12

Development of Low-Carbon Urban Forms—Concepts, Tools and Scenario Analysis

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Introduction

While cities are currently key sources of greenhouse gas emissions (GHG), there are already signs that cities can act as frontrunners of positive change in this respect towards 'low carbon' or 'decarbonisation' outcomes when aligned to regenerative urban development strategies (Girardet 2015; Wigginton et al. 2016). Given the complexity of the urban built environment in terms of forms, fabrics and spatial scales, strategies and measures devised to mitigate urban carbon emissions need to be targeted to the relevant urban settings. From a systems perspective, 'City' and 'Precinct' are two dominant and complex urban built

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forms, at the macro- and the meso-scales, respectively, representing embodiment of land, constructed facilities, transport, and physical and social infrastructures. These infrastructures support production and consumption activities in relation to particular social, economic, environmental and technological contexts. A city can be regarded as a 'system of systems' consisting of a cluster of different precincts interconnected with transport and essential service networks. Often referred to as 'neighbourhoods' or 'districts', precincts represent parts of an urban area that have defined geographical boundaries and serve certain functional or planning purpose(s). They can accommodate multiple uses such as residential, commercial, educational, health, administrative or their combinations (Huang, Xing & Pullen 2017a). They involve spatial, physical and functional interplays of landscape, zonings, buildings, infrastructures (energy, transport, water and waste), as well as occupants. A precinct can be treated as a single entity for specific analyses, planning and urban design, as well as recognising its interactions with surrounding urban features and fabrics and the sustainability implications thus incurred.

Based on such notions, 'City' and 'Precinct' present as two appropriate 'spatial lenses' for developing low-carbon urban forms. They enable urban planners and decision makers to examine and manage carbon signatures of urban settings in accordance with planning purposes at different scales and/or spatial levels. This requires keeping track of not only direct emission reductions instigated by one product, process, technology or activity, but also capturing all indirect changes in emissions instigated by the original change (Ness & Xing 2017). Therefore, a major challenge is with how life-cycle energy and carbon signatures of the fabric and metabolism of different urban forms are defined

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methodologically, quantitatively assessed, and effectively implemented in planning policies, guidelines and regulations for achieving and sustaining 'decarbonisation' outcomes in the long term (Newton et al. 2012). The carbon profiles of such multidimensional and multi-scale urban forms (buildings, infrastructures, precincts, etc.) need to be analysed through a nested, multi-scale assessment to provide urban designers and urban policymakers with an understanding of: (a) where embodied and operational carbon emissions reside, and (b) where intervention or substitution will have the biggest effect.

By drawing upon the research of the Integrated Carbon Metrics (ICM) Project funded by the CRC for Low-Carbon Living, this chapter presents two tools for interrogating and assessing the whole-of-life carbon emissions of built forms at city and precinct scale in order to map out their full carbon profiles, to identify the carbon 'hot-spots', and to analyse the potential pathways for transitions to low-carbon urban development. To this end, the next section introduces an analytical tool, the City Carbon Maps, designed to produce embodied carbon footprint estimates for transboundary emissions mapping and evaluation at the urban scale, whereby the carbon maps of Australian capital cities are also discussed. Then, the rationale and description of the Precinct Carbon Assessment method, a quantitative modelling and analysis instrument for precinct carbon accounting, are elaborated in the following section. A case study of a residential precinct retrofit with scenarios of carbon reduction options is undertaken to demonstrate its application for supporting low-carbon transformation at a precinct scale.

City Carbon Maps

As a basis for action on climate change, it is vital for cities to quantify and report their GHG emissions. It is important to have holistic and accurate carbon accounting for cities to inform the setting of meaningful targets, design successful policies and implement effective strategies for decarbonisation. In this regard, the City Carbon Maps developed under the ICM project aims to identify and manifest the complete flows of embodied carbon emissions for Australia's major capital cities.

