

Article

Transforming Built Environments: Towards Carbon Neutral and Blue-Green Cities

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Abstract: In the 21st century, the creation of built environments that are carbon neutral and water sensitive is critical for addressing sustainable urban development challenges. Both require transformative change: Decarbonisation to mitigate greenhouse gas emissions and incorporation of green-blue water sensitive solutions to adapt to climate change impacts. Transition pathways in both arenas involve combinations of new technology, innovative urban design, enabling policies and regulations, new processes for planning and managing urban development, and demand-side changes in consumer attitudes and practices for urban living related to energy and water use. In this paper, we present new knowledge, concepts and frameworks developed for application in Australia, as well as internationally, through research by the national Cooperative Research Centres for Low Carbon Living (CRCLCL) and Water Sensitive Cities (CRCWSC) between 2012 and 2020. These findings and outputs illustrate common features of the research strategies and initiatives that were central to the activities of the CRCs, and highlight promising directions for collaborative interdisciplinary and transdisciplinary research that drives urban sustainability transformations towards carbon neutral and blue-green cities.

Keywords: decarbonisation; water sensitive cities; sustainable urban development; liveable cities; climate change; urban transitions

1. Introduction

Urban science has now clearly revealed that 21st century cities in developed and developing economies must achieve multiple sustainability goals, given the central role cities play in global, national and local economies [1–3] and the pressures they exert on the Earth’s natural ecosystems [4]. In the face of global carbon constraints [5], resource constraints [6] and challenges to urban resilience amplified by climate change [7] and rapidly growing urban populations, the United Nation’s Sustainable Development Goals (UN SDGs) [8] represent a call to action on multiple fronts. These global goals and objectives are values-based and have been designed to raise awareness and create an understanding of the complex challenges facing societies and their development in the 21st century. They require a shift from “siloed thinking” to an integrated approach designed to “put to rest the futile debates that pit one dimension of sustainable development against another—each goal should be analysed and pursued with full regard to the three dimensions of sustainable development-economic, social and environmental” ([9] p. 9). The significance of the UN SDGs is this: If the values they represent are broadly shared, they provide a basis for all stakeholders to collaborate and coordinate in pursuing solutions to achieve these challenging goals.

There are numerous examples of how these global goals are being used to frame future planning strategies in multiple sectors in Australia, especially those related to building and construction [10] and transport [11], the two most energy intensive, resource-consuming, and greenhouse gas (GHG) emitting urban sectors; sectors where mitigation potential is high, but in practice is lagging [12]. A major contributor to this lag is that there is no uniform commitment in Australia across government scales (especially federal level [13]) or the built environment sector [14,15] to appropriate renewable energy goals, climate change mitigation and adaptation strategies, water sensitive urban development planning processes, green economy transition policies and sustainable urban development objectives. This inhibits development and alignment of public and private sector strategies, and investment capable of more rapidly and confidently driving the urban, infrastructure and industrial transformations required in the 21st century.

Two critical urban transformations linked to UN SDGs are the focus of this paper—transition to cities that are carbon neutral (producing net zero carbon dioxide emissions) and blue-green (recreating natural water cycles and integrating nature-based solutions to improve environmental health, urban amenity and community wellbeing). They fundamentally relate to the liveability and sustainability challenges confronting cities in both developed and developing societies, and their success in radically shrinking their ecological, carbon and urban footprints while maintaining or enhancing liveability [16]. Australasian and North American cities have world-leading ecological footprints twice that of equally liveable European cities, and at least triple those of developing countries. Principal reasons are the low-density forms of high-footprint cities, their automobile dependence, the large floor areas of (predominantly detached) housing that requires increased levels of heating and cooling and act as Trojan horses for excessive consumption [17]. These cities are not a conducive spatial context for low consumption of urban resources (e.g., energy and water [18]) or low carbon living [19].

Over recent decades, a transition pathway for cities in the 21st century has been emerging, seeking to close the door on a model of city development that has been demonstrably “exploitative” by putting economic objectives ahead of social and environmental concerns. Instead, an “eco-efficiency” framework represents an attempt to assess both the positive and negative environmental impacts associated with an urban development project (see Figure 1). It recognises that both environmental and economic calculations need to be involved in built environment decision-making (the genesis of the term “eco-efficient” [20,21]). The objective is to reduce environmental impact subject to cost, but the primacy of economic performance is typically evident—to some extent due to challenges associated with measuring the positive economic values of urban ecosystem services and the negative externalities linked to different types of urban development, and incorporating both in the development project cost-benefit spreadsheet. An inhibiting factor is that neo-liberal governments are typically not disposed to regulation requiring scientifically validated sustainability measurement; instead tending to favour industry-supported voluntary (often check-box) schemes when it comes to performance assessment.

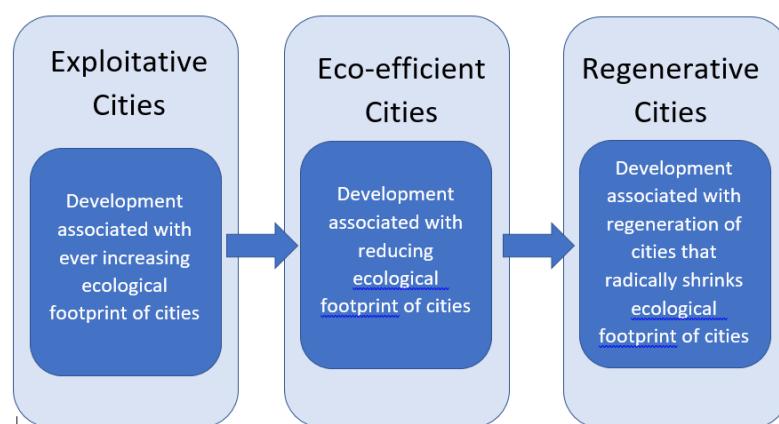


Figure 1. The transition to regenerative cities, adapted from ([22] p. 13).

“Regenerative urbanism” has recently emerged as a further step along this transition pathway, presenting a new opportunity and challenge for urban development to go beyond minimal reductions in environmental impact to a new vision of how cities can be designed and operate in an eco-positive manner, while maintaining or enhancing liveability. In other words, removing negative environmental impacts from development and providing ecological gain [23]. This requires regenerative development that is based on “giving back as well as taking” ([24] p. 11), and needs to operate across all urban sectors and all urban scales: building, precinct and city. It is a normative model with key transformative goals associated with:

- Reduction in use of natural resources—dramatically shrinking ecological footprints and removing the need to import more water and energy into cities as they continue to grow by: (1) introducing a range of distributed urban technologies enabling greater urban self-sufficiency, and (2) dematerialising industrial and construction processes by transitioning to a circular economy with high levels of recycling and reuse.
- Reduction in emissions and waste streams—with particular focus on decarbonising current energy systems that are largely fossil fuel based, significantly increasing stormwater and wastewater treatment and reuse, and identifying zero-waste pathways for industrial, construction and domestic sectors.
- Substitution of smart urban systems and processes—replacing those currently in use to achieve more effective economic, social and environmental planning, design and management outcomes for cities, by including digital systems that support new forms of governance and decision-making.
- Improvement in urban environmental quality—particularly of the public realm (e.g., waterways, green space), as well as responding to the environmental changes associated with intensified urban retrofitting and densification of private property, which is removing significant greenspace and tree canopy with implications for increased urban heat and health stress.
- Improvement in liveability and wellbeing of populations—across entire metropolitan regions, linked to the range of environmental innovations listed above, as well as equality of access to public transport, educational and health services.
- Acceleration of progress in developing resilience in cities—with awareness of the array of exogenous and endogenous pressures now evident.

