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Carbon assessment for urban precincts: Integrated model and case studies

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ABSTRACT

The building sector is the largest contributor to global greenhouse gas (GHG) emissions. Over the years, sound tools have been developed to support the life-cycle assessment of building carbon emissions performance. However, most of these tools have been primarily focused on building-scale modelling and evaluation, leaving the emissions related to infrastructure and occupant activities as well as the carbon offsetting from implementing district-scale renewable energy systems, often neglected. The uptake of macro perspective carbon evaluations at the urban precinct level has been slow due to various barriers such as system boundary definition, quantification of complex inter-building effects, availability of comparable data, integrated modelling and uncertainties related to occupants' life styles. This research developed an integrated life-cycle model to support the precinct-scale evaluation of carbon footprint for a comprehensive understanding of the emission profile. This is expected to further support low carbon planning and (re)development of urban precincts. The model structure is underpinned by four major components at the precinct level, i.e. embodied, operational and travelling associated carbon emissions, as well as the carbon offsetting from solar energy harvesting. The utility of the proposed methodology is demonstrated through preliminary case studies on representative suburban precincts in Adelaide, South Australia. Comparative studies and scenario analysis are also involved to identify the critical elements affecting the overall carbon performance of urban precincts.

1. Introduction

Taking up around 2.5% of the planet's landmass, cities contribute significantly to natural resource consumption and discharge considerable volumes of waste [1] and to study these phenomenon, cities and urban areas can be subdivided into precincts. Since there are many definitions of a precinct, a planning perspective is adopted where a precinct is taken to be an urban area with clearly defined geographical boundaries and a subdivision of the city with specific functional features (e.g. business, administrative, medical, residential, etc.). The (re)development and operation of objects within a precinct including different buildings and infrastructure, consume significant natural resources and produce large environmental burdens. As a significant part of such burdens, greenhouse emissions (or carbon dioxide equivalent, hereafter: carbon) associated with the use of fossil fuels and non-renewable energy in exploiting natural resources as well as consuming goods and services for socio-economic needs, are commonly accepted as the main contributor to global climate change. Statistics compiled by the International Energy Agency indicate that more than one third of global carbon emissions can be attributed, both directly and indirectly, to the construction, operation and maintenance of precinct objects [2]. In Australia, the building sector accounts for about 36% of the overall carbon balance [3]. With respect to human activities, transportation is found to be the largest contributor to global carbon emissions [4]; [5]. In light of a growing awareness towards the sustainability of urban development, greater attention has been drawn to the carbon performance evaluation of built environments and urban transport activities.

Previous studies in this field have been primarily focused on building-scale evaluation with the consideration of embodied and operational carbon performances over various stages of a building life-cycle, leaving other contributors within urban precincts such as infrastructure and occupant activities, largely missed [6]. In addition to precinct objects and occupant activities, inter-building effects and urban morphologies are also acknowledged as essential factors on urban carbon balance and sustainability [7]; [8]. In addition, small-scale solar harvest units (SHUs) such as roof-top thermal

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water heating (STW) and photovoltaic (PV) systems have also found a wide application for carbon offsetting in the urban environment [9]. Instigated by the emphasis on improving the overall carbon performance of cities to avoid benefiting one component at the cost of another, there has been growing interest in research on precinct-scale assessment in recent years. This is expected to lead urban design and planning with carbon assessment and decision support at the early stage [10]; [11].

There are many advantages of moving beyond the building-scale to a precinct-scale assessment when attempting to improve the overall carbon performance of the urban environment. Firstly, the overall carbon performance of an urban precinct can be estimated at the planning stage of a development cycle with a precinct-scale assessment tool. Optimal planning at a macro-level such as the precinct-scale has the potential to decarbonise the urban environment in a systematic way. Secondly, with the involvement of additional precinct elements such as transportation and renewable energy harvesting, the carbon performance of the urban environment can be assessed within a more comprehensive and holistic boundary. Thirdly, precincts are a microcosm of cities, therefore carbon assessment at the precinct level can lead to mapping and reducing the carbon signature of the entire urban system, as well as support government policy-making. However, several barriers are hindering the uptake of precinct-scale evaluations, which include system boundary definition, data availability, dynamic inter-building effects contributed by urban morphologies, uncertain preferences for occupants' life-style, integrated modelling and less standardized production process of precinct objects caused by their unique characteristics [12].

Bearing in mind these methodological difficulties, this research is the first to develop an integrated model for precinct carbon assessment which takes into account morphological factors and occupants' life styles. These factors embrace four aspects which are embodied, operational and travelling carbon emissions, as well as carbon offsetting contributed by renewable energy harvesting. The proposed model is expected to provide a more contrasted picture of precinct emission profile, which will consequently contribute to the planning and (re)development of low carbon precincts. In addition, the utility of the proposed methodology is demonstrated through preliminary case studies. Comparison and scenario analysis are also conducted to identify the key elements affecting the carbon performance of urban precincts. The rest of this paper is structured to first include a literature review of carbon assessment in the urban environment (Section 2). This is followed by the discussion on key conditions for precinct-scale assessment (Section 3). Then, an integrated model is presented (Section 4), together with comparative case studies and scenario analysis (Section 5). Finally the paper draws conclusions and describes future research work (Section 6).

2. Life-cycle carbon assessment in the urban environment: literature review

Since buildings contribute to the carbon balance directly and indirectly over their lives, life cycle analysis (LCA) is commonly employed for evaluating their energy and carbon performance. According to the definition of life-cycle analysis (LCA) published in ISO 14040, building life-cycle emissions can be broadly classified into embodied emissions, the amount of emissions contributed by the construction and maintenance of a building, and operational emissions, which are associated with the operations of a building (as for: heating, cooling, ventilation, hot water, lighting etc) [13]. Recent studies indicate that the operational carbon plays a dominant role on building life-cycle carbon emissions, ranging from 65 to 80% [14]; [15]. With respect to the embodied carbon, up to 82% of the total amount is found embodied in construction materials [16]. Studies conducted in references [9] and [17] indicate that optimal design schemes and material selections might benefit the reduction of embodied carbon by 14–30% in the building sector. While other studies claim that there is a potential carbon saving of up to 40% in the operational stage of buildings by applying automated control strategies [18]; [19]. Existing studies in this field have primarily focused on the building-scale assessment of carbon performance, leaving the emissions related to infrastructure, occupants' activities and carbon offsetting contributed by implementing renewable energy systems at the district scale, largely uncovered.

A review of current studies found that transportation facilities and activities also have significant impacts on the carbon balance of urban precincts. A census conducted by the World Resource Institute indicates that travel accounts for about 14% of carbon emissions worldwide, which is projected to increase by 50% by 2020 [20]. In Australia, transportation is found to be the third largest and second fastest growing source of carbon emissions, contributing 90 Mt CO_2 - equivalent (CO_2-e) annually or 16% of Australia's total carbon balance [5]; [21]. Within the different modes of travel, road transportation accounts for 87% of Australia's transport emissions with the majority attributed to passenger vehicles [22]. From the perspective of LCA, carbon derived from travelling can be further split into direct and indirect elements: the direct part is associated with the combustion of fuel in vehicles, while the indirect requirement is the amount embodied in the manufacturing of vehicles and fuels, as well as the service and infrastructure supports. Studies in this field found that the indirect component might contribute 25–65% of the total travelling emissions [23], and the emissions embodied in the manufacturing of vehicles might contribute up to 4.5 t CO_2-e per annum per household, or up to 2.8 t CO2-e per annum per capita [24]. Further discussion on the research conducted by Lenzen [23] showed that construction and maintenance of infrastructure for transportation might account for 11- 29% of the overall carbon emissions. While the operational carbon of passenger road transport (or travelling in this research) is commonly derived from travel distance, travel mode choice, fuel type and travel frequency. A study carried out by Beer et al. [25] indicates that biodiesel has a potential to reduce 41–51% of carbon emissions, and gaseous fuels might contribute as much as 88–92% of carbon emissions compared with diesel. It is well understood that this part of overall emissions is significantly influenced by urban morphology, infrastructure development, urban density and occupants' life styles [7]; [26].