Carbon Accounting Method

The City Carbon Map constitutes a consistent accounting framework aligned with national and regional accounting frameworks. To construct a comprehensive carbon map, territorial emissions, including those from transport, energy use, buildings and infrastructure, together with all emissions embodied in materials, goods and services imported into the boundary of a city all need to be accounted for. Following the Global Protocol for Community-Scale (GPC) Greenhouse Gas Emission standard (WRI, C40 & ICLEI 2014; WRI & WBCSD 2011), such emissions can be distinguished in forms of Scope 1 (from sources within the city boundary), Scope 2 (as the consequence of electricity use within the city boundary) and Scope 3 (occurring outside the city boundary, but as a result of activities inside the city boundary) emissions. In defining the carbon footprint of a city, Production-Based Carbon Footprint (PBCF) represents the sum of GHG emissions from all Scopes 1–3. It is important to note that this metric combines in-boundary and out-of-boundary emissions, which means that double counting of emissions may occur. Meanwhile, the Consumption-based Carbon Footprint (CBFC) methodology captures both the direct and the life-cycle GHG emissions, except those emissions embodied in goods and services exported from the city for external consumption by non-residents. Both PBCF and CBCF are covered by the carbon accounting method of the City Carbon Map to present a consistent and complete reconciliation of direct and indirect emissions of all different Scopes described in the standards.

The construct of a carbon map is simply a two-dimensional decomposition of the carbon footprint of a city's final demand. It splits up the total carbon footprint into the industry sectors from which the GHG emissions originate as well as into the product groups in which the emissions become embodied (Wiedmann, Chen & Barrett 2016). This is achieved through the derivation of specific city-scale, multi-region input-output data with environmental extensions using the Australian Industrial Ecology Virtual Laboratory (IELab http://www.ielab-aus.info) (Lenzen et al. 2014). This is a database that combines information on financial transactions between industry sectors and regions, derived from national IO tables published by the Australian Bureau of Statistics (ABS), with GHG data from the Australian Greenhouse Emissions Information System database (AGEIS 2017).

The industrial sectors are aggregated into nine categories: agriculture, construction, electricity, energy, food, goods, services, transport, and waste. The construction sector includes construction materials and services. The electricity sector is separated from other energy sectors to enable standard Scope 2 accounting. Industrial process emissions are allocated to industrial products. Direct household emissions (e.g. from heating or driving) are also included in the footprints.

Carbon Maps of Australian Cities

Based on the concept and the method of City Carbon Maps, the carbon footprints of the five largest capital cities in Australia are analysed. This sheds light on the relationship of the cities territorial GHG emissions, that is, direct emissions from within the geographical boundary of the city, and their out-of-boundary emissions. That is those that occur outside of the city but are related to the consumption of city residents (Wiedmann, Chen & Barrett 2016). The metropolitan area boundaries follow the greater capital city statistical areas (GCCSAs) published by the Australian Bureau of Statistics (ABS 2012). All data and results refer to the year 2009.

The analysis reveals several interesting aspects of embodied emission flows of cities. Perth has the highest per-capita CBCF (35 tCO_2e per capita) of the five cities studied, followed by Melbourne (25 tCO_2e per capita), Adelaide (22 tCO_2e per capita), Sydney (21 tCO_2e per capita) and Brisbane (16t CO_2e per capita). Figure 12.1 presents the relative breakdown of PBCF based on the emission scopes as well as their association with products produced within the city and those imported. Generally, Scope 1 and Scope 3 emissions make up the largest proportions of the carbon footprints of the cities. All cities, except Perth, rely more on GHG emissions from elsewhere in Australia and the world than from their own industries, to satisfy their final demand.

