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Mandatory or voluntary approaches to green roof implementation: a comparative study among some global cities

Sara J. Wilkinson[a]*, Sumita Ghosh[a] and Natalie Pelleri[b]

[a]*School of Built Environment, Faculty of Design, Architecture and Building, University of Technology Sydney, Sydney, Australia;* [b]*Senior Technical Advisory Officer, Urban Forest and Ecology, Inner West Council, Sydney, Australia*

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Green roofs can deliver multiple environmental and social benefits by reducing the urban heat island effect, reducing building energy use and greenhouse gas emissions, improving air quality, providing habitat for biodiversity and access to the biophilia effect. Green roofs provide these benefits to differing degrees in different climate zones globally. Despite known benefits, uptake of green roofs has been slow. Different cities globally adopt various policies and programmes to increase their green roofs; the question is which approach is best? This research used an in-depth review, site visits and qualitative methods, to determine whether mandatory or voluntary approaches produced greater uptake. Green roof policies and practices from selected global cities, London, Toronto, Singapore, Rotterdam and Stockholm, Sydney and Melbourne were examined. Singapore's voluntary approach led to the greater uptake of green roofs. The mandatory approach taken by Toronto, with financial grants provided meaningful outcomes. London and Rotterdam implemented useful voluntary programmes, and Stockholm required more time to evaluate the effectiveness of its voluntary approaches in increasing green roofs. A voluntary approach for retrofit and a mandatory approach for new build developments are suggested as recommendations for Australian cities. Given the increases in green roofs internationally, similar increases can occur in Melbourne and Sydney in Australia, and these findings may be transferable to other global cities investigating different approaches to the increased adoption of retrofitted green roofs.

Keywords: green roofs; living architecture; mandatory approach; voluntary approach; retrofit

1. Introduction and review

Despite known multiple environmental and social benefits, the uptake of green roofs has been slow in Australia and elsewhere (Williams *et al.* 2021; Irga *et al.* 2017; Williams, Rayner, and Raynor 2010). In different global cities, policymakers are putting significant emphasis on green roof implementation as a solution to multiple urban issues and formulating planning policies, incentives and determining green roof potential of cities to increase green roof spaces (City of Melbourne 202[illegible]; Williams *et al.* 2021; Liberalesso *et al.* 2020; Shafique, Kim, and Rafiq 2018; Irga *et al.* 2017). This paper analyses voluntary and mandatory approaches in the delivery of green roofs in seven global cities. There are significant reasons why this analysis is needed. As the

*Corresponding author. Email: Sara.Wilkinson@uts.edu.au

21st century progresses, our thinking and responses to global and local challenges are evolving. Challenges are living with a changing climate, global population growth, changing demographics, mass urbanization, inequality and instability, food security, increasing scarcity of resources, and a need for built environment sustainability (Cook and Larsen 2021; The World Bank Group (GFDDR)), 2015; United Nations (UN)), 2015). The World Bank Group (GFDDR)) (2015) reported that from 1995 to 2015, natural disasters claimed 1,300,000 lives, affected 4.4 billion people, created US$2 trillion in economic losses and called for a shift from managing disasters to reducing underlying risks. The survival of many societies and the planet's biological support systems are at risk. In response, the UN established 17 Sustainable Development Goals (SDGs). Goal 11; "Make cities and human settlements inclusive, safe, resilient and sustainable" relates to the built environment and Green Infrastructure (GI) (United Nations (UN) 2015). The case for GI is "protecting and enhancing nature and natural processes" and that it should be "consciously integrated into spatial planning and territorial development" (United Nations (UN) 2015). GI is "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" in rural and urban settings (European Commission 2013a; European Commission 2013b). Within towns and cities, GI measures in respect of buildings to achieve SDG Goal 11 comprise the design and installation of new and retrofitted green roofs and walls. Green infrastructure includes green roofs, green walls and other green spaces such as parks. Whilst all GI contributes to delivery of SDG 11, our focus in this research is solely on green roofs. The authors acknowledge that it is important to consider these solutions combined with other GI to provide ecosystem services at an urban scale. This study was relevant to cities and urban development globally. This research focused on green roof solutions. Green roofs deliver multiple environmental benefits regardless of location; such as increased biodiversity, improved air quality, storm water management micro climate and thermal performance (Fleck *et al.* 2022; Smalls-Mantey and Montalto 2021; Sultana *et al.* 2021; Irga *et al.* 2017; Dixon and Wilkinson 2016). The social benefits for those populations are increased amenity space for social interaction and engagement and economic benefits are derived from lower energy bills (Dixon and Wilkinson 2016). Despite these known benefits, the uptake of green roofs, a building technology that existed in medieval times in Scandinavian housing (Jim 2017), has been slow and patchy (Williams *et al.* 2021; Irga *et al.* 2017; Williams, Rayner, and Raynor 2010). There are references to the Hanging Gardens of Babylon and the temples in ancient Mesopotamia, which may have included green roofs (Jim 2017).