While the above studies analysed the carbon performance of precinct objects and transport activities, some studies have focused on carbon offsetting contributed by the harvesting of renewable energy [27]. In the urban precinct environment, solar energy conversion through STW and PV systems are expected to be reliable and sustainable methods to support the decarbonisation of the urban environment, although they are unable to benefit the overall energy consumption of urban precincts (e.g. improve energy efficiency, reduce energy demand etc.) [28]. Previous studies indicate that STW systems can offset 79% of the carbon associated with hot water supply, while the integration of PV systems can achieve an annual carbon reduction up to 18–160 kg per m^2 of PV panel area [29]; [30]. Similar research conducted by Gerilla et al. [9] found that a reduction of up to 73% of the total life-cycle carbon can be achieved by using solar energy at the operation phase of dwellings.

Further to the physical factors affecting the carbon balance of precinct objects, a knowledge of the inter-building effects is essential for the planning, (re)development and management of low carbon precincts. Pioneering research conducted in reference [31] indicated that the influence on travelling energy (which consequently affects travelling emissions) from urban density is likely to be very significant. Similar findings were reported by Steemers

[32]. Another study explored the impact of urban form on travelling emissions, and found that high job and retail densities were two critical factors for low carbon travelling [33]. Zhang et al. [34] investigated the influence on building sky exposure resulting from urban density and block typology, which might consequently affect the energy-related carbon emissions and the potential carbon offsetting contributed by SHUs. In a comparative study of carbon performances between city centre and suburban households, Perkins et al. [24] found that high density dwellings often offer lower environmental impacts, while the total per capita carbon of households from high density precincts exceeded those of households from low density precincts. Although previous studies have enriched our understanding of the environmental impacts on building carbon performance, they have concurrently failed to quantify how much those impacts would be in a systematic manner.

In attempting to understand the carbon performance at a macro perspective, a focus on the integrated modelling and assessment of precinct carbon with the considerations of embodied, operational and travelling carbon emissions, as well as the carbon offsetting contributed by renewable energy harvesting, is clearly more logical. Indeed, there has been an increase in studies on precinct information modelling (PIM) and management over an expected precinct lifespan [10]. However, several barriers are hindering the quantification of precinct carbon balance: firstly, inconsistent system boundaries applied in different studies make it difficult to develop a comprehensive understanding of precinct carbon profiles. The per unit life-cycle carbon contents of construction materials, precinct objects and relevant services often suffer from accuracy issues caused by the inconsistent and incomprehensive system boundary definitions. Moreover, from the systems perspective, a fair comparison between different systems can only be guaranteed when similar completeness or the same boundary is applied [35]; [36]. Additionally, any precinct object is not an isolated system, but an evolving subsystem closely linked to the life styles of its occupants and the dynamics of the surrounding environment. However, it is difficult to predict and quantify the influence of occupants and the dynamic inter-building effects determined by specific urban morphology. By examining the above studies in building and precinct carbon measures, this research is primarily focused on the integrated modelling of precinct carbon within a defined system boundary, considering the quantified morphological impacts.

3. Modelling methodology

As discussed in previous sections, precinct-scale assessment tools are expected to measure the overall carbon emissions contributed by the main objects and occupants' activities within the urban precincts. This section presents the methodology, the definition of the modelling rationale, the system boundary, the data derivation method and the key factors for morphological impacts, to underpin the development of an integrated model for assessing precinct life-cycle carbon emissions.

3.1. Modelling rationale

Since an urban precinct is 'a system of many interconnected subsystems', a realistic, holistic and accurate evaluation of its overall carbon performance can be achieved by integrating the life-cycle carbon balances of precinct projects with emissions contributed by residents' activities. The literature review in the previous section indicates that occupant travel is by far the major contributor of activities related to carbon emissions within urban precincts, while solar energy harvesting with STW and PV systems is considered as an important source for precinct carbon offsetting. Considering these inputs here, it is therefore quite reasonable to evaluate the carbon performance of urban precincts with four distinct but inter-linked components: 1) the life-cycle carbon embodied in the construction/manufacturing, maintenance, demolition, recycle/reuse of precinct objects, vehicles, as well as STW and PV systems. The travelling embodied carbon is measured based on a previous study conducted in South Australia [24]; and 2) the carbon emissions associated with the operational energy consumption of precinct objects; and 3) the carbon emissions contributed by occupants' travelling. Since the carbon associated with building material transport and construction related transport activities has been integrated into the embodied carbon of precinct objects, therefore travelling carbon is employed in this research to differentiate from the commonly used transport carbon. Passenger road transport emissions associated with commuting and entertainment related travels are termed as the occupants' travelling carbon in this paper; and 4) total carbon offsetting benefits from the harvesting of solar energy.

Based on these inputs, the modelling of precinct carbon emissions can be implemented in two phases. The downstream evaluation is focused on the baseline life-cycle embodied carbon of precinct objects, travelling vehicles and SHUs, the operational emissions of precinct objects, the baseline carbon offsetting contributed by SHUs, and the baseline carbon associated with occupant travels. Here the baseline carbon means the carbon emissions contributed by precinct objects, occupant travelling and SHUs carbon offsetting within the precinct context under ideal conditions. In this paper, a travelling energy model developed at the early stage of this research is adapted to the travelling baseline carbon evaluation through applying an energy-to-carbon factor determined by local energy production [8]. Conversely, the upstream research aims to improve the evaluation accuracy through applying morphological factors determined by precinct environmental features. This is different from the life-cycle carbon evaluation of buildings where a great deal of detailed building design, building materials and construction features are emphasized. Hence, a precinct level evaluation would devote more effort to the influence from urban morphology, occupant activities, and socioeconomic environment, since the evaluations are conducted from a systems perspective.

3.2. System boundary

Fig. 1 illustrates the boundary selected for this research. Extended beyond the building-level to the precinct-level, carbon assessment can be conducted with a greater consideration of the influences from the natural, built and socio-economic environments. Therefore, more effort is devoted to explore the macro-effects such as urban morphology, occupants' life-style preference and carbon offsetting potential, rather than detailed design, construction and operation information of precinct objects. The carbon performance of the precinct system is highly coupled with life-cycle characteristics of precinct objects, which are moderated by planning and management strategies applied over their life cycles. Therefore, a holistic system boundary needs to be defined to capture the interplays among different precinct objects in both the time and the spatial dimensions to assess the embodied, the operational and the travelling carbon profiles of a precinct, as well as the carbon offsetting performance of SHUs. Carbon variations derived from technology improvements during the predefined assessment period are neglected at the current stage of this research. In terms of spatial scale, operation and travelling associated carbon, as well as the potential and efficiency of solar harvesting, are significantly affected by urban form, location and density of precinct objects. Therefore the boundary of precinct-scale carbon evaluation is expanded with the inclusion of morphological factors and occupant life styles at both time and spatial scales.