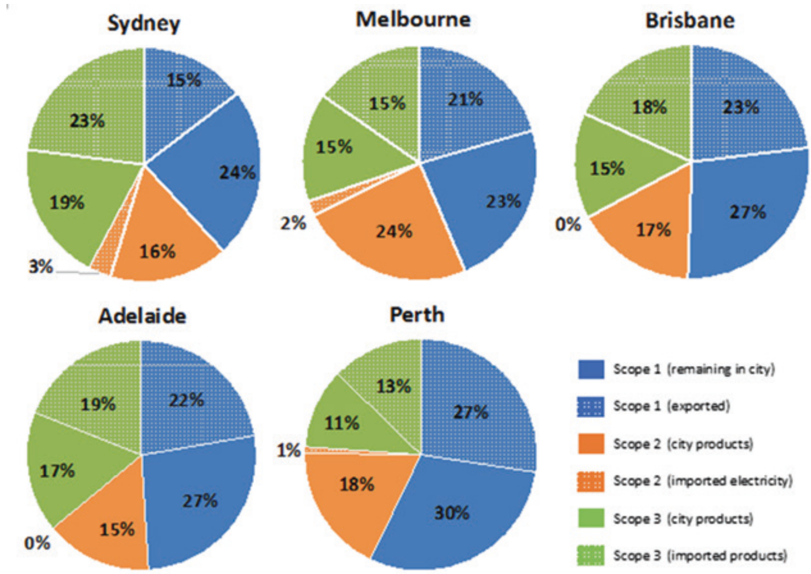

Fig. 12.1 Breakdown of city-related emissions (Production-based Carbon Footprints)

In addition, a breakdown by sectors, shown in Fig. 12.2, reveals that the majority of city carbon footprint emissions are generally attributable to three broad sectors: goods (e.g. clothing, furniture and pharmaceutical goods), construction (e.g. construction materials and services) and services (e.g. financial, legal and educational services). Electricity, food and transport rank second. The use of fossil fuels (energy) in homes and waste have only minor contributions to the overall embodied carbon footprints. Under the consumption perspective, a large proportion of Scope 1 emissions in all sectors, except transport, are exported as embodied emissions to consumption outside of the city. This means that consumers outside the city boundaries are buying goods and services that were produced or sold in the city (e.g. consumer goods or financial products). This reflects the demand for city products elsewhere and the general openness of cities to trade. Meanwhile, Scope 2 emissions are not only related to the direct use of electricity by households