In this paper, we place the spotlight on Australia, exploring how transitions to carbon-neutral and blue-green cities can be progressed through innovations that operationalise the regenerative urbanism principles introduced above. We present insights and experiences from two major research-industry-government collaborations that aimed to transform the urban water and energy systems of Australian cities: The Cooperative Research Centre for Low Carbon Living (CRCLCL; 2012–2019; <http://www.lowcarbonlivingcrc.com.au/>) and the Cooperative Research Centre for Water Sensitive Cities (CRCWSC; 2012–2021; <https://watersensitivocities.org.au/>). Each CRC received over AUD 100 million in cash funding for their research programs from federal, state and local governments, built environment industries, NGOs and universities. This, together with matching in-kind funding, enabled the development of over one hundred research projects in each CRC that sought innovation in several common arenas: Household consumption behaviour; industry practice and capability; planning and governance of urban water and energy systems; urban design at dwelling, precinct and city-scales; and new technology development. The breadth of the research programs and projects and their multi-disciplinary, multi-stakeholder and multi-scale nature (methods, data, analyses) has provided an extensive repository of outputs to the end-user communities now accessible from each CRC website. In this paper, we reflect on the transformative solutions and strategies identified through these CRCs, with the aim of consolidating key lessons for pursuing a vision of carbon neutral and blue-green cities.

2. Transitioning Australia's Urban Water and Energy Systems

2.1. Energy and Water System Transitions

Energy and water systems in cities are in transition. By this we mean they are undergoing radical structural and cultural change that, over time, involves the emergence, upscaling and stabilisation of innovative technologies and practices that increase their sustainability [25–28]. These processes are typically long-term and complex, with barriers such as path dependencies, institutional inertia and poor actor capacities that can make it difficult for innovations to mature as part of a changing system [26,29–31]. Nonetheless, large infrastructure systems can transform, as evidenced by many empirical studies in the field of sustainability transitions e.g., [32–34]

Like most countries, until recently, Australia's urban water systems comprised a centralised “linear” system involving diversion of environmental flows into dams, providing treatment for water quality, distribution for domestic and industrial use and then discharge to receiving waters with varying levels of treatment. Future urban water systems will attempt to reduce reliance on hinterland rivers by substituting (potable) water reuse from stormwater and wastewater treatment, as well as benefiting from reduced water demand linked to more efficient products and conservation behaviours [27,35,36]. The transition will also witness the emergence of integrated urban water systems that connect centralised urban networks with an increasing number of decentralised urban water systems, including nature-based solutions such as biofilters and constructed wetlands [37]. Cities are also recognising the potential for broader liveability outcomes to be supported through transformed water systems and are considering the implication for water policy and practice [38] (see, for example, Victoria's current water policy with focus on “resilient and liveable cities and towns” [39]). There are many examples of water system innovations across Australian cities, particularly in response to the Millennium Drought crisis. However, their mainstream uptake has been slow due to regime inertia and barriers relating mostly to issues of system governance, rather than technology [40–43]. Delays associated with the uptake of alternative technologies and practices has meant that many cities in regions with variable rainfall, which is being amplified by climate change and periods of drought, have resorted to expensive and high energy consuming desalination schemes as “insurance”.

Australia's energy system is also in transition. The nation's progress to a renewable energy future has stalled over the last 20 years due to the resistance of (mostly) federal political and fossil fuel regimes. Despite Australia being well-endowed with solar, wind, nuclear and hydro resources, 80% of its electricity supply is currently based on fossil fuels, creating significant path dependency. Australia is also a major global exporter of coal and gas, which bolsters lobby groups for both local and foreign interests. Successive attempts by parliament to pass national electricity market reform designed to deliver a more reliable, affordable and low-carbon national grid have stalled over the associated emissions target (currently 26–28% below 2005 levels by 2030), costing four Prime Ministers their jobs over the last decade. The consequence has been uncertainty in the financial marketplace, which has stalled large-scale private sector investment in renewable energy, while at the same time, ageing coal-fired power plants have begun to close. Electricity prices have increased as a result. Over the last decade, however, there has been exponential growth in small scale rooftop solar photovoltaics (PV) to a point where 22% of all houses (excluding apartments) in Australia have a PV system installed. The declining cost of PV relative to grid electricity prices plus the available space on the rooftops of the nation's detached dwellings—the dominant urban fabric in Australian cities—are the principal drivers of this uptake [44]. Microgrids and peer-to-peer energy trading using blockchain technology represent system innovations capable of advancing solar PV penetration further into densifying urban systems.

One third of global GHG emissions are emitted from the building sector's current operating and embodied energy consumption. Their contribution to climate change is now clear [45]. Newton et al. [19] estimate that the ratio of embodied energy to operating energy for new buildings is approaching 1:1, as the energy efficiency of buildings coming onto the market continues to improve. This is driven by government regulation on operating energy efficiency that ensures a standard

level of performance across the building and construction sector, as well as by leading property companies that conduct world-best operating practice and innovate to capture associated productivity benefits. Reduction of embodied energy has been more difficult, however. For over 20 years, building material manufacturers have resisted government attempts at product labelling that would require an accurate declaration of embodied carbon emissions, together with other resource inputs (e.g., water, raw materials). Australia's 2018 National Carbon Offsets Strategy for Buildings and Precincts (<http://www.environment.gov.au/climate-change/government/climate-active/certification>) currently excludes Scope 3 emissions (embodied energy), which remains the elephant in the room regarding attempts to decarbonise the built environment. Targets of net zero carbon emissions in the built environment sector by 2050 will require action on this issue, including commitment to a circular economy in which building products manufacturing would be a core stakeholder. Research pioneered by the CRCLCL has harmonised different data and methods such as life cycle assessment (LCA), input output analysis (IOA) and material flow analysis (MFA) to accurately calculate the embodied carbon emissions of construction materials in Australia [46,47]. Their city carbon mapping reveals between 30% to 50% of per capita carbon emissions associated with Australia's cities are embodied in the goods, services and materials imported into those cities for their construction and operation.

Energy and water systems are not isolated from each other, and with the increasing cost of fossil fuels and a delayed transition to large-scale renewable energy, there has been increased attention on the energy efficiency of water infrastructure, including water and sewerage networks, treatment plants for potable water supply and wastewater recycling, passive treatment technologies based on nature-based solutions, water heating and desalination plants. In fact, a linked water-energy transition may be an important pathway for achieving a rapid shift towards carbon neutrality, through removing their operating and embodied carbon. For example, if renewable energy transitions can be achieved quickly and cost effectively, as is being forecast [48], then their benefits also flow to the urban water sector, where affordable low or zero carbon electricity can drive the treatment plants required to make use of wastewater and stormwater streams, which to date have not featured significantly in urban water supply. Conversely, increased uptake of nature-based solutions for water treatment would reduce the energy demands of urban water systems. These types of opportunity are illustrated through CRCLCL research that assembled best practice benchmarks for optimising different types and scales of wastewater treatment operations across Australia that delivered energy efficiency improvements exceeding 10% over the two-year study period [49]. However, more information is required about the energy (and carbon) footprints of urban water systems. A landmark CSIRO study [50] found that total energy used for water and wastewater services for Australia's cities was about 0.2% of total energy use, with residential hot water heating consuming 1.3% (representing approximately one quarter of total household energy use). Depending on per capita water usage assumptions and water supply options adopted (e.g., comparing 100% desalination scenario with a mix of 40% desalination, 40% reuse and 20% additional surface water supplies), total energy demand for urban water services was projected to increase between 130% and 400% by 2030. As such, more sustainable solutions need to emerge from an urban systems perspective that recognises the integrated nature of the problems to be solved.

