, limited information about operational and financial models may jeopardise efforts to deploy it.

Technical issues. District systems face six technical barriers: the major infrastructure modifications required compared to other systems; the lack of local reference examples against which performance can be gauged; the lack of sufficient data on municipal heating and cooling; the lack of an agreed methodology to recognize energy savings and environmental benefits; the lack of agreed accounting methods to develop efficiency ratings; and the lack of labels and standards for buildings.

In addition, and specifically with regard to district-cooling systems, it has been argued that there is a risk of overestimating the demand for cooling capacity because property owners are not aware of their total annual cooling demand, even though they might know their maximum peak demand. Overestimating the demand for cooling capacity leads to unduly large estimates of the investment required, thus making investment plans more challenging than actually required. Finally, if a district-cooling programme involves the circulation of cool water from a natural source such as the sea, a lake or a river, one or more environmental permits may be required, for which an environmental impact assessment study may be needed.

Enablers to adoption

Most often, district-cooling systems are developed as a part of broader efforts to introduce district energy systems. Thus, in several locations, deployment of district cooling has been greatly facilitated by the existence of the infrastructure, the policy framework and the actors created for district heating. This has been the case in Denmark, Sweden and Finland, despite their colder climates and comparatively low population densities compared to other countries in the EU. In fact, being able to sell both heating and cooling may be a crucial incentive for providers. In addition, in the European Union local regulations concerning facades (specifically, regulations banning outward-facing air-conditioning equipment) and efforts to promote energy efficiency are reported to be major drivers of demand for district-cooling systems (60).

Experience, in the form of local or similar examples, is a clear enabler. In particular, the benchmarking of proposed customers with similar customers in existing projects, along with climate data and existing property data, can reduce uncertainties and prevent demand being over- or under-estimated.

The operator of district energy systems generally, and of district-cooling in particular, needs to be perceived as a trustworthy and reliable supplier that can arrive at long-term solutions and that has the necessary technical competence and engineering know-how. Stakeholders in a city or other municipality should consider the most appropriate business model. Non-profit organizations may view investment in infrastructure as one of their broader objectives. For this reason, they may be willing to accept a longer-term payback.

District-cooling schemes tend to produce low but stable revenues, as reported in Helsinki, Stockholm and Vienna, among other cities. As is the case with district energy systems (chapter 2), local governments are uniquely positioned to advance district-cooling systems, as they are at once planners, regulators, finance facilitators, advocates, providers of infrastructure and services, and large institutional consumers of energy.

Making connection to district-cooling systems obligatory for certain customers under certain conditions could help overcome the lack of demand, but it may face resistance and, if resorted to, needs to be accompanied by extensive transparency and the building of trust. Depending on the characteristics of the affected communities, arguments relating to reducing carbon footprints, energy resilience and improved self-sufficiency may help persuade those who are the target of these proposals.

7.2.2. Cool roofs

Compared to traditional roofs, cool roofs have lower net heat absorption. Lower heat-absorption levels are achieved by increasing the reflectivity of the roof by using lighter colours and paints, replacing or coating building materials, and/or taking advantage of the cooling effect of water evaporation.

Scope of the technology

Cool roofs can be roughly categorized into three types. First, are roofs made of inherently cool materials, such as thermoplastic white vinyl. Second, there are roofs with solar-reflective coatings, such as paints or membranes. Third, with green roofs, cooling is achieved through the shading and evapotranspiration of greenery and plants.[16]

The health benefits of cool roofs have been evaluated in a variety of developed- and developing-country urban settings (63). They are a particularly effective city-wide heat-reduction strategy in urban settings where substantially increasing green spaces may not be possible (64).

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In this chapter, green roofs are not discussed further on account of the additional expertise and maintenance, including irrigation, required, which limits their applicability. Besides, in most cases, and compared to other types of cool roofs, they are less effective at reducing heat.

Key strengths of the technology

Environmental aspects. As a passive cooling strategy, cool roofs, pavements and walls are less energy-intensive in their operation than the equivalent active cooling alternatives, though this and other environmental impacts need to be evaluated through their life-cycles (65). The potential reductions in greenhouse-gas emissions from cool urban surfaces are clear, however. One study estimates that, should cool roofs and pavements be implemented globally across all urban areas, they would save 44 gigatonnes of carbon-dioxide emissions from avoided electricity and fuel consumption, counted as a one-time offset over the lifetime of the affected infrastructure, and compared with a business as usual scenario (66). Subsequent studies have reconfirmed the tremendous mitigation potential of increased albedo (49,67).