Increased resilience is correlated with high-income countries with advanced building code systems, who experienced 47% of disasters but only 7% of fatalities and therefore, a prima facie case exists for rigorous regulation (The World Bank Group (GFDDR)), 2015). Green roofs have become vital for the establishment of living architecture, as cities globally continue to transform into high-density settlements to accommodate population growth. Emerging green cities have become exemplars of collective and positive experience (Shafique, Kim, and Rafiq 2018; Liberalesso *et al.* 2020; Irga *et al.* 2017; Wilkinson, Ghosh, and Pelleri 2017a; Beatley 2012). Therefore, high-density cities integrated with nature are becoming more common (Wilkinson, Ghosh, and Pelleri 2017a; Beatley 2012); however, what regulations exist in respect of buildings and green roofs? Various countries and cities globally adopt different approaches to increasing the uptake of green roofs from mandatory regulations to voluntary programmes. Mandatory green roof regulations have been operating in German cities since the 1980s (Ansel and Appl 2009). In Munich, all suitable flat roofs over 100 m^2 are to be installed with a green roof, while in Stuttgart all new developments with flat or pitched roofs (up to 12 degrees) require to be greened to specific standards (International Green Roof Association (IGRA)) 2015). ~~Federal Nature Conservation Act (1993) requires that all new buildings compensate for the loss of habitat and green space through the greening of the developments.~~ Hamburg City, in Germany, has incorporated green roofs in landscape plans for the last twenty years and initiated a comprehensive Green Roof Strategy in 2014 supported by the Ministry for Environment, Climate, Energy, and Agriculture (Rizzi, Utkarsh, and Vallejo 2020). This Strategy aims to install or retrofit at least 70 per cent of both new and existing buildings with green roofs on flat or gently pitched roofs (Rizzi, Utkarsh, and Vallejo 2020). In Linz, the Austria Green Roof Plan existed since 1984 to increase the greening degree through green roofs and the city has approximately 55 hectares of green roofs (Tóth, Damyanovic, and Reinwald 2019). In Basel, Switzerland under Building and Construction Law green roofs have been required on new buildings with flat roofs since the early 2000s (Kazmierczak and Carter 2010). A bio-neighborhood incentive program in the city of Faenza in Italy has green roofs as part of its planning regulations (Kazmierczak and Carter 2010).

Examples of voluntary approaches to delivering green roofs are found in various cities globally. In the United States, in Portland Eco-roof floor area ratio (FAR) bonus (2008–2012) allowed an extra 3 square foot per foot of green roof without additional permits (City of Portland 2018). Hong Kong has a well-established program of green roofs initiated by the University of Hong Kong and promoted by the government since 2012 under the Greening, Landscape and Tree Management section of the Development Bureau (Jim 2019). Technical guidelines for green roofs were formulated (Hui 2011) and green roof projects on university, school, shopping mall, library, government buildings and other buildings by government and developers and owners date from 2005 in Hong Kong (Jim 2019)) . In Tokyo, Japan, the urban heat island effect had led the government to establish an informal free consulting service as an incentive program and a subsidy program. This voluntary approach has resulted in 7000 m^2 of rooftop greening in Tokyo from 2000 to 2007 (Urbis Limited 2007). Tokyo's Green Plan then accelerated the process by mandating that all new private buildings larger than 1,000 m^2 and public buildings larger than 250 m^2 must green 20% of the rooftop area or pay an annual penalty of US$2,000. This mandatory approach doubled the net area of green roofs in the city from 52,400 m^2 to 104,400 m^2 from 2000 to 2001 (Urbis Limited 2007). The National Building Law also requires 20% green roof coverage in new apartments or office buildings in urban locations (Dong, Zuo, and Luo 2020). The government has also constructed a series of demonstration projects on public buildings to encourage uptake (International Green Roof Association (IGRA) 2015). An example of the Japanese Government's green roof demonstration project in Roppongi Hills in Tokyo CBD includes a rice paddy and vegetable plot on the rooftop of Keyakizaka complex (Greenroofs.com 2022). Extensive research literature reviews had indicated efficacy and increased use of green roofs as green infrastructure in cities to mitigate the adverse effects of climate change and connect urban built environments to nature (Williams *et al.* 2021; Liberalesso *et al.* 2020; Shafique, Kim, and Rafiq 2018; Tayouga and Gagné 2016).

In summary, there are examples of mandatory and voluntary approaches to encourage the adoption of green roofs in many global cities from Europe, Asia and the Americas (Liberalesso *et al.* 2020). The question this research seeks to answer is; *which approach, mandatory or voluntary, is the most effective?* In the study, the policies, and approaches from five global cities in the northern hemisphere in North America, Asia, and Europe: Toronto, Stockholm, London, Rotterdam and Singapore and two Australian cities, Sydney and Melbourne were compared. This research investigated, which approach, mandatory or voluntary, would initiate better green roof delivery in Sydney and Melbourne.

2. Research method

This is qualitative research which seeks to ascertain which approach, voluntary or mandatory, is delivering more green roofs in selected major cities (Silverman 2016). A two-stage process was developed, comprising a review of secondary data followed by empirical data collection, which is a standard approach adopted in most research (Silverman 2016).

A review of key literature, a content analysis of key words and themes, was conducted to identify drivers and barriers and roles of voluntary and mandatory urban policy approaches for the uptake of green roofs and walls. Our approach followed best practices identified by Silverman (2016). Based on the literature review, it was apparent that several cities had established voluntary or mandatory approaches to promoting and delivering targets with respect to the adoption of green roofs. Toronto, Rotterdam, Stockholm, London and Singapore, and two Australian cities, Sydney and Melbourne, were selected and their policy documents provided an in-depth investigation of the policy approaches and review of the innovative precedents adopted in each city (Figure 1). The international cities were selected through the literature review based on the following selection criteria.

a. Well-established green roof policies
b. Innovative and diverse approaches that encourage the implementation of living architecture practices, mainly "green roofs"
c. Population densities
d. Governance structures
e. Climatic patterns.

The Green Roof policy documents and materials that were posted on the city websites were used to gain a deeper understanding of the drivers and parameters of the policies developed. It should be noted that some cities combine green roof and green wall policy into one document. The analysis of third-party documentation enabled the researchers to obtain unbiased information that each city authority had chosen to represent their rationale for the policy approach and the incentives, where available (Silverman 2016). This secondary data collection was then supplemented with primary data collection.