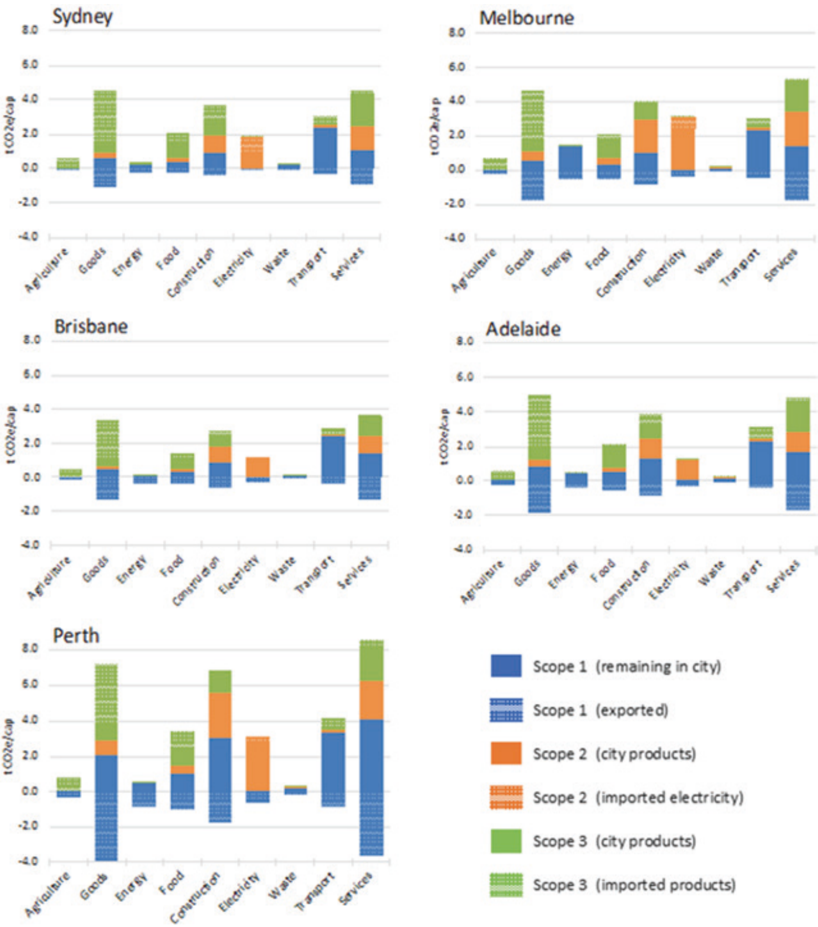

Fig. 12.2 Per-capita carbon footprints of five cities by product categories and scopes (Production-based Carbon Footprint = all values, Consumption-based Carbon Footprint = all values above the zero line)

and businesses (electricity category in Fig. 12.2), but also largely embodied in other sectors, most notably construction and services. Apart from the use of energy (fossil fuels), electricity and transport, Scope 3 emissions make up around one third to over half the carbon footprints of all sectors. There is a very high proportion of Scope 3 emissions from imported goods to Australian cities from overseas. Other sectors that contain significant proportions of Scope 3 emissions are food and agriculture, construction, transport and services.

Implications

For all five cities studied, the City Carbon Maps identify that the top 3 sectors driving carbon footprint emissions are services, goods and construction. While Scope 1 and 2 emissions contribute substantially, it is also the Scope 3 emissions in these sectors that need attention if full carbon neutrality is to be achieved defined here as balancing the total amount of GHG emissions emitted with the equal amount being either reduced or offset through carbon mitigation projects. Scope 2 emissions are certainly the easiest to reduce, by switching to 100% renewable electricity supply. Mitigating the emissions from the electricity sector will in particular benefit the service and construction sectors in all cities as they are all heavily reliant on electricity. Scope 1 emissions from buildings can be tackled with energy efficiency measures and incentives (related to envelope and built-in services and appliances) to a maximum possible extent, before further offsetting by renewable electricity (Newton & Tucker 2011).

Households are responsible for about two-thirds of the city CBCFs, while government and business drive the remaining one third (Wiedmann, Chen & Barrett 2016). More than half of the nation's CBCF is attributable to consumption in the five large cities, with many of those GHG emissions embodied in international imports of goods and services. This suggests that the current focus on territorial emissions would be ineffective at reducing city, national and even global emissions in the absence of mechanisms to monitor and report emissions embodied in trade of imported goods and services. Carbon footprinting should become part of the National Cities Performance Framework (Commonwealth of Australia 2017), with both the emissions embodied in imports and exports monitored, especially for embodied emissions of goods and services that have been shown to make up substantial parts of city carbon footprints. This would complement the approach currently focused solely on Scope 1 and 2 emissions, already implemented by most current city carbon accounting standards and Australia's National Carbon Offset Standards (http://www.environment.gov.au/climate-change/government/carbon-neutral/ncos).

Precinct Carbon Assessment Tool

Precinct Carbon Assessment (PCA) is a carbon modelling and analytics tool developed as part of the ICM Project to examine the whole life cycle of carbon of the urban built environment at a precinct scale. The PCA tool aims to provide both highly aggregated as well as more detailed assessment of *operational **and** embodied carbon* of precinct objects (residential buildings, commercial buildings, and infrastructure), building appliances, transport vehicles and discrete energy generation via solar PVs and storage units. With such functionality, the tool offers the capability to assess different low-carbon development options, including alternative travel modes and renewable energy systems. Figure 12.3 presents a schematic view of the functional features of the PCA tool.

Modelling and Key Parameters

To perform the carbon assessment, the PCA tool supports precinct carbon modelling at the building level, the product level, and the material level. Modelling can range from rapid assessments using highly aggregated data and standard/typical precinct object types (provided by the built-in database) to more detailed analysis using refined data and user-defined precinct object types. Such features can accommodate the needs of those users having different technical competence, resources and objectives.