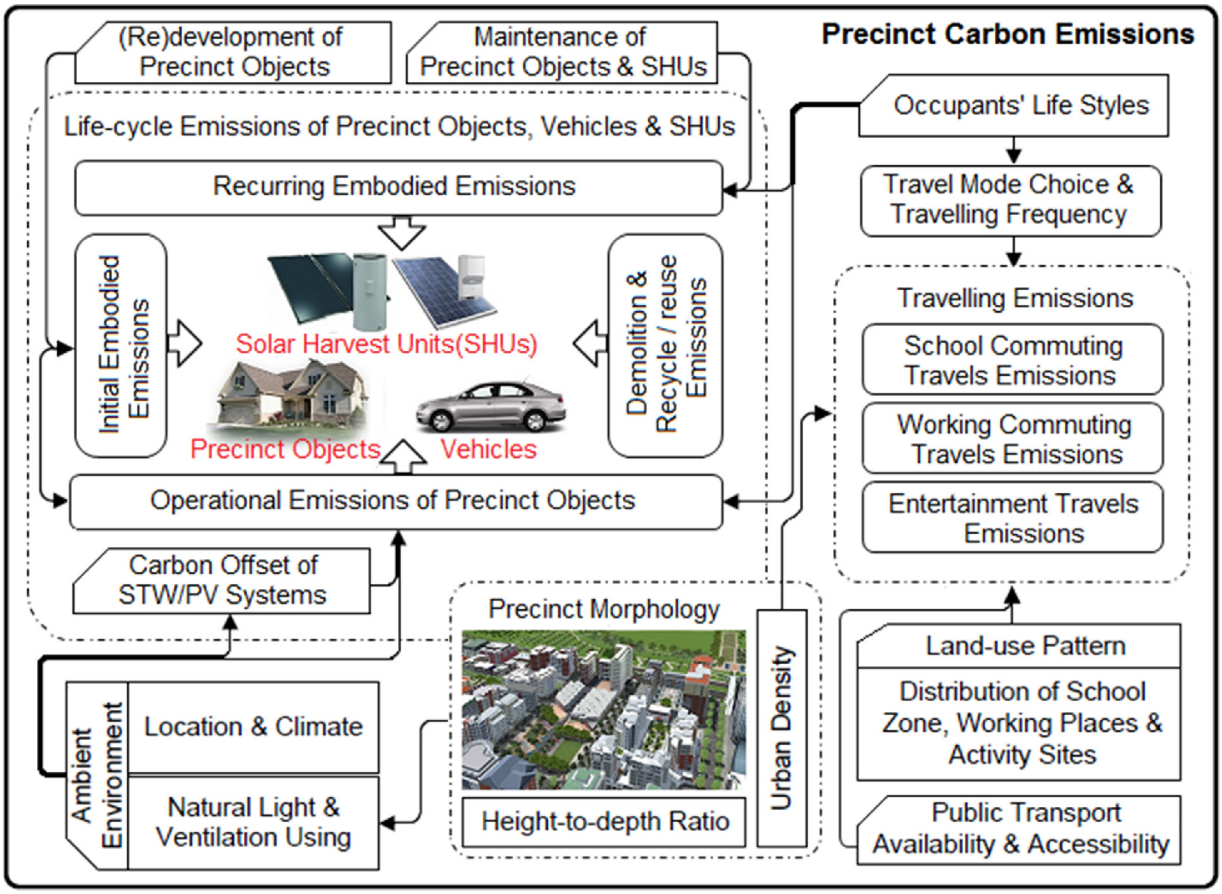

Fig. 1. System boundary for carbon evaluation of urban precincts.

3.3. Carbon data method

The quality, currency and availability of the life-cycle inventory data relevant to the measurement of precinct carbon emissions is a challenge for all assessment tools. There is a variety of methods such as input-output (IO) analysis, process analysis and hybrid analysis, which have been developed and used to compile life-cycle inventories, each having their own benefits and limitations. IO analysis is known as a top-down economic technique that uses sectoral monetary transactions to describe and explain the complex interdependences of industrial activities within a given national or regional economic system [37]. Therefore, the data identified by IO which is regularly compiled as part of national statistics, can simplify modelling, and explain the spatial distribution and consumption in complicated multi-regional and dynamic scenarios [37]; [38]. However, this approach is often limited by uncertainties arising from basic source data, proportionality, imports and homogeneity assumptions, as well as incompleteness of sectoral environmental statistics (e.g. Treloar [39] and Lenzen [40]). Moreover, since blind to individual processes, IO analysis can distort the physical flows between industries, and fail to guide technological and consumer choices [41]. As a detail-oriented bottom-up approach, process analysis can provide more recent, accurate and detailed process information, as well as a deeper understanding of the construction and consumption nature at the product level. However, it typically suffers from system boundary constraints and truncation errors, as it is impossible to exhaustively assess the supply chain of any given product due mainly to cost and time constraints, data availability and/or significance, modelling simplifications and knowledge limitation [37]; [42]. Previous research on the built environment indicates that some energy intensities derived from IO data may differ substantially (by as much as four times greater) from those derived from process based data [43]. Considering the advantages and disadvantages associated with IO and process based data, hybrid analysis is postulated as an approach to overcome the limitations such as data availability, physical flow distortion, and boundary constraints [61]. However, this data method still suffers from uncertainty and inconsistency to some extent, causing implications akin to 'mix five apples with two apple trees to make seven sources of fruit' [62].

To address such issues, this research adopts an integrative approach for the precinct carbon assessment to balance the quality and availability of data. Instead of using hybrid LCI data, data generated with single-disciplinary approaches, i.e. IO and process-based LCA, are adopted, but applied for different precinct objects and life-cycle aspects of precinct carbon modelling. Process-based data is applied where physical flows can be identified quantitatively and volumetric values are possible to specify for precinct objects and their components. This is particular suitable for calculating embodied carbon of a precinct object from the component/material level in a 'bottom up' manner, applicable to objects such as various residential and commercial buildings, roads and SHUs. For precinct objects that represent complex systems whose life-cycle carbon is hard to assess from the component/material level, IO-based data can be adopted to determine the embodied carbon profile by using non-physical measures, e.g. economic values, following a 'top-down' approach. In this model, the embodied carbon assessment for those services and utility infrastructures (e.g. water, waste, power and transport), which are established in a precinct, but managed and utilised for public access beyond the precinct boundary. The allocation of embodied carbon to the precinct level is on the basis of consumption or occupant access within the precinct in relation to the entire urban scale.