This research is a part of a larger collaborative project funded and supported by prime industry, green roof consultant firms in Australia. Under this large project, a literature review and analysis, quantitative and qualitative data collection and analysis on seven case study cities and business modeling were conducted and three industry

Vertical greening in Singapore
(Photo by: Author)

Green roof on sloping roof in Sydney, Australia
(Photo by: Author)

Figure 1. Examples of green roofs and green walls in cities.

reports were prepared. Toronto, Rotterdam, Stockholm, London and Singapore, Sydney and Melbourne were visited throughout 2016 and 2017. Site visits to buildings with green roofs and semi-structured interviews with key green roof stakeholders (such as government employees involved in policy, university and industry representatives) were conducted. Semi-structured interviews were selected, as they give the researchers, an opportunity to follow up areas of questioning where appropriate (Denzin and Lincoln 2008).

Semi-structured interviews tend to flow better with a more fluid exchange of information and opinions (Silverman 2016). The interviews were divided into four sections, and interview discussions included a total of twelve questions. Respondents were asked about their backgrounds, professional experience on providing advocacy for green roofs and the standards and guidance they use, to ascertain their level of expertise with regards to planning policy and green roofs. Questions on participants' views on a mandatory or voluntary framework, advantages and disadvantages, challenges, barriers and drivers to the adoption of a mandatory approach and ways to overcome challenges for green roof implementation were included. A total of twenty-eight interviews were conducted. A semi-structured interview process for qualitative data collection, with a desktop review of green roof practices in the selected cities from multiple secondary sources, provided an in-depth investigation of the mandatory and voluntary policy approaches to green roofs and reviewed innovative precedents in each city. The

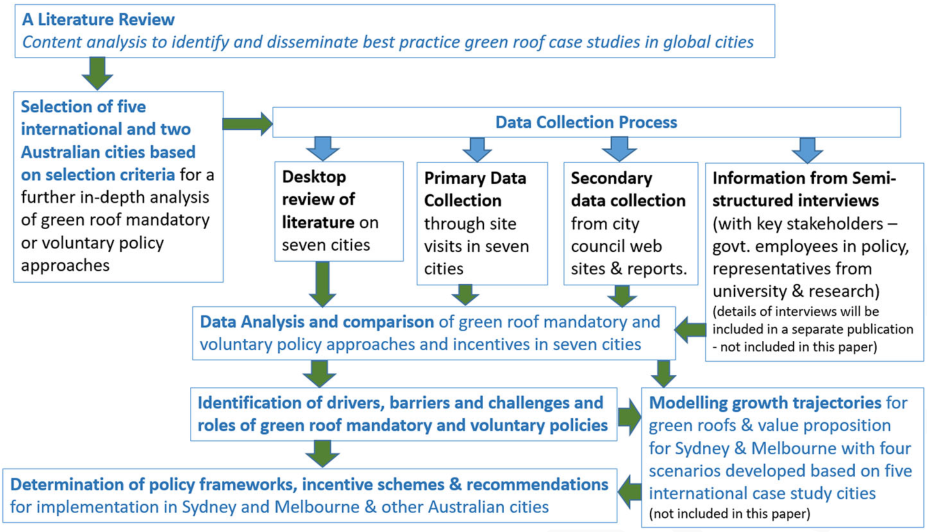

Figure 2. Research methodology flow chart for the large collaborative project.

interviews and the analysis will be part of another publication in progress, therefore, not included in this paper.

Four modeling scenarios were developed based on mandatory and voluntary policy approaches that are leading green roof uptake in the selected five international cities. Using these estimates, the growth trajectories for green roofs and value proposition were modeled for Australia's most populous cities, the City of Sydney and the City of Melbourne. This paper includes only a part of the larger study, a literature review and case studies of seven cities. This paper details outcomes from the review, site visits and green roof policies referred to during interviews and identifies the barriers, and challenges. This study does not include outcomes from the interviews and the modeling scenarios developed, as they lie outside the scope of this paper. Other factors such as market forces, technological developments and public perceptions of green roofs may impact green roof uptake. This paper did not focus on analyzing individual influencing factors and combined influences of all these factors on the green roof policy approaches in the research. This research specifically looked into cities' mandatory and voluntary policy approaches related to green roofs. The research methodology flow chart in Figure 2 presents the sequence of steps in the larger project. Further details of the results are discussed in the next section.

3. Results, discussion, and recommendations

A review of mandatory and voluntary policies was conducted, and barriers and challenges were identified after assembling the information from the case study cities.

3.1. Drivers and barriers to green roofs

An important evolving driver for green infrastructure is people's changing views. The cities are no longer considered as an "antithesis of nature" (Klinkenborg 2009).

Regenerative processes in the cities guide the development of naturalized, or biophilic, built environments. In planning and design of contemporary cities, nature manifests itself in urbanized forms such as green roofs, walls, and facades (Klinkenborg 2009). The decisions of stakeholders to install green roofs depend on the capabilities of multiple factors bringing in positive benefits, such as better thermal performance (Sultana *et al.* 2021) improved microclimate trends and reduction in Urban Heat Island (UHI) impacts (Smalls-Mantey and Montalto 2021; Fleck *et al.* 2022) and storm water attenuation (Wilkinson *et al.* 2015). Also, biodiversity enhancement, conservation of endangered flora and fauna, urban food production and provisions of social spaces influence decision making (Dixon and Wilkinson 2016). Although some of these factors are more relevant at a city scale, a significant share of stakeholders primarily focus on the benefits available at the building level rather than the city level (Dixon and Wilkinson 2016). Irga *et al.* (2017) concluded the Green Wall and Green Roof (GWGR) drivers in Australia might vary compared to Europe and North America, where environmental benefits may be stronger drivers. Internationally, there is increasing awareness among the general public of the value of GWGR projects (Hui, Jim, and Tian 2022; Pérez-Urrestarazu *et al.* 2015), which is occurring in Australia. The examples now installed, demonstrate to stakeholders both what is possible and successful to a somewhat risk-averse industry (Perkins and Joyce 2012). The policies and initiatives for green roof promotion and public views of green roof perceptions and needs are disconnected as limited work has been conducted (Hui, Jim, and Tian 2022). A perception study conducted in the City of Sydney (2017) before developing their Green Roofs and Walls Strategy indicated that associated social amenity values are a primary driver for the acceptance of accessible green roof installation in buildings (City of Sydney 2017). A questionnaire survey compared perceptions of GRGW benefits, negative impacts and attitudes toward government GRGW promotion in Beijing and Hong Kong (Hui, Jim, and Tian 2022). The socio-demographic, living-environment, and greening-attitude factors influenced public views. The residents of Beijing were proactive, had sound positive perceptions of benefits and supported effective green roof promotion policies by the government. Hong Kong's participants from younger age groups and proficient educational backgrounds supported better greening attitudes and recognition of the positive benefits of green roofs (Hui, Jim, and Tian 2022). Carter and Fowler (2008) found that policy instruments and mechanisms related to GWGRs were a major driver globally in affecting the quantity of GWGR projects. In the case study cities, main drivers of these policies were natural events such as heatwaves, rainfall, and flooding, and the vital importance of urban green space, reduction of air pollution and carbon emissions enhancing biodiversity and storm water management.