To satisfy the requirements of different assessment scenarios, the input parameters, in relation to geographical attributes, demographic profiles, precinct morphology, infrastructure attributes, travel modes and energy and carbon intensities of building components, are structured for three

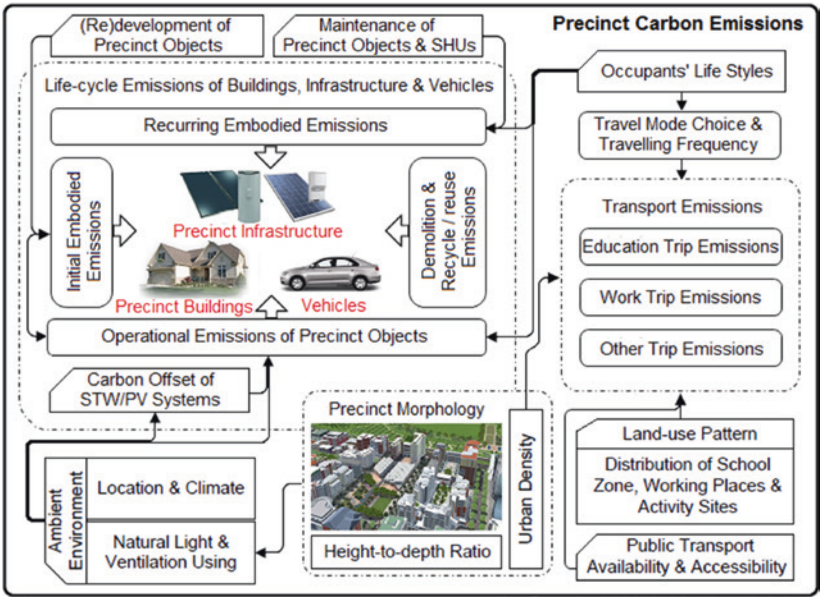

Fig. 12.3 A schematic representation of the PCA tool functions

levels of modelling as shown in Fig. 12.4. Level 1 is designed to suit urban planners and government agencies. It predominantly focuses on early-stage planning at a macro level. Therefore, highly aggregated data on energy/carbon intensity per square metre of each object type is used as the primary input for assessment. The Level 2 modelling is intended for the building and construction phase and associated practitioners. It aims to improve the carbon performance by material/components selection and optimal scheduling of operations for precinct objects. Hence, the data on MJ or tCO_2-e per square metre used in the modelling is built up from the product level, including detailed volumetric data of materials used, energy/carbon intensity of each material/product type, as well as units of use and the operating schedule of each appliance type (built-in and plug-in). For the Level 3 modelling, more detailed information about precinct object designs and travel mode selection is required as input data to support the examination of overall carbon performance from the perspective of design and development.