2.2. CRC Research for Accelerating Built Environment Transformations in Australia

The Australian Government's Cooperative Research Centre (CRC) program provides large grants for industry-led collaborations between industry, researchers and the community. The program aims to use high quality research to solve industry-identified problems that will improve the competitiveness, productivity and sustainability of Australia. The program has funded more than AUD 4.9 billion to more than 225 CRCs since its inception in 1990, generating a net benefit of AUD 7 billion to the economy over the 30-year period. It is a unique Australian model for driving innovative collaborative applied research (<https://crca.asn.au/>).

The CRCLCL and the CRCWSC both aimed to address established national challenges, reflected in a succession of federal government State of Environment Australia Reports on Human Settlements and

the Built Environment since 1996 (<https://www.environment.gov.au/science/soe>). Following established literature that emphasises the importance of vision in guiding system reorientations e.g., [51–53], the CRCs each developed an overarching vision for transformed urban systems. For the CRCLCL's energy focus, there were the twin challenges of carbon mitigation (decarbonisation) and climate change adaptation (Figure 2). Carbon mitigation requires alignment of energy and climate policy, given the strong sectoral nature of the challenge; while climate change adaptation requires integrated urban planning, given the strong spatial nature of the challenge. For the CRCWSC's water focus, a water sensitive city transition model (Figure 3) framed its research program, articulating the changes in policy and practice needed to achieve water sensitivity. Fundamental principles are whole water cycle management at integrated scales, combined with nature-based technologies, urban design solutions and empowered communities.

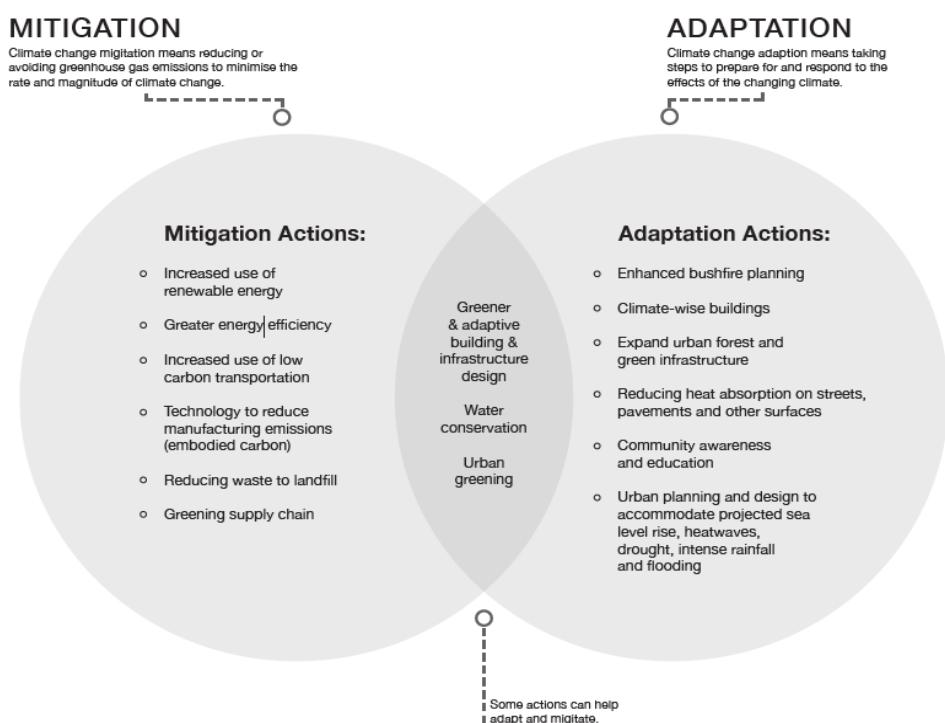


Figure 2. Mitigation-adaptation nexus and opportunities for blue-green innovation [21].

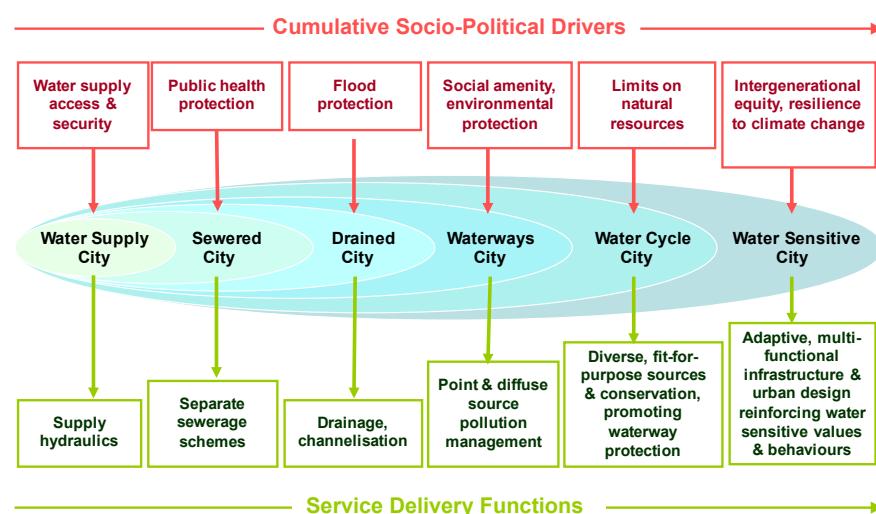


Figure 3. Urban water management transitions framework [54].

Guiding the activities of both CRCs was a systems framework for achieving a sustainability transition (Figure 4). It involved four features, each of which were represented in their research programs:

1. Introducing new urban technologies capable of disrupting and substituting for poorer performing systems that deliver demonstrably superior performance (e.g., eco-efficiency, self-sufficiency, amenity and liveability).
2. Overcoming regime resistance and barriers to socio-technical innovation that have built up around industries, government and communities by creating new governance frameworks for urban development. These recognise that: (1) There are multiple stakeholders (actors) involved with differing levels of agency; (2) there is a need for governance processes that allow for participation and engagement by communities beyond traditional modes, as well as across service provisions and silos to enable better horizontal integration; (3) multi-scale governance structures and processes need to correspond with nested biophysical scales; (4) local government must have an enhanced role and increased transformative capacity for implementing local solutions; (5) adaptive governance principles are important for driving responsive processes within dynamic and complex urban environments; and (6) small-scale interventions are valuable opportunities for de-risking a novel concept and learning how they can inform and accelerate change in governance processes.
3. Developing and applying smart built environment design tools and methods that can more effectively and efficiently scope, plan, assess and construct the massive pipeline of urban development projects forecast to occur in 21st century cities, highlighting the role of analytics in assessing alternative urban development projects within a time scale that allows informed decision-making.
4. Encouraging new low carbon and water sensitive practices among urban residents that voluntarily shifts established high urban consumption habits of energy and water to sustainable levels, as well as changing other energy or water management behaviours that negatively impact on the urban environment. This includes increased community preparedness to accept that ageing neighbourhoods need to adapt to respond to new sets of urban challenges such as population growth, increased density of development and climate change [55,56].