Research suggests that barriers to living architecture span economic, environmental and social and technological domains. Receiving meaningful financial returns on living architecture as public benefits at broader community and government levels and the private benefits for building owners and occupants are central to the uptake of living architecture practices (Hopkins and Goodwin 2011). A main concern of the stakeholders and professionals is the high costs of green roof installation and maintenance (Downton and Clarke 2020; City of Sydney 2017; United States General Services Administration (GSA)), 2011). Living architecture practices are subject to market competition. Developers often tend to consider other established sustainable technologies (e.g., solar PV installation) as more feasible for better economic returns compared to green roofs (City of Sydney 2017). Research shows that a combination of green roofs and solar PV actually improves PV performance (Cook and Larsen 2021). Continuing maintenance of plants is an added cost, and overall, the considerable cost of installing a green roof is a significant barrier to their uptake. Hopkins and Goodwin (2011) identified a lack of structured methods and the absence of data on material covers. Measuring the performance of green roofs is a problem for establishing quantitatively positive environmental and ecological contributions of the green roofs (Wilkinson and Page 2014; United States General Services Administration (GSA) 2011).

An estimate suggested that 87% of all buildings in 2050 have already been built and retrofitting is a potential solution to integrate living architecture into existing developments. In existing buildings, structural load-bearing capacities, access to green roofs, power and water supply, orientation to sunlight, and occupational health and safety are determinants of suitability to retrofit and to select the type of green roof to install (Feitosa and Wilkinson 2016; GSA, 2011). The City of Melbourne had completed a spatial mapping project of Melbourne CBD, which showed that out of a total of 880 ha of available rooftop area, 26.81% is suitable for intensive and 37.27% for extensive green roof retrofits (City of Melbourne 2022). Also, the reliability of green roof systems and associated risks of leaks, are obstacles for implementation (City of Sydney 2017), storm water management, dynamics, and monitoring are critical challenges for green roofs, as increased rainfall could lead to flash flooding (Wilkinson *et al.* 2015). The capacity of the construction industry is limited to roll out green roof

Table 1. Barriers to the uptake of green roofs.

Type of barrier	Description
Economic	• Stakeholders' perceptions of high installation and maintenance costs • Lack of knowledge regarding property capital and rental values uplifts by green infrastructure
Environmental and ecological	• Limited practice advice on suitable climate-based plant types and their biodiversity potential • Lack of knowledge about plant lifecycle and replacement rates • Additional water and energy consumption possibilities • Competition with other sustainable technologies, e.g., rooftop solar PV, hot water
Social	• Occupational Health and Safety needs during installation and maintenance • Limited access to the green roof as social networking public space • Limited community awareness for green roof health benefits
Technological	• Reliability of green systems – leaks, durability, flash flooding & maintenance types • Adequate access to the roof for installation and maintenance • Relevant solar orientation and wind flow • Lack of guides for building owners and property managers/facility managers • Insufficient construction industry capacity and appropriate skills training

(Source: Authors).

installation at building, precinct and city scales. Further training and skill development across the built environment stakeholders to retrofitting green roofs is essential. Table 1 summarizes barriers for the uptake of green roofs.

3.2. Mandatory and voluntary policy approaches in international and Australian cities

International case studies revealed a mix of mandatory and voluntary approaches to the implementation of living architecture in cities across Europe, Asia and North America. In Australia, there are no mandatory policies or legislation on constructing green roofs. Four different types of mandatory or voluntary policy mechanisms identified through this review included: information and advocacy; incentives; government demonstration and provision and regulation (Maddison and Denniss 2009). Mandatory approaches fell into the regulation category, while the remaining three types were included in voluntary approaches. Table 2 summarizes the green roof policy mechanisms. Supporting policy instruments from Singapore, London, Stockholm, Toronto and Rotterdam were consolidated into ten categories and compared for the selected global cities in Table 3.

Singapore leads in respect of adoption of green roofs, and has the greatest variety of voluntary measures. The city has been very proactive and markets itself as a “garden” city and attracts investment, visitors and commerce to the city. This approach has resulted in an 80% increase in green roofs and a flourishing economy. In Singapore, the Skyrise Greenery Incentive Scheme funds up to 50% of the installation costs of green roofs, and has led to an increase of 110 projects in 2015 and 80 ha of green roofs by 2017 (Wilkinson *et al.* 2017b). Toronto has the second largest recorded area of 346,000 square meters of green roofs, delivered through a highly effective mandatory approach, commencing in 2010 (Wilkinson *et al.* 2017b). Their mandatory program is enhanced with financial incentives of grants for structural assessment and the green roof itself. London has increased its green roof area by 360% over eleven years, purely on a voluntary approach and illustrates the capacity of voluntary approaches to deliver very good outcomes (Wilkinson *et al.* 2017b)