Economic aspects. Cool roofs can be very cost-effective, though actual performance depends heavily on local labour and materials costs. Thus, whereas a study in California found that increasing albedo (to reduce the urban heat-island effect) would save very little money (68), a global study estimated that changing a fifth of a city's roofs and half of its pavements to 'cool' versions may save up to 12 times the cost of installation and maintenance, while reducing air temperatures by 0.8^{0}C on average (69).[17] In addition, the specific choice of technology for making the roofs 'cool' also determines the cost of the relevant materials and labour.[18]

Health and social aspects. The health benefits of cool-roofing technologies affect both the buildings' occupants directly because of the reduced overheating of dwellings, rooms and workspaces, as well as both them and others due to the reduced contribution of the building to the urban heat-island effect. Increased rooftop albedo may significantly reduce heat-related mortality (70), mainly by reducing residents' exposure to indoor heat. The reduction of mortality through a reduction in the urban heat-island effect is much smaller, particularly if it is not accompanied by measures to reduce energy poverty and thermal inequalities.[19]

The health-related benefits of cool roofing can be measured beyond reduced mortality and illnesses, notably in terms of improved thermal comfort – both measured and perceived – inside the buildings (71,72). When cool roofs are implemented on a sufficient scale, improvements in thermal comfort are also measurable outdoors. Indeed, the social benefits of this set of technologies depends heavily on their deployment at a sufficient scale.

Affordability is in turn a key factor in the deployment of this technology, for which the main potential benefits are related to thermal equality (that is, reaching those who cannot afford cooling) and reducing the urban heat-island effect. The fact that a viable market can be found in urban slums in India, though propped up via microfinance or other instruments, is a solid basis on which to consider potentially large-scale deployment in many settings.

17
A life-cycle analysis in southern Spain found generalized cost-effectiveness for cool-roof retrofitting under local conditions and over a twenty-year lifespan (88). Perhaps the best demonstration of affordability comes from the proliferation of the technology in low-income settings, like the slums of Ahmedabad (Gujarat), where four low-cost solutions all provided varying but significant levels of protection (89).

18
For example, in Ahmedabad, India, in 2017, locally available sunlight-reflective white lime paint could be acquired at a cost of around $0.75 per square metre (90). Low-income communities in the same city used various other technologies: modular roofing manufactured from packaging and agriculture waste (local estimated cost $42 per square meter); ventilation sheets on roofs to allow air circulation and light (various prices); and false ceilings underneath primary ones (locally sourced at around $20 per square foot, for materials only). Another cool-roof programme in Hyderabad used a high-density polyethylene (HDPE) cool-roof coating which retailed for $2.15/square meter, though it was provided at a lower cost by the relevant company as a corporate social responsibility initiative (91).

19
Although, in some instances, reductions in the urban heat-island effect have shown to have a significant impact on mortality levels (92), by and large such impact is limited (Goggins et al., 2012) (Milojevic et al., 2016). Nevertheless, if reductions in the urban heat-island effect are coupled with interventions to reduce thermal inequities and energy poverty – as they should be – then the protective effects are multiplied.

Moreover, often times it is women and children who spend more time at home, with women in these slums frequently being informally and self-employed. Achieving tolerable thermal comfort increases the productivity of home-based workers in boosting their income and empowering them.[20]

Trade-offs

An increase in reflective surfaces within cities to reduce the intensity of the urban heat-island effect, such as through cool roofs and surfaces, may have unintended consequences. A significant possibility is the potential increase in concentrations of ozone, a secondary pollutant whose formation is aided by direct and reflected sunlight (73). Moreover, some cool-roof technologies have other specific disadvantages: their suitability and actual cost-effectiveness is highly dependent on local climate and conditions, as well as several other factors, including building location, building construction, and building type. Not least, lighter coloured roofs cause glare that may result in annoyance, or disturb some activities, whereas lighter colours make dirt and grime more visible, both reducing the roof's cooling and having aesthetic consequences. In northern, temperate latitudes, cool-roofing may end up increasing heating energy bills.[21]