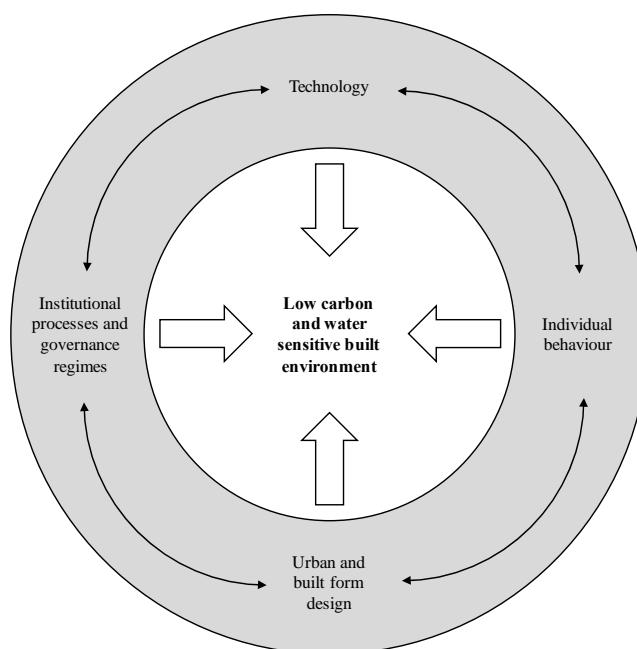


Figure 4. Innovation pathways to a low carbon and water sensitive built environment [21].

Also common to both CRCs was a spatial framework that accommodated multiple, linked scales and distinctive urban arenas within which urban development and renewal takes place (Figure 5). Different concepts, instruments and processes for planning, design and engagement operate at each scale: City, precinct and household/building. Capacity to nest scales was important for the research (e.g., buildings within neighbourhoods, within local government areas, within catchments). This is where object-oriented representation of urban elements presents a major breakthrough in modelling related to sustainable urban development. We now have building information modelling (BIM), precinct information modelling (PIM) and city information modelling (CIM) that can be jointly brought to bear for complex analyses of the type that will be demonstrated in the following section [57]. The three distinctive urban arenas constituting cities are defined as greenfield, brownfield and greyfield [58]. Each attracts distinctively different types of urban development and each bring their distinctive development challenges, as will be further explored in the following section.

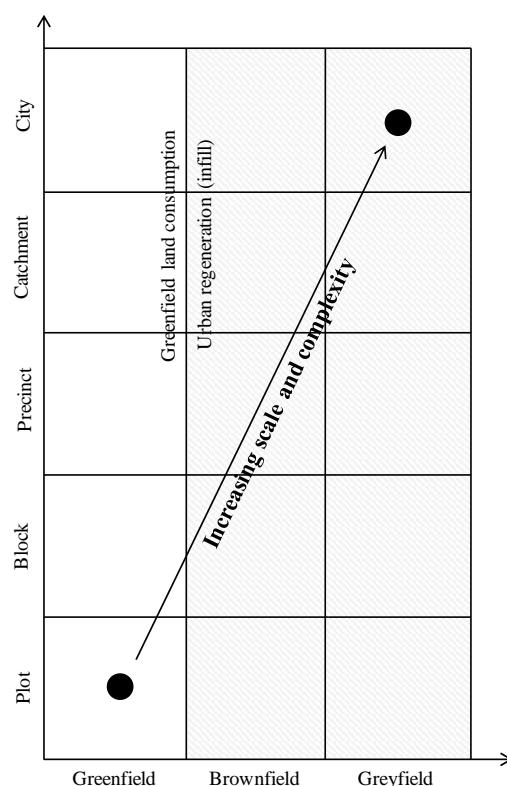


Figure 5. Urban arenas, project scale, complexity and contribution to sustainable urban development, adapted from [59].

Based on these guiding conceptual frameworks, the next section showcases key CRCWSC and CRCLCL projects that demonstrate positive interventions designed to decarbonise the built environment and deliver water sensitive urban systems. This is followed by a critical reflection on the ingredients needed to mainstream these energy and water innovations to fully transform urban policy and practice.

3. Innovations for Carbon Neutral and Blue-Green Urban Transformation

The energy and water transformations outlined in the previous section involve fundamental shifts for cities over the long-term. But their pathways of change will need to comprise a range of intermediate innovations that are transformative in nature. In other words, if cities are able to identify interventions that will catalyse a step-change in community expectation, technology, governance, and practice for their desired future built environment, then transformation may be accelerated.

The important role of research in driving change in policy or practice, for example through interventions, experiments and demonstrations, has been well-documented e.g., [60–62]. The experiences of the CRCLCL and CRCWSC confirm this finding, with transformative outcomes being achieved through diverse initiatives, including new instruments for urban design and planning, collaborative processes that reshaped stakeholder relationships, experiments with new solutions to test their effectiveness, and larger demonstrations that de-risk an innovative concept by proving it at scale. In this section, we highlight some examples from the CRCLCL and CRCWSC to illustrate the types of interventions that may be fruitful for cities to experiment with.

3.1. City-Scale

The CRCWSC's project, WSC Visions and Transition Strategies [63] (Figure 6) developed and implemented a participatory process for city stakeholders to develop strategic guidance for transformative water sensitive action based on a normative future vision. The project involved a series of workshops in six Australian cities, engaging a total of more than 250 leading water policy-makers, planners and practitioners in iterative discussions to envision 50-year water sensitive futures, identify key enabling pathways for achieving the vision and develop strategic priorities for action. The CRCLCL's aligned project, Vision and Pathways 2040 (VP2040) [64,65] envisioned plausible pathways for an 80% decarbonisation of Australia's largest capital cities by 2040. Here, a panel of 120 experts in a workshop series produced a set of narratives linked to four scenarios capable of achieving the targeted reduction of CO₂ emissions, distinguishing between top-down vs bottom-up action, and private vs social benefit motivation and elaborating each for high, medium and low density living outcomes (Figure 7). Visualisations were important features of both CRCWSC and CRCLCL projects, bringing to life and communication the future city visions showcased in ways that would resonate with diverse audiences, for example in community planning workshops at metropolitan and municipal scale (Figure 8).



Figure 6. Stages in the CRCWSC's WSC vision and transition strategies project workshop series.