Rotterdam in the Netherlands had applied different policy instruments such as a strategic planning document; “Making sustainability a way of life for Rotterdam: Rotterdam Programme on Sustainability and Climate Change 2015–2018” and sets the goal for living architecture (City of Rotterdam 2016). A series of policy mechanisms including grants, a subsidy scheme, tax benefits, campaign periods, demonstration projects, information days and personal advice have been implemented (London, on the other hand, placed an emphasis solely on the planning policy. The “The London Plan 2016” has initiated a significant increase in the green roof area. The recent “The London Plan 2021” is a spatial development strategy for Greater London that places significant emphasis on green roof installation and considers Urban Green Factor (UGF) rules. In Stockholm, the Green Space Factor (GSF) tool (Juhola 2018) and the Stockholm Plan (Stockholm stad 2018) drive living architecture in the city.

In contrast, Melbourne and Sydney had not initiated their green roof policies until, 2015 and 2012, respectively (City of Melbourne 2017; City of Sydney 2014). In 2015, the City of Melbourne had five hectares of green roofs and rooftop gardens out of the total 880 hectares of available rooftops in the city (City of Melbourne 2017). The rooftop mapping project estimated that Melbourne has potential for retrofitting

Table 2. Green roof policy mechanisms.

Policy mechanisms	Policy Instruments
Information and advocacy	• Community information, engagement and participation • Guidelines and toolkit • Data collection, monitoring and evaluation • Research • Awards and recognition programs
Incentives	• Green building certification (voluntary or mandatory sustainability rating tools) • Incentives during the planning process for proposals incorporating green roofs (e.g., increased floor area ratio, waiving planning fees, fast-tracking & exemption) • Stormwater discount with increased pervious surfaces • Grants, rebates and financing for the installation • Awards and recognition programs
Government demonstration and provision	• Leadership including demonstration green roof • Integrated government decision making on urban infrastructure and land use planning • Integrated government decision making: ensure existing regulations do not pose a barrier for green roof installations • Data collection, monitoring and evaluation • Research • Awards and recognition programs
Regulation	• Mandatory green roof /rooftop landscaping on all new buildings (may only apply to specific building types or to buildings above a certain threshold area) • Planning scheme overlays (identifying specific areas for mandated green roof on new buildings) • Green building certification (mandatory sustainability rating schemes)

(Source: Based on Pianella et al. 2016 p. 800).

236 ha of intensive green roofs and 328 ha of extensive green roofs (City of Melbourne 2022). By March 2014, the City of Sydney had recorded more than 98,000 m^2 of green roofs and walls installed in the local government area; however, green roofs equate to less than 1% of the total roof space available in the city (City of Sydney 2014). The City of Sydney's policy with the detailed technical, research-based guides, introduction of standards, and financial incentives was seen as very effective in the Australian context (City of Sydney 2014; City of Sydney 2020a). The Growing Green Guide (City of Melbourne, City of Stonnington, City of Yarra, City of Port Phillip, the State of Victoria and The University of Melbourne 2014), available to the Greater Melbourne councils, helps to overcome the barriers to uptake outlined by Williams, Rayner, and Raynor (2010) and may have contributed to increased uptake in these councils. Given the increases in green roofs that have resulted internationally, there is an optimism that similar increases can occur in Australia. How much of an increase can be expected in Melbourne and Sydney? The final stage of the research models the rates of increase that could be expected in Melbourne and Sydney based on the different scenarios found in Singapore, Toronto, London, Stockholm and Rotterdam.

Table 3. Green roof support instruments in the international cities.

	Selected international cities				
Supporting Policy Instrument	London, England	Rotterdam, The Netherlands	Singapore	Stockholm, Sweden	Toronto, Canada
Planning policy	X	X	X	X	X
Guidelines		X	X	X	X
Grant Scheme		X	X		X
Tax benefit		X	X		
Density bonus		X	X		
Demonstration projects		X		X	X
Personal advice		X		X	X
Public awareness campaigns & information day		X	X	X	X
Awards		X	X		
Research		X	X		

(Source: Authors).

Irga *et al.* (2017) concluded that population size did not correlate with the number of green roofs. Williams, Rayner, and Raynor (2010) concluded there was more limited uptake of green roofs in Australia compared to many other countries. There is increasing popularity in green roof technology in Australia; however, it is in its initial stages of development (Irga *et al.* 2017). Williams *et al.* (2021) synthesis on green roof research and overcoming barriers in Australia over a decade identified that there is already an evidence base on green roofs which is central to development of green roof policies and programs. Some examples are included in the green roof policies of the City of Sydney and the City of Melbourne. Williams *et al.* (2021) research concluded that green roof policies in Australia provide information and encouragement for installation, but do not include regulatory or mandatory requirements for inclusion of green roofs in new developments. In Australia, the local government is responsible for land management, land-use planning, policy development, and developmental control. The voluntary and mandatory policy approaches in selected cities were analyzed following selected key factors covering planning context, mandatory and voluntary requirements, green roof uptake data, policy effectiveness and approach (Tables 4 and 5).

3.3. Recommendations

In investigating ways to expand living architecture in Australia, this research analyzed whether mandatory or voluntary approaches would deliver more living architecture, based on the case study cities. Singapore has the greatest variety of voluntary measures and was very proactive; marketing itself as a garden city. This approach has resulted in a huge increase in green roofs and a flourishing economy. Toronto, with the second-largest recorded area of green roofs, adopted a mandatory approach which was enhanced with financial incentives for structural assessment and the green roof itself. London has increased its green roof area by 360% over eleven years completely based on a voluntary approach. Planning policy was used to promote sustainable urban redevelopment in Stockholm; however, the implementation of the Green Space Factor

Table 4. A comparison of drivers, voluntary and mandatory policy approaches in five international case study cities.