Barriers to adoption

The main economic and financial barriers to the adoption and deployment of cool-roofing technologies relate to the high initial capital investment that, in certain settings, some cool-roof technologies show. Indeed, the installation of some cool-roofing solutions may require a significant initial investment, whereas returns in the form of energy savings take time to accrue. Moreover, depending on the specific technology and the local costs of materials and labour, cost-effectiveness could be severely diminished, making the investment unattractive to developers, local authorities and residents. Market conditions – specifically, insufficient demand for actors to enter the market – can also hinder this technology. Despite overall global increasing trends in the demand for cool roofing (74), there may not be enough aggregated demand in a given location to make it a worthwhile activity for technology providers.

Legal and regulatory barriers include:

- Lack of regulatory mandates for energy efficiency: if energy efficiency is not mandatory in new projects, there may not be enough incentives for promoters to consider cool roofing.
- Low levels of inspection: in cases where some types of cool roofing may be required, there may not be enough capacity for inspecting compliance.
- Slow/no granting of construction licenses when required may occur if the licensing authorities are unfamiliar with the technology.
- Unclear land and building ownership provisions: a lack of formalized property rights, commonly found in slum settings, may discourage dwellers from any building modifications.

Limited capacity can represent a significant barrier. Local authorities may lack the know-how or capacity to promote the technology. Similarly, the technical skills required for the installation of some types of cool roofing may not be available locally.

20
The Mahila Housing Trust supports self-employed women with pro-poor financial mechanisms and technical guidance to make their houses climate-resilient (cool roofs are the main intervention). This demonstrates that it is possible to mainstream climate-resilient practices in the housing sector by targeting the most vulnerable population, thereby promoting economic empowerment, gender equality, health, sustainable livelihoods and climate-resilience as benefits.

21
A comprehensive review of trade-offs of the main cool-roofing options has been compiled recently (93).

Social, cultural and behavioural factors can also pose barriers. A lack of familiarity with the technology and negative pre-conceived ideas may steer consumers away from it. The same may be true for aesthetic reasons.[22]

A lack of information and awareness may be crucial barriers. Prospective customers may not be able to find enough information to make informed choices or to assess the technology's likely performance in their location. More generally, there may not be enough awareness of the individual and collective benefits of cool roofing.

Lastly, various technical barriers may hinder the adoption and/or deployment of cool-roofing technologies. Key among these are aspects related to construction work: while some cool-roofing solutions require minimal retrofitting, others imply major interventions, potentially discouraging residents and other stakeholders.

Enablers to adoption

Targeted financial mechanisms can be a key enabler of the adoption of cool roofs. For example, low- or no-interest loans, conditional grants, rebates and generally pro-poor financing tools can go a long way toward facilitating the implementation of cool roof programmes. The combination of such tools, coupled with adequate technical guidance by qualified personnel, would ensure that the selected cool-roofing portfolio is cost-effective under local conditions, is culturally and socially acceptable, and has been correctly implemented. The promotion of cool roofing through a combination of economic and regulatory incentives can help overcome initial insufficient demand for suppliers to enter the market. Subsidies are an obvious option in the early stages of adoption, as well as the gradual establishment of cool roofing as a way to achieve compulsory energy-efficiency standards for buildings, provided they exist and can be enforced. A clear regulatory framework for cool roofing provides a safer ground for providers and end-users, facilitating adoption.

Greater awareness of the benefits of cool roofs can also help drive demand, which needs to be supported thereafter through capacity-building to seed local capacity to install and maintain the roofs. Engaging real-estate developers to install cool roofs on a voluntary basis can have a multiplier effect, serving as local reference examples to increase uptake. Long-running local examples also generate locally relevant information and awareness that can nudge consumer preferences towards the adoption of cool roofing, whether in new buildings or through retrofitting.

7.3. Key policy-related issues

7.3.1. The overarching importance of building quality and targeting vulnerable buildings

Cool roofing and district cooling are not meant to replace adequate building standards and quality in providing thermal comfort. Though intuitively obvious, the age of the existing building stock, the percentage of homes in good condition, and rehabilitation

22 Colouring, proneness to visible darkening (notably, via depositions) and other external attributes of cool roofing may be perceived as aesthetically undesirable.

licenses are indicators of the extent to which buildings are well protected against extreme temperatures (75). They are of even greater importance than other socioeconomic factors, such as the level of income as determined through deprivation indices. This is also true for the mitigation aspects of building interventions (chapter 2).