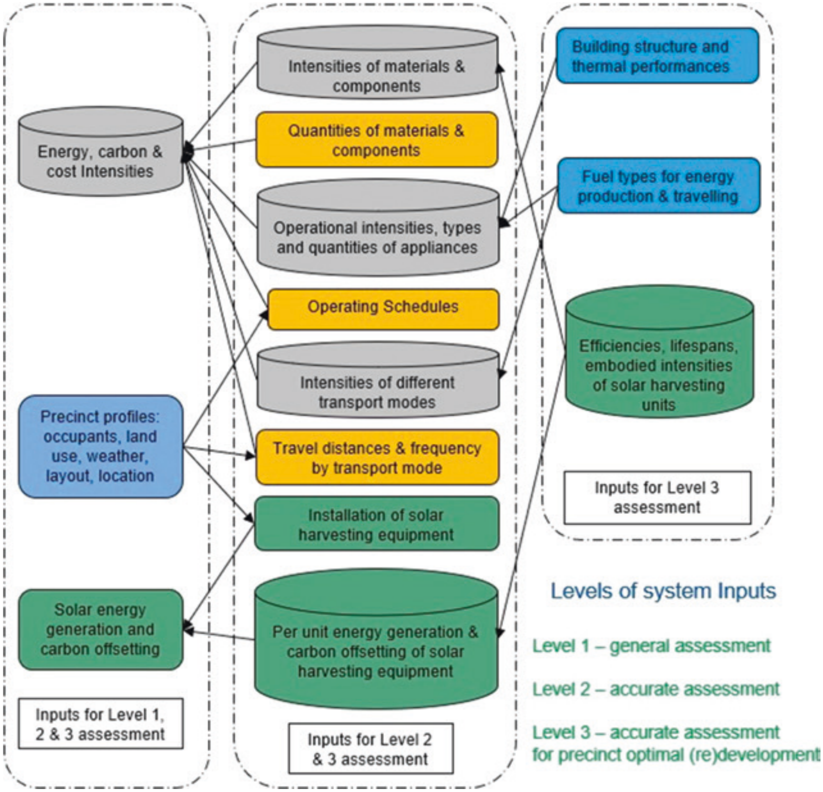

Fig. 12.4 Levels of modelling and input requirements for tool application

Carbon Assessment and Performance Metrics

To support scenario analysis and decision making, the PCA tool employs performance indicators that interrogate operational energy and embodied (both initial and recurrent) energy of buildings, appliances, and infrastructures for transport, energy, water, and waste; transport energy in relation to different transport modes and vehicle uses for commuting and lifestyle; as well as energy generation from deployment of Renewable Energy Harvesting Systems (such as solar PVs and solar thermal hot water units). Based on local power mix and fuel types, these indicators are converted from energy metrics (in MJ) to respective carbon metrics (in tCO_2-e), in terms of both life cycle and annual, for the whole precinct, for different building/object types, and for different types of occupant. Furthermore, Life-Cycle Cost (in dollar value), Cost-Carbon Intensity (in dollar per tCO_2e) and Payback Period (in years) can also be incorporated for analysis and decision making.

The precinct-scale carbon assessment is underpinned by an integrated model that consists of three key phases. At Phase 1, carbon intensities for embodied, operational and transport-related emissions are identified. The embodied carbon intensity of each precinct object type is determined by the life-cycle carbon intensities of main construction materials, the amount of each material required for construction, replacement and waste ratios of building components, as well as the carbon embodied in construction activities (e.g. material and equipment transportation, equipment use, onsite assembly, etc.). The recurrent embodied carbon is measured as the replacement ratios of major building components over the lifespan of precinct objects. As for operational carbon, operational energy intensities of precinct objects are firstly assessed and then emission factors (with the unit of $kgCO_2$-e/MJ) determined by local energy production are used to convert into operational carbon intensities. Transport-related carbon intensities are calculated from fuel consumption considering multiple fuel types, measured as $kgCO_2$-e/km/passenger. Phase 2 is designed for the evaluation of precinct baseline emissions associated with buildings, vehicles, as well as infrastructure services including energy, water and waste. In this stage, parameters interlinked with the environment, local climate, and occupant life-style preference (e.g. total floor area of each building type, schedule of appliances, travelling frequency and distance, etc.) are identified to support the calculation of precinct baseline emissions, together with the carbon offsetting contributed by renewable energy systems. Phase 3 is developed to improve the accuracy of precinct carbon evaluation. At this stage, precinct baseline emissions are moderated by morphological characteristics in relation to factors such as density, compactness, building orientation and obstruction angle. The occupants' life-style preferences are considered and integrated into the baseline carbon measurement by affecting operating hours of appliances, maintenance and refurbishment cycles of precinct building objects and transport mode selections. The impacts of actual precinct morphology or master planning of an urban precinct are analysed to identify the strength of characteristic influencing factors such as urban density and solar potential. Finally, these influencing factors are modified iteratively in order to improve the overall carbon profile of the precinct. More detailed information about the precinct carbon model and the assessment methods can be found in Huang, Xing and Pullen (2017b, 2017c).