3.4. Morphological factors and impacts

As mentioned in the previous discussion, precinct objects are evolving subsystems closely linked to the dynamic surrounding environment. With respect to solar harvesting, the uptake and efficiency of SHUs are significantly affected by the local climate as well as shading effects of the neighbourhood. Therefore, morphological factors referring to urban form, residential density and inter-building effects take a predominant role in precinct carbon emissions and carbon offsetting. Previous studies indicate that morphological factors can greatly and directly affect operational and travelling associated emissions [7]; [26]; [44]. A review of the relevant literature indicates that effective use of daylight can save 20–40% of lighting energy consumption [45]; [46]. Previous studies even provide an approach for the approximate quantification of the environmental influence on lighting energy consumption [47]; [48]; [49]. A common finding of studies conducted by Steemers [32] and Pacheco et al. [50] is that morphological factors such as orientation and obstruction angle have potential to change the energy consumption on HVAC up to 15% and 50%, respectively. These studies also recognise the influence on mechanical ventilation and air conditioning (HVAC) on energy expenditure with diagrams reflecting the interactions between orientation, obstruction angle and HVAC energy consumption. As to the travelling energy consumption, early research completed by Newman and Kenworthy indicates that urban density is likely to be the most significant factor [31]. A diagram demonstrating the relationship between urban density and changes in travelling energy consumption is also published in this study.

Despite the above studies being focused on the interactions between morphological factors and energy consumption, it is reasonable to use them to identify the morphological factors μ_l (lighting coefficient), μ_{hvac} (HVAC coefficient), μ_t (travelling coefficient) and μ_{sp} (solar potential coefficient) employed in the integrated model of this research. As discussed in the previous section, since the operational and travelling carbon is converted from energy consumption according to the local energy production and fuel types, respectively, it is reasonable to interpret the interactions between morphological factors and energy consumption into relationships between these factors and carbon emissions.

4. An integrated model for precinct carbon assessment

In this section, a framework with the mathematical formulation of models is introduced for the integrated assessment of precinct carbon performance in accordance with the system boundary defined in Section 3. The model is based on carbon intensity per unit of material or activity, and structured in such a way that alternative carbon intensities can be adopted as more refined data become available.

4.1. A framework for integrated modelling

Developing an integrated framework to measure the precinct carbon emissions is, in essence, a complex endeavour. With the expansion of the system boundary and consideration of morphological factors and occupants' life styles, a great number of parameters and variables are involved. The complexity of modelling and evaluation is therefore remarkably increased, which correspondingly makes many existing tools and methods less suited to the precinct-level assessment. In this research, an integrated model is developed which strives to model and assess the precinct carbon at a macro level. As shown in Fig. 2, the modelling of precinct carbon represents baseline emissions, which are moderated by morphological factors reflecting the ambient natural and built environment. At the current stage, 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 objects and travelling mode selections. The morphological impacts are focused on the influence of precinct global carbon emissions, which then involves more than the single aggregation of individual assessments.

Table 1
Australian emission factors of different energy types.
(Based on references [51] and [52])

Energy Type	Emission Factor (kg CO2-e/MJ)
Electricity	0.0746
Natural gas	0.0600
Petrol	0.0693
Petrol (E95, wood)	0.0360
LPG	0.0700
Diesel	0.0800
Diesel (Low sulfur diesel)	0.0810
Diesel (ultra-low sulfur diesel)	0.0820
Diesel (BD20, Biodiesel)	0.0870
Diesel (BD100)	0.0480
Aircraft fuel	0.0715

Since the number of variables, complexity of interactions and constraints significantly increase with the expansion of system boundaries, it is necessary to satisfy some assumptions for the simplification of modelling and evaluation. Referring to the earlier work in this research, the assumptions established for precinct energy modelling and assessment were adopted in the integrated carbon modelling and evaluation processes [8]. Corresponding to the features presented, the developed framework can be conducted in three stages. At Phase 1, carbon intensities for embodied, operational and travelling emissions are identified. The embodied carbon intensity of each precinct object type (measured as kg CO_2-e/m^2 floor area) 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.). A study conducted by Junnila et al. indicated that the recurrent embodied carbon might be significant amounting to about 5% of the overall office building carbon balance [63]. In this research, the recurrent embodied carbon is measured as the replacement ratios of major building components over the lifespan of precinct objects. Since the operational carbon is associated with energy consumption, operational energy intensities were firstly measured with the model developed at the early stage of this research, then emission factors (with the unit of kg CO_2-e/MJ), which are determined by local energy production (as shown in Table 1), are used to convert operational energy intensities into operational carbon intensities. Travelling carbon intensities were calculated from the fuel consumption considering multiple fuel types, measured as kg CO_2-e/km/passenger.

Phase 2 is designed for the evaluation of precinct baseline emissions. In this stage, parameters inter-linked with the environment, local climate, and occupant life-style preference (e.g. total floor area of each building type, operation schedule of appliances, travelling frequency and distance, etc.) are identified to support the calculation of precinct baseline emissions. It is necessary to keep in mind that since the embodied carbon intensities of vehicles and SHUs are measured as per capita, per unit or per kW capability, this amount of embodied carbon is assessed with the parameters of population size, installation ratios, as well as the carbon intensities provided by references [24]; [28]; [53]. The carbon offsetting contributed by SHUs is included with the consideration that STW units only offset