The degree of home conservation, housing-material quality, thermal insulation and air-conditioning and heating systems have been shown to play a pivotal role in modulating the effects of heat and cold waves (76). A thermal extremes hazard-reduction policy based on the identification of vulnerable buildings can apply rehabilitation, insulation and energy-efficiency programs (including cool roofs and/or DCS) to dwellings where dangerous overheating is most likely to occur, thus contributing to reducing energy poverty and emissions of greenhouse gases (77,78).

7.3.2. Technologies against heat waves as part of a heat-health action plan

While technologies are fundamental to protecting cities and their residents from heat, it is important to keep things in perspective: protection from heat requires heat-action planning. The World Health Organization (2008) has identified the following core elements of health-heat action plans (80):

- **Governance:** agreement on a lead body to coordinate a multipurpose collaborative mechanism between bodies and institutions and to direct the response if an emergency occurs
- **Early-warning systems:** heat-health warning systems to trigger warnings, determine the thresholds for action and communicate the risks
- **Communication:** a heat-related health-information plan about what is being communicated, to whom and when
- **Reducing indoor heat:** medium- and short-term strategies, including, but not limited to, advice on how to keep indoor temperatures low during heat episodes
- **Care for the vulnerable:** particular care for vulnerable population groups, including identification, localization and outreach
- **Preparedness of the health and social-care system**, including staff training and planning, appropriate health care and the physical environment
- **Long-term urban planning:** addressing building design and energy and transport policies that will ultimately reduce heat exposure; and
- **Real-time surveillance** of heat-related health outcomes, and monitoring and evaluation of both processes and outcomes.

For a city in the initial stages of combating heat waves, there is a plethora of publicly available heatwave plans to use as templates from almost every world region, and at various levels of governance, from national/federal to regional to local. However, there is a clear bias in this pool, with most publicly available plans coming from high-income countries and settings. An exception to this trend is the rapid development of local heatwave plans in several Indian cities. Many of these efforts can be traced back to the heat action plan of Ahmedabad, in the Indian state of Gujarat. First implemented in 2013, the plan includes four key strategies:

- Building public awareness and community outreach to communicate the risks of heat waves and to implement practices to prevent heat-related deaths and illnesses
- Initiating an early-warning system and inter-agency coordination to alert residents of predicted extreme temperatures
- Capacity-building among health-care professionals to recognize and respond to heat-related illnesses, particularly during extreme heat events; and
- Reducing heat exposure and promoting adaptive measures.

The latter (heat exposure reduction) comprises a pool of low-cost solutions, including a variety of cool roof options: reflective paints, white gravel or mosaic, rooftop gardens, cool sheds through organic material lining, solar photovoltaic panels and modular roofs. The Ahmedabad plan received support and assistance from an international consortium, which undoubtedly contributed decisively to its success. The plan's roll-out, implementation, monitoring and evaluation showed that heat action planning saves lives, as proved by an independent public health evaluation of their efforts, that activities can be scaled up quickly with enough buy-in, and that a low-income city can successfully implement a heat-health action plan. Other cities and states in India followed Ahmedabad's example, designing and implementing extreme heat-warning systems and preparedness plans. In 2020, the national government was working with 23 states and over 100 cities and districts to develop and implement heat-action plans across India (81).

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TECHNOLOGY NEEDS ASSESSMENT

This guidebook is produced as part of the GEF-Funded Global Technology Needs Assessment (TNA) Project, which is implemented by UNEP and UNEP DTU Partnership. Since 2009, close to one hundred countries have joined the Global TNA Project.

Urban areas are home to an increasingly large share of the world's population. As a result, a growing proportion of global greenhouse gas emissions are stemming from activities located in cities and towns, where many of the adverse impacts of global warming are also being felt strongly. This guidebook provides information on technologies for climate change mitigation and adaptation that are relevant in an urban context, specifically in relation to buildings, transportation and waste management for mitigation, and in relation to droughts, floods and heatwaves for adaptation. It aims to provide TNA stakeholders and city-level decision-makers with information about various technological options and potential challenges and opportunities for their use in cities.

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