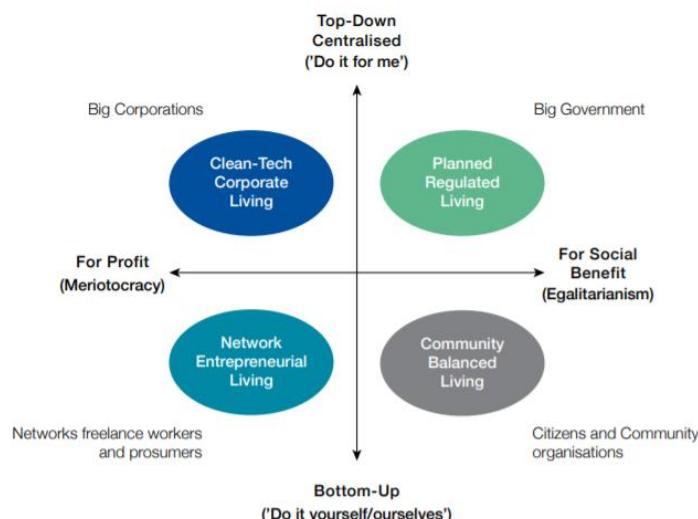


Figure 7. Characterisation of four scenarios in visions and pathways for low carbon cities [64].



Figure 8. Imagery of future visions. (a) Visions of water sensitive city Adelaide, Bendigo and Sydney, developed through the CRCWSC IRP1 WSC Visions and Transition Strategies Project [63,66,67]. (b) Visualisations of the medium density perspectives of the planned balanced living and community balanced living scenarios, developed through the CRCLCL Visions and Pathways 2040 Project [64].

These action research interventions brought industry and government stakeholders together to be guided through structured discussion that stretched their frame of reference beyond their daily work, synthesised their tacit knowledge together with scientific knowledge, and led to shared foundations from which to orient their strategic action. We also learned the value of interim objectives that operationalise the envisioned pathways to help cities be targeted in their short-to-medium term strategies in order to achieve successes to celebrate along the way. It was important to translate high-level visions and strategies into tangible actions or strategies that have meaning in an operational, spatial, organisational and/or corporate context.

City-scale assessment tools were another element common to both CRCs. The Water Sensitive Cities Index (WSC Index) [68] was co-developed by CRCWSC researchers and industry partners as a tool for benchmarking current water management practice with reference to water sensitive aspirations

(Figure 9). In the three years since its release, more than 40 cities (metropolitan and municipal) around Australia have been benchmarked. The rapid uptake of the WSC Index as both a certified benchmarking tool and framework for structuring urban water strategies and performance evaluation highlights the value of tools that can guide a common understanding of the current situation and future direction amongst the diverse stakeholders that need to collaborate to transform built environments.

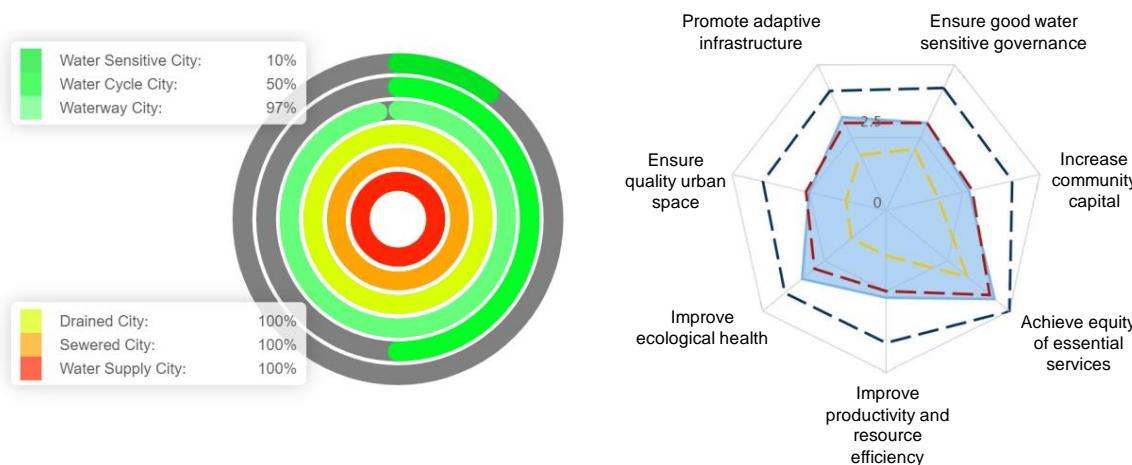


Figure 9. The WSC index is a benchmarking and diagnostic tool to assess the water sensitive performance of a city (municipal or metropolitan scale). Thirty four indicators are organised into seven thematic goals, and results can be analysed through the filter of the city-states set out in Brown et al.'s [54] (Figure 3) urban water transitions framework.

Given that estimates of emissions from individual cities range from several million tonnes of CO₂ emissions to over 250 Mt, depending on population size, level of income, density and stage of economic development [7,69], CRCLCL has developed carbon accounting instruments capable of reporting on Scope 1 (operational), 2 (electricity generation) and 3 (indirect or embodied) emissions in order to better track and attribute sources. Under most national reporting schemes, Scope 3 emissions are not yet mandatory, given the complexity of international supply chains and international trade agreements. Yet they can make up the most substantial proportion of total national emissions—and need to become “in scope”. The Embodied Carbon Explorer online tool and database assists practitioners and governments better assess Scope 3 carbon emissions from the built environment at a range of scales, ranging from building to precinct to city in accordance with the Climate Active Carbon Neutral Standard [70,71] (Figure 10).

Both CRCs undertook significant programs of research on climate change adaptation, especially targeting mitigation of urban heat, which is projected to increase four- to five-fold in Australia's largest cities by 2090 under a high emissions scenario [13]. Heat vulnerability analyses of Sydney revealed that air temperatures currently can vary up to 11 degrees Celsius between coastal suburbs and those 35 km further inland [72]. This exerts significant impact on cooling energy consumption of buildings, as well as affecting human health and comfort—an emerging social justice, as well as engineering, issue [73,74]. CRCLCL interventions to mitigate urban heat islands (UHI) focused mainly on building-scale innovations and strategies (e.g., roofs and façade materials, orientation and shading). CRCWSC focused on greening and shading streetscapes (e.g., canopy trees, biofiltration systems) and irrigating greenspace to gain evaporative cooling benefits, especially by using alternative water sources like harvested stormwater and recycled greywater to substitute potable water supply [75]. Both CRCs developed UHI assessment tools e.g., [76,77] and planning and design guidelines e.g., [78] for analysing the local and city-scale impacts of urban development projects that increase neighbourhood density and reduce tree cover, developing strategies for improved heat outcomes and assessing their associated economic benefits [21,79]. For example, the CRCWSC's WSC Scenario Tool, used by planners to

assess the multiple benefits of green infrastructure solutions from precinct to city-scales, integrates TARGET—a microclimate model that can produce a time series of land surface and air temperatures and human thermal comfort indicators [76].

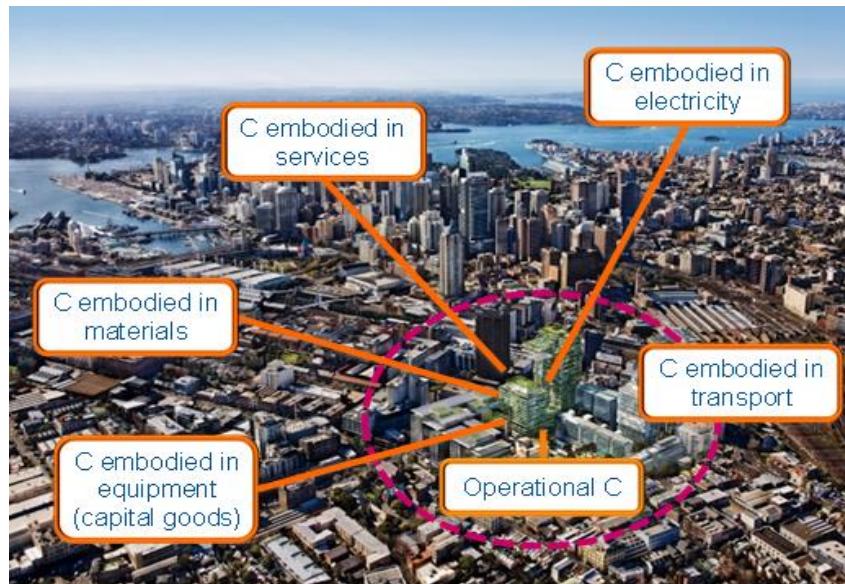


Figure 10. Operational and embodied emissions from a precinct ($C = \text{carbon}$) [47].