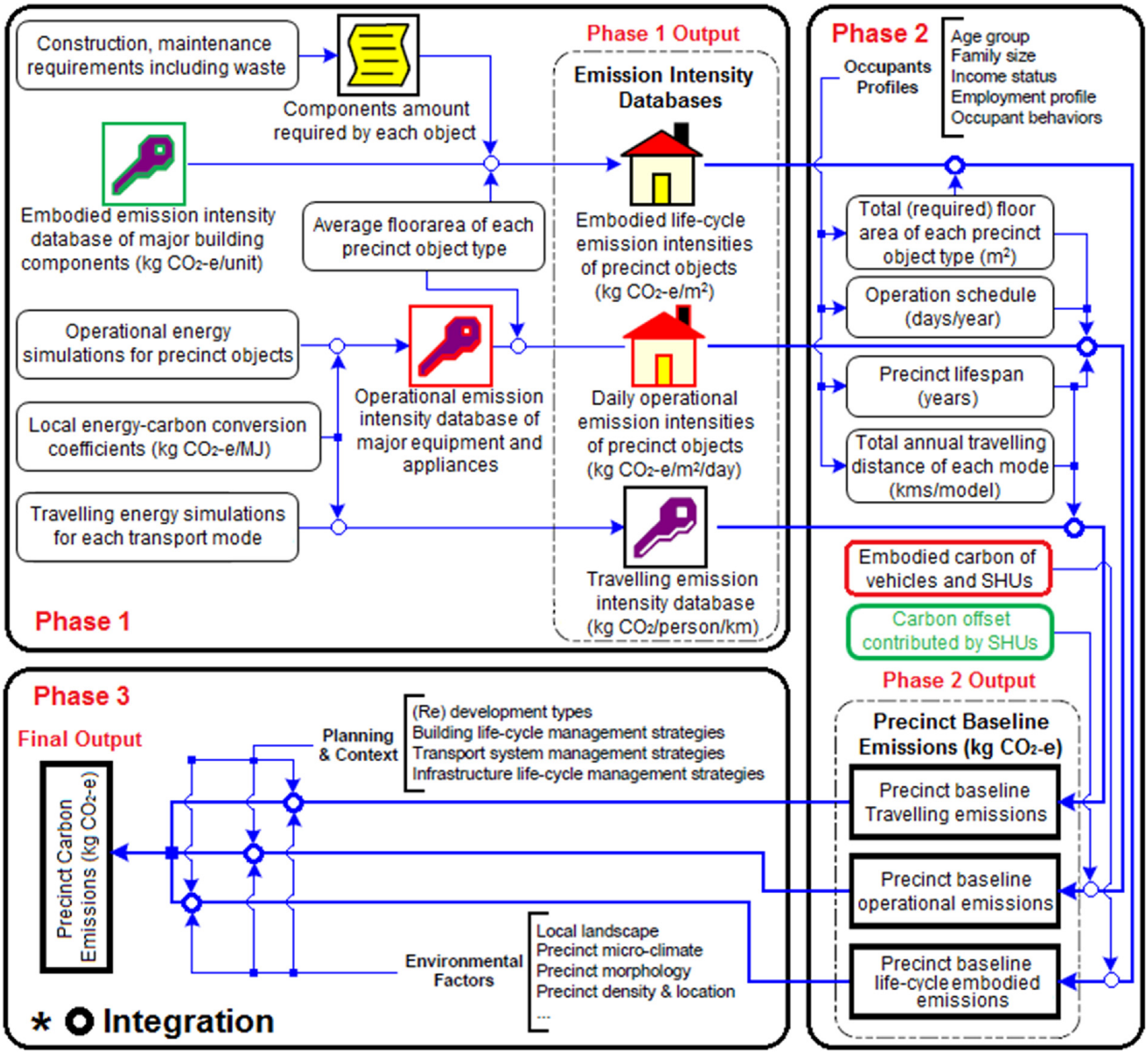

Fig. 2. System framework for carbon evaluation of urban precincts.

that amount of household carbon associated with water heating energy consumption (up to 100%) due to lack of a hot water grid or energy conversion equipment for uploading and sharing.

Phase 3 is developed to improve the accuracy of precinct carbon evaluation. At this stage, the real precinct morphology or master plan of an urban precinct is transformed into a notional grid using models proposed in previous studies [54]. Characteristic parameters such as urban density, obstruction angles and solar potential are then identified. With the morphological impacts identified by existing studies, which are mainly focused on the relationships between obstruction angles and operational energy consumption, daylight ability and solar energy harvest, population density and travelling energy consumption, the morphological factors of precincts are then determined. Finally, those factors are applied to adjust the baseline carbon balance to improve the assessment results.

4.2. Model formulation

As discussed in previous sections, the precinct-scale model proposed in this paper measures emissions generated by precinct objects and occupant travelling, as well as the offsetting amount contributed by SHUs. The precinct baseline carbon (B_{PC}) composed of embodied (B_{EC}), operational (B_{OC}) and travelling (B_{TC}) emissions then can be measured as:

$$B_{PC} = B_{EC} + B_{OC} + B_{TC} = \Big(\sum_{i=1}^{n}\big(A_i \times ECI_i \times \frac{L_{pc}}{L_{bi}}\big) + EC_{stw} + EC_{pv} + (ECI_t \times L_{pc} \times pop_{size})\Big) + \Big(\sum_{i=1}^{n} OEI_i \times A_i \times \varepsilon - OE_{off-stw} \times \varepsilon - OE_{off-pv} \times \varepsilon_e\Big) + TOC \qquad (1)$$

In this equation, ECI_i is the life-cycle embodied carbon intensity of precinct object type i and TOC is the occupants travelling carbon expenditure over the expected lifespan of the urban precinct. Referring to the models developed at the early stage of this research, these parameters can be obtained by replacing the energy intensities of components with the relevant carbon contents [12]. OEI_i which is the operational energy intensity of precinct object type i, can also be measured using the model proposed in the above reference. A_i and L_{bi} denote the total floor area and lifespan of precinct object type i. ECI_t and pop_{size} are the annual per capita travelling embodied carbon intensity and precinct population size. L_{pc}, ε and ε_e represent the lifespan of precinct, energy-to-carbon and electricity-to-carbon conversion coefficients (kg CO_2-e/MJ), respectively. Since mixed energy types are consumed and multiple sources are employed for electricity production, ε and ε_e are mean values determined by the local energy production.

EC_{stw} and EC_{pv} are the carbon embodied in the manufacturing, installation and maintenance of STW and PV systems, which can be identified with the model in Eq. (2) and 3.

$$EC_{stw} = Q_{ph} \times \tau_{stw} \times (\lceil \frac{L_{pc}}{L_{stw}} \rceil \times (\sum_{i=1}^{4} EC_{stwc-i} + EC_{Ins} + EC_{stwd}$$

$$+EC_{stwt}) - \lceil \frac{L_{pc}}{C_{y-m}} \rceil \times EC_{stwm}) \tag{2}$$

Hereby, Q_{ph} and τ_{stw} denote the amount of households in precincts and the installation ratio expressed as percent of household. Factors EC_{stwc-i},EC_{Ins},EC_{stwd}, EC_{stwt} and EC_{stwm} represent carbon embodied in components, as well as activities such as installation, disposal and recycle, transportation and maintenance. L_{stw} is the lifespan of STW system, while C_{y-m} is the service cycle.

$$EC_{pv} = A_{Sp} \times (ECI_{Sp} \times \lceil \frac{L_{pc}}{L_{Sp}} \rceil + ECI_{BoS} \times \lceil \frac{L_{pc}}{L_{Bos}} \rceil + ECI_{Ins}$$

$$\times \lceil \frac{L_{pc}}{C_{y-Ins}} \rceil + ECI_{O\&M} \times \lceil \frac{L_{pc}}{C_{y-O\&M}} \rceil) \tag{3}$$

Subscripts *Sp*, *BoS, Ins* and *O&M* refer to solar panel, balance of system, installation, as well as operation and maintenance, respectively. L and C_{y-} stand for lifespan and service cycle. A_{Sp} is the total PV panel area installed at precinct (m^2), while *ECI* denotes the embodied energy content expressed as per m^2 of solar panel. Details about embodied carbon of STW and PV systems, as well as their system features can be found in Appendix A and B.

$OE_{off-stw}$ and OE_{off-pv} are the amount of energy generated by STW and PV systems, which are further explained in Eq. (4) and (5).

$$OE_{off-stw} = Q_{ph} \times \tau_{stw} \times L_{pc} \times EI_{wh} \times q_r \times \eta_{stw} \tag{4}$$

In this equation, EI_{wh} is the water heating energy content (MJ/L), q_r indicates the annual household hot water demand (L/year), while η_{stw} stands for the energy efficiency of STW systems.

$$OE_{off-pv} = A_{Sp} \times EI_{Sr} \times \eta_{Sc} \times \left(1 - \tau_{Sys} \times \tau_{Net}\right) \times L_{pc} \tag{5}$$

Hereby, EI_{Sr} is the annual solar radiation per m^2 (MJ/m^2), η_{Sc}, τ_{Sys} and τ_{Net} stand for the energy efficiency of solar cells, as well as the energy loss (%) of PV systems and local electricity grid.

The emissions of urban precincts (C_{pc}) with the consideration of morphological factors can then be expressed as:

$$C_{pc} = \sum_{i=1}^{n} A_i \times (ECI_i + [OCI_{i-l} OCI_{i-hvac}][\mu_l \ \mu_{hvac}]^T + OCI_{i-ap}$$

$$+OCI_{i-infr}) + (ECI_t \times L_{pc} \times pop_{size}) + EC_{stw} + EC_{pv}$$

$$+TOC \times \mu_t - (OE_{off-stw} \times \varepsilon + OE_{off-pv} \times \varepsilon_e) \times \mu_{sp} \tag{6}$$

In this equation, OCI_{i-l}, OCI_{i-hvac}, OCI_{i-ap} and OCI_{i-infr} represent the emission intensities associated with the operation of artificial lighting. μ_l, μ_{hvac}, μ_t and μ_{sp} are the morphological factors of precinct.μ_{sp} denotes the solar potential of the precinct and can be either identified using the solar potential map developed by the Australian PV Institute (APVI) [55] or by simulations.