A Case Study of Precinct Redevelopment

In this case study, the PCA tool is applied to explore and assess different scenarios associated with the densification of an established low-density residential precinct. This is a common challenge for infill associated with development in all major capital cities, given the rapid surge in population and housing demand. The objective is sustainable low-carbon regenerative redevelopment (Newton 2018). The precinct selected for this study, Andrews Farm, is located 30 kms to the north of Adelaide CBD in South Australia. It represents a typical outer established residential suburb that can be found in any Australian city. Based on 2011 Census data, the precinct had a population size of 7197, with 48.6% of the occupants being less than 25 years old. There were 2034 dwellings within the 273-hectare precinct, which were predominantly single-storey, detached houses. In this study, it is anticipated that the precinct will experience a population growth of 15%. This will require small lot subdivision of land, replacing some of the existing low-density dwellings with medium-density dwellings and introducing an additional 680 new townhouses (two-storey, semi-detached) as part of the densification process (Newton, Meyer & Glackin 2017). It will also lead to increased transport activity and infrastructure for essential services.

For planning purposes, the options for achieving low-carbon redevelopment are:

- Option 1: high energy-efficiency new buildings (i.e. 7-star rating equivalent assumed; current standard is 6 stars),
- Option 2: precinct scale renewable energy system deployment (i.e. increase of rooftop PV installation to 90% with an average of 5 kWp per household assumed), and

Table 12.1 Scenario analysis and comparisons

Carbon measure	Baseline (in tCO_2e)		Scenario 1 (in tCO_2e)		Scenario 2 (in tCO_2e)	
	per annum	per capita per annum	per annum	per capita per annum	per annum	per capita per annum
Embodied carbon	14.9×10^3	2.1	18.2×10^3	2.2	19.0×10^3	2.3
Operational carbon	21.7×10^3	3.0	25.7×10^3	3.1	25.7×10^3	3.1
Transport carbon	18.2×10^3	2.5	19.1×10^3	2.3	10.8×10^3	1.3
Carbon offsetting	−775.0	−0.1	−989.4	−0.1	-4.8×10^3	−0.6
Total carbon	54.1×10^3	7.5	62.1×10^3	7.5	50.8×10^3	6.1

- Option 3: change of occupants' travel mode choice to low-carbon transport for commuting (i.e. increased use of public transport by 35% with an average of 30 km per round trip per day assumed).

Three main scenarios, representing incremental changes, can be considered for the carbon reduction potential. In this analysis, two scenarios are examined and presented to compare with the current 'Baseline', that is, Scenario 1 (changes mainly to the dwelling types based on Option 1) and the Scenario 2 (changes with a combination of Options 1–3).

Table 12.1 summarises the comparison between different scenarios in relation to their carbon signatures. The total carbon of the current precinct (i.e. the 'Baseline' scenario) is assessed as 3243.1×10^3 tCO2e over 60 years or 54.1×10^3 tCO2e per annum, including 775 tCO2e per annum of onsite carbon offsetting from rooftop PV.

According to the results, the carbon signature of Scenario 1 goes up by 15% (i.e. 8.0×10^3 tCO_2e) from that of the 'Baseline', despite having new dwellings of much higher energy efficiency. This is mainly attributed to the increase of embodied carbon (i.e. more houses and expanded infrastructure) and operational carbon from total energy use (i.e. more occupants and more services required for water and waste management) by 22 and 18%, respectively. Consequently, these also lead to slight increase of carbon per capita. Since Scenario 1