City & drivers GR	The City	Planning context	Mandatory requirements	**Voluntary requirements**	Green roof uptake data	Approach & Policy effectiveness	References
London, England *Drivers:* Flood risk open space, urban greening, biodiversity, sustainable development, climate change factors – carbon emissions, air pollution	*-Metropolitan population:* 13.9 million (2016) *-Area:* 8382 km^2 *-Climate:* Temperate oceanic	*-The London Plan* (2021) is a Spatial Development Strategy for Greater London, In this Plan Policy G5 Urban greening implements Urban Greening Factor (UGF) for proposed developments to determine an appropriate amount of greening required. An intensive green roof has 0.8 & an extensive green roof has 0.7 urban greening factor. The London Plan (2016) –previous was consistent with *National Planning Policy Framework* (NPPF). In this Plan, Chapter 5, in "Climate Change Adaptation Policy 5.11 Green roofs and development site environs," links to "Sustainable Design and Construction" under "London Plan guidance and SPGs" giving importance green roofs and green walls.	The London Plan 2021 is part of the statutory development plan. None	*-Planning Practice Guidance* -Green roofs gain credit in sustainability rating tools such as *BREAAM (Building Research Establishment Environmental Assessment Method)*	–14, 750 m^2 (2005) to 53,200 m^2 (2016) –52% extensive roofs built (2005–2016) and 39% are intensive roofs. -In 2019 in Greater London had green roof coverages – Intensive 3[illegible]5075.47 m^2 or 2[illegible].54% (0.04 m^2 per person(pp)), Extensive 11[illegible]2859 m^2 or 74.46% (0.[illegible]1 m^2 pp) & Biosolar (extensive) 130647.63 or 11.63% ([illegible]0.01 m^2 pp)	**Voluntary** -Increase in green roofs by 360% (2005–2016) & 33.0% per year -Very good spatial distribution throughout the city. -Completed spatial mapping of whole of London in 2019. -Additional capital value increases attributed to green commercial buildings	Greater London Authority 2021 Green Infrastructure Consultancy and The Ecology Consultancy 2018 Greater London Authority 2016
Toronto, Canada *Drivers:* Rainfall, flooding, Strategic Plan 2013–2018; Amenity and	*Metropolitan population*: 5.9 million (2016) *Area*: 5,906km^2 *Climate:* semi-continental	*City Planning's Strategic Plan 2013–2018*	*Toronto Green Roof Bylaw* – mandatory GR on all new developments of 2000 m2 + GFA on 20%–60% of Available Roof	*-Toronto Green Roof Construction Standard: Supplementary Guidelines* *-PAL/PPR Project Reviews* –GR pre-application stage assessment	–420 new green roofs were approved 2010 to 2017 and were equivalent to 450,000 m^2 of green roof space. –500,000 m2 of green	**Mandatory** -Significant policy effectiveness due to mandatory policy. -The combination of the Green Roof	C40 Cities Climate Leadership Group Incorporated 2022; Dong, Zuo, and Luo

(*Continued*)

Table 4. (*Continued*).

Issues & drivers GR	The City	Planning context	Mandatory requirements	**Voluntary requirements**	Green roof uptake data	Approach & Policy effectiveness	References
green social space, livable city			Space. Eligible GR in industrial development receive $75/m2 up to $100,000 -Mandatory provisions in *Toronto Green Roof Construction Standard*	-*Green Roof Designer Checklist* -*Green Roofs and Building Permits* under *Toronto Green Construction Standard* -*Structural Assessment Grant (SAG)* – GR retrofit potential of existing building; -Grant of C$100/m^2 of the GR provided & exceeding C$100,000 require council approval; -GR credit *BREEAM Canada* and *Green Globes –Eco-roof incentive program* -*Guidelines for Biodiverse Green Roofs 2013*	roofs were developed from 2009 to 2018.	Bylaw, the Green Roof Construction Standard and a grant program works very well.	2020; City of Toronto 2021; Toronto City Planning 2013
Singapore *Drivers:* Heatwave, pollution and environmental degradation, rainfall, flooding, high density, compact city, enhance biodiversity	-*Population*: 5.5 million -*Area*: 697 square km^2 -*Climate*: Tropical	-*Singapore Green Plan 2030*, a ten-year plan, a whole-of-nation sustainable development agenda with Pillar 1: City in Nature. -*Singapore Green Plan 2012* – was a ten year plan to achieve a holistic sustainable development considering multiple domains. -*Sustainable Singapore Blueprint 2015* – a plan of action for all stakeholders to work together to achieve a	-Mandatory implementation of skyrise greenery in public sector projects -Higher levels of Green Mark certification for specific land sales	-*Centre for Urban Greenery and Ecology (CUGE)* for research in 2007; -*Landscape Excellence Assessment Framework (LEAF)* a certification program in 2012; -*Building and Construction Authority (BCA) Green Mark Scheme* in 2015; -*Skyrise Greenery Incentive Scheme (SGIS*) in 2009 provides developers up to 50% costs of GR/GW installation;	-Housing and Development Board (HDB) projects, which houses 80% of Singapore's population, integrate skyrise greenery.-SGIS resulted in retrofitting more than 110 existing buildings with extensive GR/GW, edible and recreational rooftop gardens. -More than 50% of eligible new residential projects applied for at least one LUSH incentive (2012–2014),	**Mix of Mandatory and Voluntary** -Increase in green roofs by 805% (2009–2017) & 101% increase per year -Excellent policy effectiveness achieved through skyrise greenery policy instruments and the wide range of incentives and grants.	Ministry of Education et al. 2021; Juhola 2018; National Parks Board 2017; Ministry of the Environment and Water Resources and the Ministry of National Development 2014; Ministry of the Environment and Water

(*Continued*)

Table 4. (*Continued*).