In order to support the evaluation of precinct carbon performance at the planning stage when information is normally scarce, for precinct object type (i), the required floor area of each residential dwelling type (A_i) can be estimated based on parameters such as age group, income and family size of occupants, as well as the average per capita occupant floor area of each dwelling type. While the required floor area of non-residential buildings and infrastructure is predicted based on their functions, occupants' employment profile, local land use regulations and precinct density.

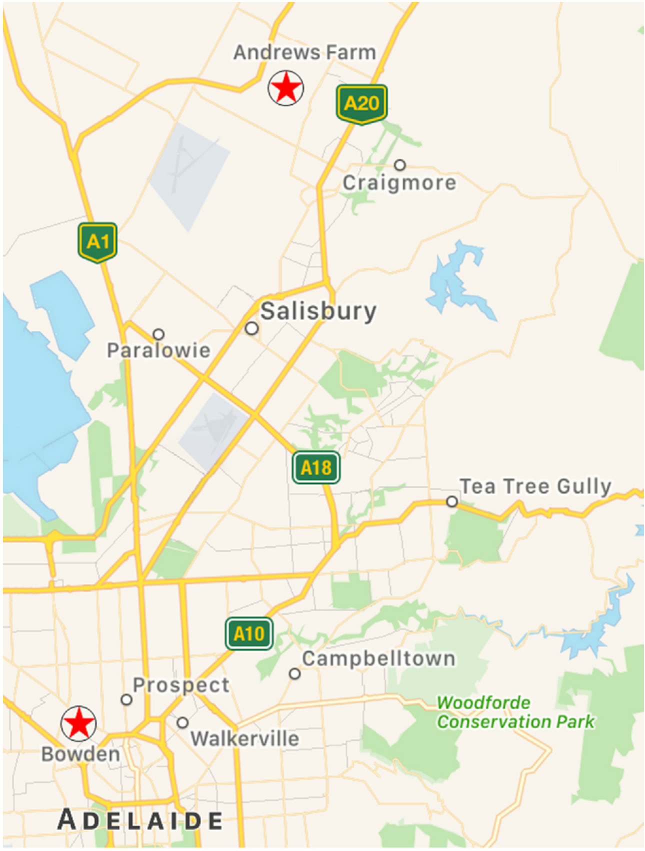

Fig. 3. The case study precincts.

5. Case studies and comparative analysis

In order to demonstrate applications of the precinct carbon assessment model and to highlight which inputs most significantly affect the precinct carbon balance, case studies considering an inner suburb and an outer suburb in Adelaide, South Australia are conducted in this research. Comparative analysis between these two studied precincts is carried out to explore the significance of different parameters, especially urban morphological factors on precinct carbon emissions.

5.1. Case contexts

The selection of precincts for case studies and model demonstration is guided by factors such as precinct morphology, employment profile, location and dwelling types. As an established inner city suburb in South Australia, Bowden appears to be a representative option for the carbon assessment of inner precincts with its geographical, morphological and demographical features. Founded in 1839, Bowden is part of Hindmarsh Ward in the City of Charles Sturt, located about 5 km northwest to the city centre of Adelaide – the capital city of South Australia (as shown in Fig. 3). Being an early-developed suburb, Bowden has been undergoing an urban renewal for transit-oriented development (TOD) and has a very

Table 2
Dwelling and infrastructure types and amounts in precincts.

Precinct dwelling and infrastructure types	Bowden		Andrews Farm	
	Amount	Total area/length	Amount	Total area/length
Detached house	948	147,888.00 m^2	2073	472,644.00 m^2
Townhouse	940	136,582.00 m^2	32	6,208.00 m^2
Apartment	23	7,388.00 m^2	0	0.00 m^2
Dwellings	1911	291,858.00 m^2	2105	478,852.00 m^2
Hospital (estimated)	–	3,026.00 m^2	–	4,736.00 m^2
Office (estimated)	–	16,604.00 m^2	–	24,053.00 m^2
Commercial (estimated)	–	27,594.00 m^2	–	43,182.00 m^2
Schools (estimated)	–	7,004.00 m^2	–	18,345.00 m^2
Roads network	–	194,874.50 m^2	–	370,237.20 m^2
Pipe network	–	51,730.00 m	–	66,635.00 m
Electrical network	–	51,730.00 m	–	66,635.00 m
Driveway	–	102,416.00 m^2	–	74,908.80 m^2
Footpath	–	44,902.00 m^2	–	95,755.00 m^2
Amount of solar water heater	200		238	
Amount of solar PV (Pieces)	4426	7,303.00 m^2	9810	16,187.00 m^2

efficient access to various public transport links, including trains, trams and buses. In addition, its rectangular shaped land area makes the precinct very convenient for carbon intensity and land-size based carbon measurement. Despite the majority of the dwellings in Australia being separate houses (around 70.0%), Bowden is profiled with high–density townhouses and apartments [56].

The other precinct examined in this study is Andrews Farm. Founded in 1991, Andrews Farm is an outer northern suburb in Adelaide (approximately 30 km away from the CBD area) and a subdivision in the Munno Para Council with a rectangular shaped land area. This suburb predominantly consists of dwellings, which are mostly detached single-storey houses, and has the population profiles highly representative of typical Australian outer-metropolitan suburbs, according to the data from the Australian census in 2011. Furthermore, this particular residential area situates within the Adelaide Northern Rail Corridor and has local bus services to a nearby major rail station (about 3.5 km). Whilst the majority of the households still travel by private cars, the suburb has the potential for an improved access to use public transport facilities for low carbon commuting, which forms an essential part of TOD for future urban planning.

5.2. Profiles of the selected precincts

The selected area for study is the inner suburb Bowden which has an overall land area of 255 ha, with its geographical boundary defined by Torrens Road in the east, Wood Avenue and Blight Street in the north, Port Road and a railway line in the west, and Park Terrace in the south. As for Andrews Farm, it has the Northern Expressway, Curtis Road, Stebonheath Road and Petherton Road around its borders and has an overall land size of 273 ha. The available census data shows 4217 residents with 2140 private dwellings (1911 of them were occupied, 49.2% of the dwellings are medium- or high-density types) and a labour force of 2294 (2106 of whom were employed) in Bowden, whilst Andrews Farm has 6244 residents, 2311 private dwellings (2105 of them are occupied, 1.5% of the dwellings are medium- or high-density types) and a labour force of 3062 (2862 of whom are employed) [56]. More detailed profiles of these precincts with respect to object types and amounts, age groups, household structure, car ownership, employment status and mode of commuting are depicted in Tables 2 and 3 and Figs. 4–7. Compared with Bowden, Andrews Farm is much bigger in both land and population sizes, as well as much younger in demography. Around 35% of the local residents in Andrews Farms were under 18 years old, whilst only 14% of Bowden's population were in the same age group. Bowden, however, has a higher percentage of people aged 50 years or above. In terms of household size, Bowden is overrepresented with smaller households of 3 people or less (i.e. 86% of the total), whilst Andrew Farms only has 67% of its households in the same categories. Having younger families in low-density housing also sees Andrew Farms being high in private car ownership, with 91.4% of the households owning at least one motor vehicle and 57.5% having two or more vehicles. In comparison, the residents in Bowden tend to use more public transport (particularly buses and trams) as well as bicycles and walking for commuting, due to its higher-density housing style, TOD features and vicinity to the CBD. The contrasts between these two precincts well suit a comparative analysis on how such geographical, demographical, and morphological differences affect their life-cycle carbon balances.