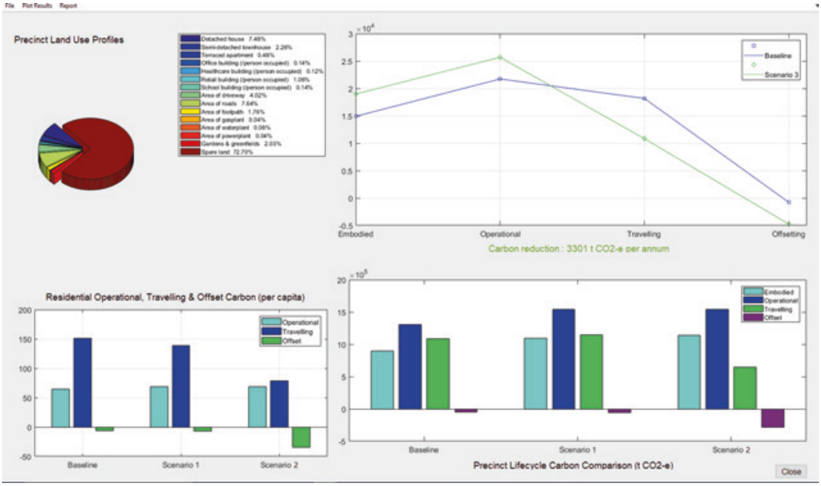

Fig. 12.5 Reporting of the PCA results

incorporates 15% population growth, with anticipated demographic changes related to more small households with young children, it contributes to a marginal increase of total transport carbon and slight decrease of transport carbon per capita. In comparison, Scenario 3 presents potential for achieving more reduction in total carbon, leading to 3.3×10^3 tCO2e (or 6%) less than that of the 'Baseline'. This is a result of having higher onsite carbon offsets generated from a large increase of precinct-scale PV deployment and more uptake of public transport for commuting, as shown in Fig. 12.5.

Implications

The results from applying the PCA tool can provide insights capable of informing planning and policy decision making for low-carbon urban renewal of residential precincts. Firstly, it is clear that population increase will have a major impact on a precinct's carbon signature due to increased housing, transport activities, and consumption of services. Secondly, increasing provision of high energy-efficient houses to reduce operational energy alone has a limited effect on carbon reduction, especially when used as infill in redevelopment and urban densification. In the meantime, the contribution of embodied carbon to the total carbon can rise significantly when infrastructure, especially transport infrastructure (e.g. roads, driveways, paths and pavements), is considered in the assessment. Thirdly, transport carbon represents a very large part of a precinct's carbon signature, particularly for outer suburbs (as shown in this study). Encouraging and facilitating occupants to adopt carbon-efficient travel modes for commuting can be the most effective way for reducing transport carbon, which underscores the importance of Transit-Oriented Development (TOD) and more incentives for the uptake of electric vehicles in urban planning—more so if they are shared (Dia 2019). Furthermore, the effect of solar PV on carbon abatement may not be as strong as what was expected. In this analysis, the implementation of community-scale PV contributes to 8.5% carbon reduction on the basis of an uptake rate of 90%. A precinct-scale deployment of renewable energy harvesting systems (with and without energy storage) needs to be strategically planned and analysed for both carbon offsetting and economic effectiveness. A combination of solutions for housing, infrastructure, travel and renewable energy is required to address all carbon measures holistically for developing precincts capable of achieving low-carbon targets.

Conclusion

A major challenge with 'decarbonising' urban development is how life-cycle carbon signatures of different urban forms are defined and quantitatively assessed in the context of twenty-first century built environments. In this chapter, two assessment tools developed from the ICM project are applied to the assessment of carbon footprints of built forms at the city scale and at the precinct scale.

The City Carbon Maps aim to examine the embodied carbon emissions of cities from the perspective of production and consumption, as well as from the import and export of goods and services both within and across city boundaries. The complete carbon flows of the five major

Australian metropolitan areas are analysed as examples to inform possible decarbonisation strategies and policies by different urban stakeholders—especially Federal governments, where embodied carbon in international trade flows have been ignored to date.

While the City Carbon Maps tool provides a 'whole-of-system' view of the carbon profile of a city, the Precinct Carbon Assessment (PCA) tool adopts a bottom-up approach to model and analyse the life-cycle carbon metrics of a precinct, in the context of its built environment objects and morphological features. It provides users with flexibility to adjust precinct design settings, renewable energy system options and carbon intensity data of precinct building material objects in order to conduct quantitative analysis in the pursuit of finding best-practice solutions. By doing so, it can help to identify carbon 'hot-spots' and to assess different design and development options directed towards 'decarbonisation' outcomes for the built environment.

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