City & drivers GR	The City	Planning context	Mandatory requirements	**Voluntary requirements**	Green roof uptake data	Approach & Policy effectiveness	References
		livable and sustainable Singapore.		-The "Guide to Skyrise Greenery" and "Guide to Skyrise Greenery – safe practices" in 2015; -In 2009, the Landscaping for Urban Spaces and High-Rises (LUSH) program provided a Gross Floor Area (GFA) incentives & exemptions for building greening, including GR/GW -The Skyrise Greenery Awards -National Parks Board published a handbook on developing high rise greenery in 2017.	and more than one-third of shopping centers, offices and hotels have benefited from these incentives. –10 hectares (ha) of sky rise greenery in 2009 increased to 80.5 ha in 2017 across 182 projects.		Resources 2021
Rotterdam, The Netherlands *Drivers:* Heatwave, rainfall, flooding	- *City of Rotterdam population*: 630,000 (2014) -*Area*: 325.79 km^2. -*Climate*: Mild temperate	-*Making sustainability a way of life for Rotterdam: Rotterdam Programme on Sustainability –Climate Change 2015–2018* targets to install 40,000 m^2 of GRs per year	None	-*Rotterdam Urban Vision: Spatial Development Strategy 2030* -*The Rotterdam Climate Change Adaptation Strategy* (subsidy program part of this strategy) - Total subsidy to €30 per m^2 to install green roofs (City of Rotterdam €25 per m^2 plus two local water authorities €5 per m^2) on the condition that at least 15 liters of water retained per m^2; - Tax deductibility (36%) under Environmental Investment	–100,000 m^2 (2012) to 220,000 m^2 (2017) to more than 360,000 m^2 (2018) and to reach a goal of 800,000 m^2 (2030) and install green roofs on at least 50% of municipal buildings	**Voluntary** - Increase in green roofs by 120% (2012–2017) & 24% per year – sets the agenda and associated tools -Increased cross-institutional collaboration through the Climate Adaptation Strategy	Municipality of Rotterdam 2018, 2015, 2007; Rotterdam Climate Initiative 2017; City of Rotterdam 2016; Rotterdam Climate Initiative 2017

(*Continued*)

Table 4. (*Continued*).

City & drivers GR	The City	Planning context	Mandatory requirements	**Voluntary requirements**	Green roof uptake data	Approach & Policy effectiveness	References
				Deductibility; - Rotterdam Municipal Council's *2019–2022 Multifunctional Roofs Programme Plan* includes seven possible options for roof space.			
Stockholm, Sweden *Drivers:* Pop. growth, open space, biodiversity, stormwater	*Metropolitan population*: 2.4 million (2019) *Area:* 6,526km^2 *Climate*: Cool- temperate	- *Stockholm City Plan* (Stockholm stad 2018) – provides guidance and support in decision making on land and water uses and protection of the built environment to 2040. - *Vision Stockholm 2030* – long term vision and strategic direction toward a world-class Stockholm.	- A *comprehensive plan* - *The Building and Planning Act* - *Areas of national interest under the Environment Code*	-*Green Space Factor (GSF)* to secure a certain ratio of green cover in every building lot, and to minimize impervious surfaces. In Stockholm, GSF is mandatory in Royal Seaport Redevelopment, (min target 0.6). - *Green Points System*	- In Stockholm, Royal Seaport Redevelopment has constructed 22,500 m^2 green roofs between 2009 and 2020;	**Voluntary** Policy effectiveness would require further evaluation of the GSF tool. Mandatory policies do not adequately regulate green roof uptake.	Salmhofer, 2020; Stockholm stad 2018; Vartholomaios et al. 2013; City of Stockholm 2007

(Source: Compiled by Authors).

Table 5. A comparison of drivers, voluntary and mandatory policy approaches in Sydney and Melbourne.

City & drivers GR/GW	The City	Planning context	Mandatory requirements	**Voluntary requirements**	Green roof uptake data	Approach & policy effectiveness	References
City of Sydney, Australia *Drivers:* Heatwave, Rainfall, Flooding	*Greater Sydney population: 4.8 million (2016)* *Area*: 12,368 km^2 *Climate*: Humid subtropical	-Sydney Local Environmental Plan (LEP) 2012 -Sustainable Sydney 2030: Community Strategic Plan 2017–2021 (Local Government Area: City of Sydney)	None	-*Green Roofs and Walls Policy* (2014) - *Green Roofs and Walls Policy Implementation Plan* (2014) - *Green Roof Resource Manual* - *Green roofs and walls: DA and design advice* - *Green Roofs and Walls Perceptions Study* - *Greening Sydney Plan;* - *Decentralized Water Master Plan;* - *Environmental Action 2016–2021 Strategy and Action Plan* (2017) - *Urban Forest Strategy* (2013); - *Urban Ecology Strategic Action Plan* (2017)	-City of Sydney had more than 98,000 m^2 of green roofs and walls installed (March 2014); - In 2017, 75 green roofs and walls (53 green roofs, 17 green walls and 5 with green roofs and walls). - Green roof & walls locations for City of Sydney and case studies; - City of Sydney has experienced 23% increase in total GRGW coverage.	**Voluntary** - Progress in policy alignment to promote green roof and walls; - Expected rise in green roof numbers;	Australian Building Codes Board (ABCB)), 2019; City of Sydney 2020a, 2020b, 2017, 2014; City of Sydney website.
City of Melbourne, Australia *Drivers:* Heatwave, Rainfall, Flooding	*Greater Melbourne population*: 4.5 million (2016) *Area*: 9990 km^2 *Climate:* Temperate oceanic	-*The Melbourne Planning Scheme* -*State Planning Policy Framework* (Local Government Area: City of Melbourne)	None	- City Strategic Action Plan 2017–2021 - *Growing Green Guide* - *Urban Forest Strategy* - *Urban Ecology and Biodiversity Strategy* – *Central City Urban Forest Precinct Plan 2013–2023* - Melbourne rooftop mapping project- University of Melbourne Green Infrastructure Research Group – Green Star rating tool	- Under Climate Change Adaptation Strategy and Open Space Strategy *Rooftop Mapping Project* in 2015. - In 2015, the City of Melbourne had 5 hectares (50000 m^2) of green roofs and rooftop gardens. - The total numbers of green walls and facades were 50 in 2016. -By 2015, 54,000 m^2 of green roofs and 0.36 m^2 per capita green roof area in Melbourne. .	**Voluntary** -Progress in policy and rooftop mapping project estimated a total of 880 ha of rooftop area available, with 236 ha (26.81%) for intensive and 328 ha (37.27%) for extensive green roof retrofits	Dong, Zuo, and Luo 2020; Australian Building Codes Board (ABCB)), 2019; City of Melbourne 2017; City of Melbourne, City of Stonnington, City of Yarra, City of Port Phillip, the State of Victoria and The University of Melbourne. 2014; City of Melbourne website