The city-scale interventions and innovations presented in this section have highlighted the importance of establishing the frameworks, processes and tools that enable collaborative vision and strategy development among diverse stakeholders, as well as integrated planning and assessment of complex urban environments, so that opportunities for transforming a city over time can be identified and pursued.

3.2. Precinct-Scale

Both the CRCLCL and CRCWSC found that the precinct was an important focus for considering carbon mitigation and water sensitive interventions. The precinct-scale demands consideration of new energy and/or water system technologies and how they are designed into the urban form and fabric, as well as giving insight into the local practice changes that are needed for their successful adoption and the broader policy and regulatory changes that would be needed to support their implementation.

For example, the CRCWSC has developed a flagship research synthesis process—a facilitated design charrette-style intervention that combines the latest science from different disciplines with local industry expertise to collaboratively develop and rapidly evaluate practical ideas [80]. This has been applied to generate innovative ideas for the development of low carbon and water sensitive precincts in the three urban development arenas: Greenfields, brownfields and greyfields, each of which demands tailored urban designs and performance assessments [17,81]. The synthesis process involves a series of workshops in which participants explore the precinct's key challenges and agree on the shared parameters and language around it, before arriving at solid, tangible propositions for the precinct, with benefits and costs clearly defined. This process has been applied to many precincts. For example, Aquarevo is a 42-hectare greenfield residential development south east of central Melbourne on the site of a former wastewater treatment plant. The "Ideas for Aquarevo" process identified solutions for urban planning and design, green infrastructure and intelligent water and energy systems that create local closed loops [82]. Following the CRCWSC's intervention, the developers (a joint venture between local water utility South East Water and land developer Villawood) implemented many of the water sensitive ideas introduced by participants and/or developed collectively in the research synthesis process. These include a sophisticated rain-to-hot-water-system for bathing and showering,

wastewater recycling for use in garden irrigation, toilet flushing and washing machines, rainwater tanks with technology that receives weather forecasts and releases water before heavy rainfall to minimise flooding in local waterways, and technology that controls the water system in each home for remote monitoring of water and energy consumption and performance. Upon completion of the development, properties sold out quickly and it has won numerous awards. Most importantly, it has become a demonstration site for water sensitive city solutions in Melbourne, hosting regular study tours and visits from industry locally, nationally and internationally.

Another precinct-scale intervention example is a CRCWSC project on enhancing the flood resilience of Elwood, a flood-prone inner Melbourne suburb located next to Port Phillip Bay at the bottom of the Elster Creek catchment. This action research project [83] brought together Elwood residents to explore their future vision for Elwood and develop flood resilience ideas that would also contribute to their broader water sensitive aspirations such as biodiversity, liveability, community connections and a strong local economy. The community's ideas were then further developed by urban design and engineering researchers to provide tangible propositions for transformative solutions to the flood challenges experienced in Elwood. Following this intervention, the local council (City of Port Phillip) and flood manager (Melbourne Water) invited the CRCWSC to convene a series of roundtable discussions with the relevant stakeholders to reflect on the research findings and map out a pathway forward. This led to the Elster Creek Working Group being established, involving representatives from the four municipal councils in the catchment, Melbourne Water, retail water utility South East Water and the state government's Department of Environment, Land, Water and Planning, as well as a parallel CEO/Mayor's Forum. An Elster Creek Action Plan was developed [84], guiding catchment-wide strategy and precinct-scale implementation that would see some of the Elwood community's ideas for flood resilience realised. A key feature of this project was its cross-jurisdictional nature, requiring new approaches to the urban governance of impacts of climate change which do not respect municipal borders and require a catchment framework [13].

A third example of precinct-scale visioning and concept planning involved a joint CRCWSC-CRCLCL research synthesis project for Fishermans Bend [85]. Fishermans Bend is a 480-hectare site adjacent to both the Melbourne CBD and Docklands, where current industrial land use has been rezoned for mixed use redevelopment in order to accommodate a projected 120,000 residents and employment for 80,000 people. The Government of Victoria established a strategic framework for its development over 40 years, which clearly identified a set of sustainability objectives: Low carbon, water sensitive, climate resilient, low waste, and liveable. The two CRCs were invited to develop a concept plan for a low carbon, water sensitive built environment where innovative infrastructure and building options needed to be identified and modelled in order to realise the life cycle benefits capable of being captured. The vision created was a regenerative redevelopment where most new energy and water demands could be met from distributed renewable energy and storage, energy efficient buildings, integrated water systems, water sensitive urban design and elevated podiums that could accommodate occasional flash flooding. From a resource perspective, the additional water and energy inputs to a precinct such as Fishermans Bend are substantial, if delivered in a traditional manner. For example, if all water is imported, a precinct of 120,000 residents is estimated to need approximately 11 GL/year, and if all buildings are designed to current standards, then additional electricity required is approximately 3 GJ per year and, if sourced from the grid, would require additional power station capacity of 220 MW to supply the precinct's peak demand. By introducing water sensitive design innovations related to stormwater capture, rainwater harvesting and greywater recycling—all of which can be directed to non-potable uses within the precinct and its buildings—the volume of imported water can be almost halved. By mandating that all buildings be designed to world-best energy rating standard (compared to local minimum), an over 40% reduction in annual energy demand and carbon emissions is achievable; greater if low or zero carbon precinct-scale distributed renewable energy generation systems are also employed. The governance of Fishermans Bend redevelopment will be

what proves critical in whether it becomes a showcase for brownfield precinct regeneration or a repeat of the business-as-usual developer-led project that occurred at neighbouring Docklands [86].

Smaller scale interventions have also been developed in both CRCs for greyfield residential redevelopment. The greyfields are ageing, occupied residential tracts of suburbs which are physically, technologically and environmentally obsolescent and which represent economically outdated, failing or under-capitalised real estate assets. They are extensive, typically occurring in a 5–25 km radius of the centre of each Australian capital city, and are service, transport, amenity and employment rich compared to the outer and peri-urban (greenfield) suburbs [58]. Most of the redevelopment in these suburbs occurs as infill housing on small lot subdivision: Fragmented, piecemeal “knock-down-rebuild” of detached housing on blocks of land typically 700–1200 square metres in area. Yields of 1:1 (construction of “McMansions”) and 2–4:1 (townhouses) are most common, resulting in most of the site becoming impervious. Currently over 30% of private greenspace is being removed, with serious urban environmental consequences if this trend continues for the next 20–30 years. Modelling suggests flash flooding and urban heat would be intensified significantly [87]. Extensive research in both CRCs has developed tools to aid design and assessment of carbon neutral and water sensitive greyfield redevelopment—at small lot subdivision [88] as well as larger precinct-scale [56].