5.3. Results and discussion

As discussed in previous sections, the precinct carbon balance is derived from combining the baseline carbon emissions (embodied, operational and travelling) and the carbon offsetting contributed by solar harvesting, which are adjusted with the impacts of morphological and occupant life-style factors. The integrated model developed in this research uses carbon intensities in conjunction with morphological factors and occupant choices to measure the embodied and operational carbon emissions at precinct level. In addition, the carbon associated with occupant travelling is assessed based on vehicle embodied carbon and operational emissions concerning fuel type combusted and the efficiency of local traffic network (e.g. speed limits, maximum and minimum speeds). The census data from ABS and APVI [55]; [56] is applied to identify parameters such as amounts and operating schedules of different appliance types, frequencies and travelling distances of various travel modes, installation ratios of SHUs, average working hours of artificial lighting and HVAC systems, as well as population densities. Meanwhile, with density and orientation data obtained, the actual precinct morphologies are converted and analysed as notional grids using the model proposed by reference [54]. Obstruction angles and morphological factors are then identified (as shown in Table 2).

Fig. 7 illustrates the overall embodied, operational and travelling carbon amounts, as well as the total carbon offsetting contributed by SHUs in the studied precincts, amortized over an estimated 60-year lifespan. According to the assessment results, Andrews Farm has a modestly higher life-cycle carbon than that of Bowden due to its size and location. By looking into different carbon measure components, operational carbon clearly represents the largest portion of the total life-cycle carbon balance for both precincts. However, the results also highlight the significance of embodied (including both initial and recurrent) carbon and travelling carbon, which together account for 49.9% and 58% of the overall precinct

Table 3
Morphological profiles and factors.

Parameters and factors	Bowden	Andrews Farm
Precinct land size (ha)	255.00	273.00
Orientation of buildings	About 25% on each direction	East: 24.5%, West: 23.25% South: 25.85%, North: 26.4%
Total perimeter on main orientation (North-south, m)	13,257.20	27,553.75
Total perimeter on second orientation (East-west, m)	31,324.65	66,360.73
Average height of buildings (m)	House: 4.5, Townhouse: 6.60, Apartment: 20.34, non-residential: 11.00	House: 4.5, Townhouse: 6.60, Apartment: 9.30, non-residential: 5.50
Obstruction angle on the N-S axis	5.31°	3.28°
Obstruction angle on the E-W axis	8.04°	4.36°
Population density (persons/acre)	6.69	9.26
Average lighting factors	1.14	1.09
Average heating factors	1.10	1.08
Average cooling factors	0.98	0.99
Average travelling factors	1.89	1.35
Average SHU factors	0.97	0.98

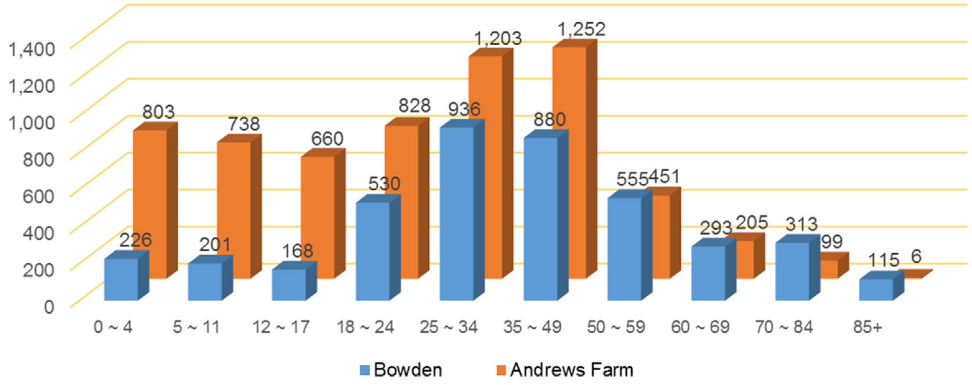

Fig. 4. Precinct age structures.

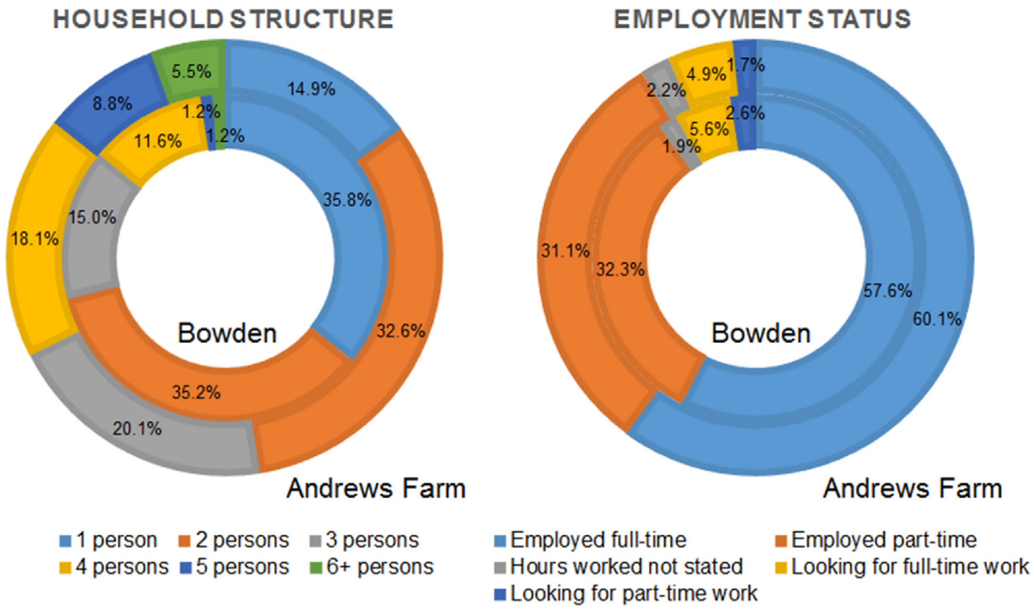

Fig. 5. Precinct household structures and employment status.

carbon in Bowden and Andrews Farm, respectively. Meanwhile, Andrews Farm is considerably higher than Bowden in travelling associated carbon due to the carbon intensive travelling mode of its occupants, compounded with its geographical location and low-density morphology. The limited access to and use of public transport makes the occupants in Andrews Farm highly dependent on private-car commuting, which is evidenced by a much higher private vehicle ownership in Andrews Farm compared with that in Bowden (about 1.50 vehicles per household in Andrews Farm and 1.18 vehicles per household in Bowden). However, the