(Source: Compiled by authors).

(GSF) is voluntary, aiming to deliver a green cover across building lots. But GSF is mandatory in some developments such as Royal Seaport Redevelopment project in Stockholm with a minimum target of 0.6 (Vartholomaios *et al.* 2013). Rotterdam also used a voluntary approach to increasing the installation of green roofs, through incentives, grants, tax benefits, and demonstration projects. Rotterdam achieved an increase of 120% of the green roof area in the five years through its voluntary policy supported approach and 2018 had 360,000 m^2 of green roof area (Municipality of Rotterdam 2018). Voluntary approaches can be enhanced, either through incentive programmes which can be financial in the form of grants, or allowances for building to greater densities, thereby offsetting the costs of green roof installation against higher capital and rental values. In each city, green roof policies are well established, although they have diverse approaches. Based on the analysis, a range of strategies were recommended.

The analysis suggested a mix of voluntary and mandatory policy for green roofs, with a predominantly voluntary approach for retrofit. This voluntary approach could include a mix of initiatives to enable value to be realized for building owners, such as tax benefits, avenues for accreditation or financial incentives as direct incentives such as grants and subsidies and indirect incentives such as energy cost savings. A mandatory approach for new build and renovations as enforcement can be tied to the approval process. The policy package should reflect a mix of elements and a greater range of approaches, which could influence the adoption of green infrastructure in a wide range of settings (Tayouga and Gagné 2016). Policies should focus on inclusion of GI in those spaces where it performs equally or better than traditional infrastructure. Focus on education in the policy package could enhance awareness, knowledge, and understanding of the general public, stakeholders, and policy and decision-makers about types and uses of GI in providing ecosystem service benefits (Tayouga and Gagné 2016). Green roofs should be included within urban ecology, resilience, building energy savings and other relevant strategies in cities.

Conducting scenario-based modeling for the potential uptake in green roofs in Melbourne and Sydney based on approaches taken in Singapore, Toronto, London and Rotterdam. Geographic Information System and remote sensing methods provide useful information on potential performance and limitations through mapping and analysis. Evaluation of green roof potential for LGAs outside Sydney, Melbourne and in Perth, Brisbane and Adelaide would provide Australia-specific data and information on performance potential and how they vary across Australian cities with varying climatic conditions. Research in practical projects to further quantify CO_2 emission savings, UHI and stormwater attenuation and building energy savings with a view to identifying high performing green roof designs lead to the greatest effect in the Australian context. Establishing experimental sites in key cities to evaluate the relative merits of various configurations, such as the one established at The Hills BARK BLOWERTM landscape yard at Kenthurst, Sydney (Morris 2011) and a microclimate study compared two adjacent green roofs in Barangaroo, Daramu House with a green roof, built in 2019, and International House with a conventional roof built in 2016 in Sydney (Fleck *et al.* 2022). This critical infrastructure would enable the emergence and identification of better designed green roof installations. Collaborative networking with industry would connect research to practice, enabling formulation of appropriate designs and implementation pathways.

The quality of information needs to be improved and easily accessible to better inform policymakers, building owners and other key stakeholders. Establishing a database, clear data management and access mechanism whereby data on innovation and information needs could be addressed through an evaluation of structural characteristics of the built environment to enable the emergence of more cost-effective ways of installing green roofs. This evaluation would include physical, institutional, and legal aspects which currently manifest as barriers to green roof uptake. Also, analyzing the extent to which emerging and existing accreditation systems, such as Green Star, could support a vibrant GI industry would be beneficial.

4. Conclusions

Green roofs are an essential component of livable, sustainable and resilient cities. This paper presented seven global case studies to illustrate the mandatory and voluntary approaches, drivers and related policies for adoption of green roofs in each case study city. Overall, the most successful approach was that adopted in Singapore which is a largely voluntary programme with economic incentives, but also the requirement of the Housing and Development Board being such a large property owner is highly influential. The second-ranked approach was the mandatory approach taken by Toronto, also supported with financial grants. The third most effective program was that of the City of London, a more free-market scenario and a wholly voluntary approach. Rotterdam's voluntary approach had more generous subsidies and tax benefits. Finally, Green Space Factor (GSF) did not have sufficient time in Stockholm to evaluate how effective it has been in the green roof uptake. This analysis shows that our cities and their societies are complex and that it is too simplistic to say a voluntary or a mandatory approach is unequivocally the best approach to delivering more living architecture. City authorities globally have a choice between mandating for green roofs and adopting a market-led voluntary approach, whereby the market determines whether to install green roofs. Given the increases in green roofs that have resulted internationally, and highlighted in this paper, similar increases can occur in Melbourne and Sydney and other Australian cities. Equally, there are opportunities for other global cities not featured in this research to evaluate their existing policy and regulatory frameworks and options for adoption of different measures and incentives to promote their uptake of green roofs.

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