The CRCWSC has also produced tools to conduct economic assessments of innovative precincts. The Investment Framework For Economics of Water Sensitive cities (INFFEWS) consists of a comprehensive benefit-cost analysis tool [89] that supports balanced and systematic decision making and provides evidence for use in business cases; and a values tool [90,91], which provides a database of studies that provide values for various non-monetary benefits of water sensitive systems and practices, such as amenity and ecological value and guidance for how these values can support business case development using benefit transfer. Applying these tools can help stakeholders tangibly provide the costs and benefits of solutions that may have previously only been conceptual. For example, the economic value of urban heat island mitigation was assessed for a case study precinct in Melbourne, finding that a maximum greening scenario resulted in 2 degrees of cooling, which was valued at over \$1500 per household over the 50 year study period [92].

These precinct-scale case studies, as well as other similar experiences with research synthesis [80] and subsequent implementation of key innovations, highlight the value of partnership between research, government, industry and community in exploring and developing precinct-scale innovations. Scientists and innovators working together with key stakeholders and decision-makers to design and implement precinct-scale solutions can be transformative. It provides an opportunity for experimentation and learning at a scale where risks can be effectively managed, it tests the boundaries of existing governance arrangements to identify reforms needed for replicating the demonstration elsewhere, and it forges strong relationships between key stakeholders as they collectively create new possibilities for change through vision and demonstration. These partnerships can also lead to the prototype technologies, buildings, infrastructures, innovative design and development systems (termed Horizon 3 innovations [93]) being taken from the research laboratory to be “field tested” and monitored for real world performance assessment against Business as Usual in Living Laboratories (Horizon 2)—as a precursor to wider diffusion and take-up (Horizon 1). White Gum Valley (Perth), Lochiel Park and Tonsley (Adelaide) were established as CRCLCL living laboratories to trial and monitor innovative energy and water systems [94,95].

3.3. Household and Building-Scale

Household-scale water and energy technologies to support supply-side innovations were also part of the CRCWSC and CRCLCL research scope.

For example, solar rooftop photovoltaics (PV) was a core technology focus for CRCLCL. Rooftop solar installations increased exponentially over the lifetime of the CRC to a point where PV panels had been installed on more than 2.2 million homes (one in four) by the end of 2019. Its solar PV research was part of a larger portfolio of research focusing on pathways to carbon-negative residential buildings

that required improved design and technical innovation represented by a number of steps illustrated in Figure 11, based on energy modelling of different residential scenarios [96]:

- An energy-efficient shell that achieves an operating energy rating of at least 6 stars (since 2004 energy assessment of new building design has been mandated in the Building Code of Australia) [97]. A major challenge for the sector (domestic and commercial) is retrofitting to a level that would enable net zero emissions to be achieved [98].
- Energy efficient built-in appliances that include heating and cooling systems, lighting, kitchen and laundry appliances, given that all have significant operating lifetimes.
- Rooftop PV and storage (or access to offsite renewable energy) [99].

The extent to which such buildings achieve net zero energy (a target in an increasing number of countries) or can export excess electricity to the grid or to onsite storage (carbon negative) also depends on the performance of the PV panels [100], the size of the dwelling (heating and cooling demand), size of load from plug-in appliances and occupant behaviours associated with dwelling use. In the two years following installation of rooftop PV, Sydney households demonstrated a rebound effect estimated to have eroded up to one fifth of the carbon benefit of renewable energy that had been generated [101].

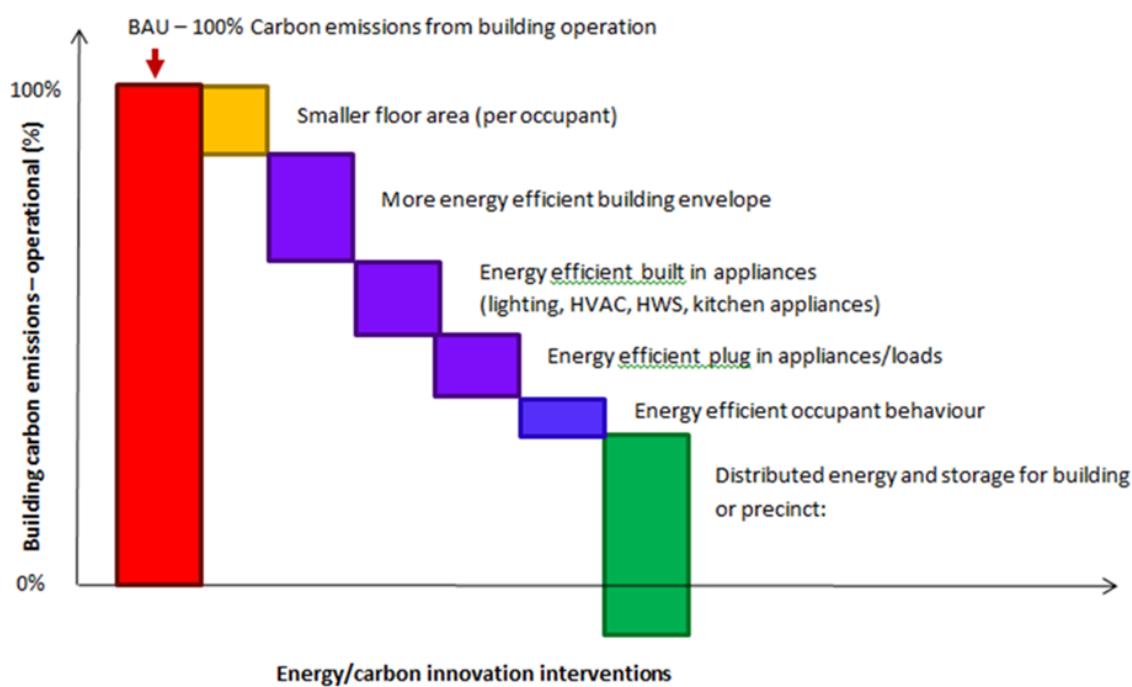


Figure 11. Innovation staircase to carbon negative buildings [96].

The CRCWSC has advanced a number of site-scale biofiltration technologies, which are passive, low-energy, nature-based water treatment systems that deliver additional benefits such as urban greening and evaporative cooling. For example, incorporating living walls into building designs to treat greywater for onsite reuse [102], designing hybrid biofilters that treat stormwater in wet periods and greywater in dry periods [103], and improving the aesthetics of raingardens through ornamental plants to increase community receptivity. Insights from this research led to the development of green technology adoption guidelines, which provide information on how to design, operate and maintain these treatment systems at various scales, including private backyards and in streets, to maximise their multiple benefits [104].

The CRCWSC's research on smart water meters used state-of-the-art sensors and telemetry together with algorithms for big data analysis to extract knowledge about water consumption patterns [105]. Working with Western Australia's Water Corporation, this research has led to a new understanding of

peaks in demand, which points to the most likely effective targets for behaviour change campaigns with residents. It has also enabled early detection and notification of leaks for the Water Corporation, saving millions of dollars for customers. This research has given the Australian water sector confidence in the value of smart metering, in terms of both water and money saved. Similar studies were undertaken in CRCLCL on smart metering of electricity [106,107].

Household-scale opportunities for water sensitive and low carbon living were also identified through a range of social studies. CRCWSC research examined the water cultures and water literacy of different Australian communities, identifying a typology of community profiles that set out demographic and psycho-social characteristics that influence how readily (or not) they would engage in water sensitive behaviours: Disengaged, aware but inactive, active but not engaged, engaged but cautious, and highly engaged [108,109]. Tailored strategies to influence community attitudes, behaviours and practices were then developed, for example: Implementing behaviour change campaigns [110]; developing community-friendly messaging [111]; and tailoring engagement processes to support local and household action by communities [112,113]. CRCLCL household-oriented research established that the dwelling context (type, size and vintage of building) and the structural characteristics of occupants (number, income, education) explained much of the variance in models of domestic energy and water consumption [18]. Harder to model successfully, with respect to actual consumption behaviours, was the influence of social practices [114] and individual attitudes [115,116], despite a growing body of theory pointing to their significance. This remains a critical focus for ongoing research, and industry interest in these social processes is strong, reflecting a growing policy and practitioner awareness that solutions for built environment transformations are also socio-technical and behavioural in nature.

4. Mainstreaming Innovations

The innovations highlighted in the previous section, and others like them, present promising solutions to improve the sustainability and liveability of built environments. CRCWSC and CRCLCL research found that while there have been significant advances in the application of carbon neutral and water sensitive technologies for individual lots, the increasing governance complexity at precinct and city-scales makes their mainstreaming difficult. Individual cases of implementation are not sufficient for the widespread societal transformations needed for cities to become carbon neutral and blue-green. Achieving this will require deep structural and cultural shifts that support a new set of technologies and practices.

CRCWSC and CRCLCL research has, however, generated insights and guidance on how these shifts can be achieved: Governance is key. Governments need to have clarity and boldness of vision and direction, informed by stakeholder interests and aspirations that have been identified through inclusive processes [63]. They then need to support implementation through enabling pathways that mobilise resources, build capacities and facilitate collaborations [117]. Leadership, partnerships, innovation and supporting policy and regulation are critical enablers. The CRCWSC's Transition Dynamics Framework (TDF; preliminary version shown in Figure 12) [118,119] was developed to provide a roadmap for city stakeholders wanting to mainstream water sensitive innovations. It distinguishes key characteristics of enablers as a system's transformation unfolds over time. The TDF has been used with industry and government partners as a tool to determine key strategic priorities for action in the short-to-medium-term, based on a diagnosis of the current enabling environment e.g., [63,66,67]. The TDF highlights that mainstreaming blue-green or carbon neutral innovations requires interventions to be defined, designed and evaluated not only with reference to their specific "project" objectives, but also with reference to how they contribute to the broader process of system change. For example, will it disrupt business-as-usual practice by demonstrating an alternative approach? Will it provide an opportunity for knowledge generation and learning? Will it help to forge new long-term relationships among key stakeholders? Understanding these dynamics may provide city stakeholders with an

opportunity to accelerate the scaling up of socio-technical innovations in the quest to transform built environments.

Transition phase	Domains of change				
	Actors Key networks of individuals	Bridges (Semi) Formalised organisations, structures, & processes for coordination & alignment	Knowledge Research, science, & contextualised knowledge	Projects Experiments, demonstrations, & focus projects	Tools Legislative, policy, regulative, & practice tools
1. Issue Emergence	Issue activists	N/A	Issue discovery	High profile scientific studies	N/A
2. Issue Definition	Science leaders	Science-industry	Cause-effect	Laboratory-based & scientific solution prototypes	N/A
3. Shared Understanding & Issue Agreement	Technical solution coalition	Science-industry-policy	Basic technological solutions	Minor scientific field demonstrations	Draft best-practice guidelines
4. Knowledge Dissemination	Informal policy coalition	Science-industry-policy-capacity building	Advanced technological solutions	Major scientific field demonstrations	Best-practice guidelines, targets
5. Policy & Practice Diffusion	Policy & decision coalition	Science-industry-policy-capacity building	Modelling solutions, capacity building	Numerous industry-led field experiments	Legislative amendments, market offsets, national best-practice guidelines, regulatory models
6. Embedding New Practice	Multi-agency coalition	Formalised institution	Next research agenda	Standard practice	Political mandate, coordinating authority, comprehensive regulatory models & tools

Figure 12. Preliminary transitions dynamics framework: Understanding key enabling factors as a transition unfolds across six phases [118].

CRCWSC and CRCLCL research also highlighted that both formal and informal governance dimensions are important, and that a focus on one but not the other will impede transformation. Processes to understand community values and priorities, foster advocates of new solutions, influence decision-makers, broaden support for the solutions, and facilitate long-term collaborations are informal, but provide a critical authorising environment for mainstreaming innovations [120,121]. At the same time, their widespread adoption requires formal policy, planning processes and regulatory frameworks that require the practices that facilitate their implementation [117,122]. CRCWSC and CRCLCL research found that of these formal governance dimensions, a critical challenge is that land use planning and urban development processes do not traditionally accommodate innovation at a rate that is necessary to regenerate our cities. For example, a lack of strategic corridor planning as well as greyfields precinct planning means opportunities for implementing low carbon and water sensitive solutions are often missed, and the business pressures for land developers do not typically allow for the incorporation of innovative solutions that risk delayed approvals [123,124]. There are equivalent challenges for buildings, and especially transport. Cities wanting to mainstream carbon neutral and blue-green solutions as part of their built environment transformations will need to give these challenges priority consideration.

5. Conclusions

We could not have imagined, when commissioned in August 2019 as Special Issue Editors of *Transforming Built Environments: Towards Carbon Neutral and Blue-Green Cities*, that over the ensuing months a global pandemic of historic proportions would have begun to wreak havoc on national economies and health systems worldwide. Cities have been at the epicentre of the COVID-19 virus outbreaks, given their pivotal roles in 21st century systems of production and consumption. At the time of writing, it is not under control. Yet there had been no shortage of warnings. Australian Nobel Laureate in immunology, Peter Doherty, has written on the topic from a health and a cities perspective [125,126] as have multiple others, but neoliberal governments have been disinclined to adopt precautionary principles and planning in advance of a potential crisis.

There is an unfortunate parallel with another invisible enemy—carbon emissions. Their “slow burn” build-up in the atmosphere, which has been accelerating over the past 50 years, is ushering in climate change, whose impacts are now clear at local and global levels. Its potential for disruption and devastation is greater than the current pandemic if not brought under control by mid-21st century (COP21 Paris Agreement). A sample of the applied research undertaken by two Australian Cooperative Research Centres (Low Carbon Living and Water Sensitive Cities) has identified multiple mitigation and adaptation pathways for transitioning urban energy and water systems in Australia. COVID-19 is revealing a capacity for governments to rapidly mobilise to tackle wicked problems—albeit belatedly—by effectively adopting a bipartisan war-footing to address what is a major threat to our civilisation. Post-pandemic, equivalent efforts by governments regarding investments for economic reconstruction should have transformation of our energy and urban systems as a core part of their portfolio. We hope that the insights, innovations and interventions presented in this article offer inspiration and guidance on tangible solutions that can form part of collective efforts to support both economic recovery and the transition to carbon neutral and blue-green cities.

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