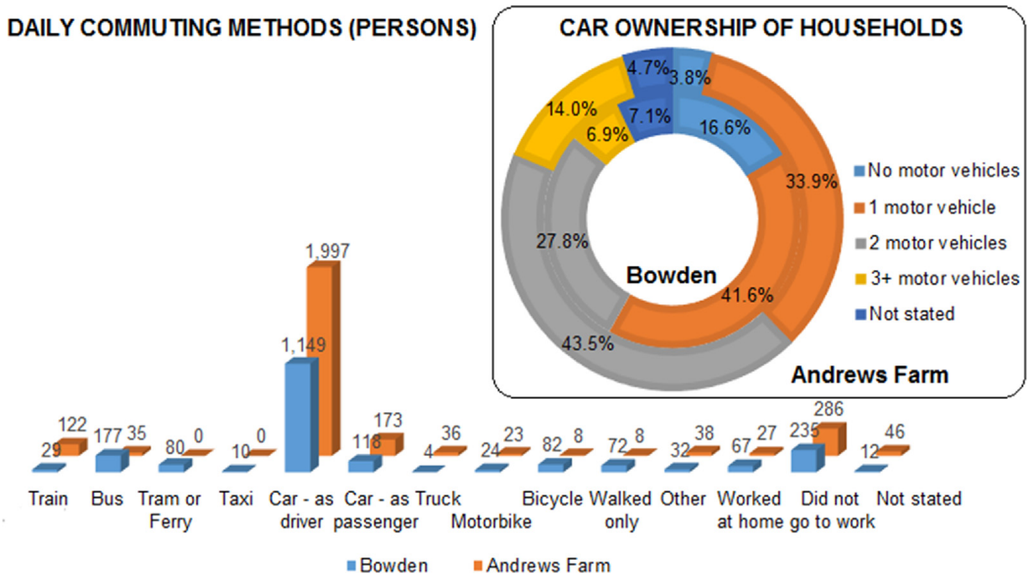

Fig. 6. Car ownership of households and commuting methods.

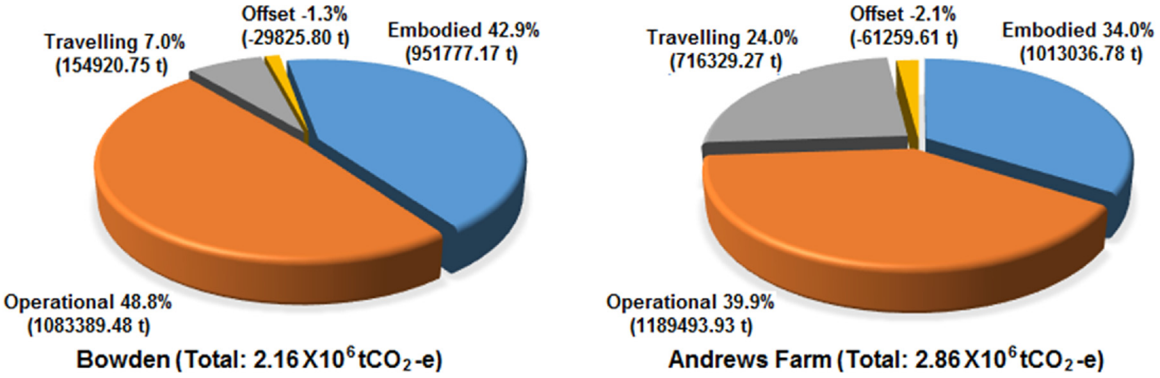

Fig. 7. Life-cycle carbon profiles of precincts.

inner-suburban occupants in Bowden produce more overall operational carbon from artificial lighting, HVACs and appliances. This may be attributed to the demographical and morphological differences (e.g. more elderly residents, more medium- and high-rise buildings, higher density). Solar access and natural ventilation are commonly affected by high-rise high-density dwellings in inner suburbs, which consequently results in higher emissions associated with artificial lighting and HVACs. This can be supported by the morphological factors listed in Table 2. With respect to carbon offsetting, the amount in Andrews Farm is slightly higher than that in Bowden because of more efficient solar harvesting and higher household take-up of SHUs, commonly seen in outer suburbs. According to the Australian national PV market analysis conducted by APVI [55], about 32% of households in Andrews Farm have installed solar PV systems, while the take-up in Bowden is only 20%.

In order to eliminate the influence of precinct population size and household size, comparisons on a per capita basis are also performed. As demonstrated in Fig. 8, the total annual per capita carbon contributed by an inner-suburban occupant in Bowden is just slightly (about 3.0%) lower than that generated by the outer-suburban occupant in Andrews Farm. Differences are also signified by less embodied and travelling carbon accounts, lower carbon offsetting, but higher operational carbon per capita in the inner suburb. This may be attributed to the higher occupancy of high-rise-high-density semi-detached townhouses and apartments (as shown in Table 2) that are less intensive in embodied carbon, the lower ownership of private vehicles (as seen in Fig. 6), relatively more significant inter-buildings effects, as well as shorter travelling distance required and efficient access to public transport.

Based on an estimated lifespan of 60 years and current building standards, the operational carbon associated with the operations of buildings and infrastructure is a main contributor to the total life-cycle carbon, although this amount has been reduced with the improvements of optimal planning, design and control techniques, as well as the application of energy efficient appliances. As shown in Fig. 9, carbon emissions contributed by HVACs are by far the largest component in the operational carbon balances of both precincts. This carbon measure is much affected by precinct morphology and density. The analysis suggests that a high-density precinct produces more HVAC associated emissions than a low-density one under the local climate of South Australia. For non-residential buildings, lighting and hot water supply are major contributors to their operational carbon balances. Correspondingly, solar harvesting and natural light access, which are affected by local climate and urban morphological form, play predominant roles.

Apart from precinct morphology and local climate, employment status is also considered as a critical factor in operational emission assessment. As discussed in the previous section, Bowden is profiled as a high-employment inner suburb. Compared with Andrews Farm, Bowden's lighting and HVAC associated emissions per capita is lower in residential buildings, but higher in offices (as shown in

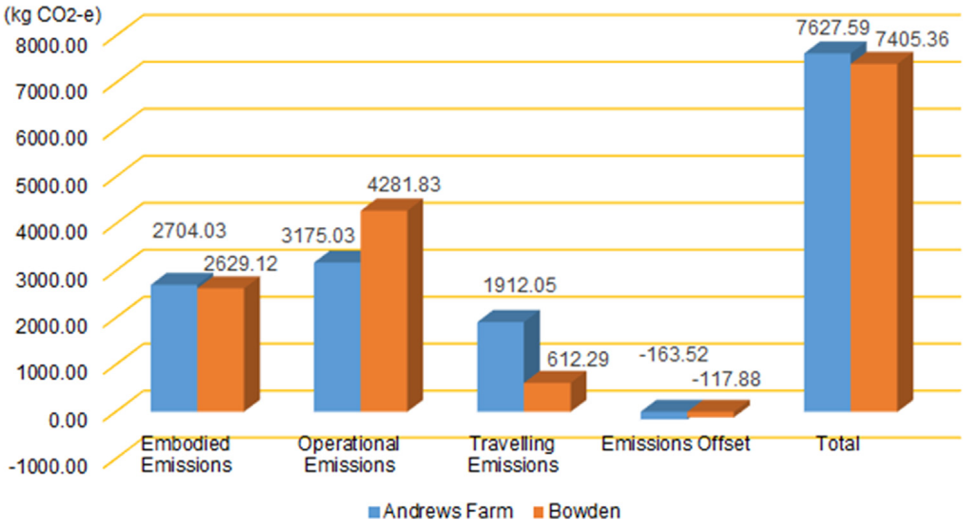

Fig. 8. Per capita annual emissions of precincts.

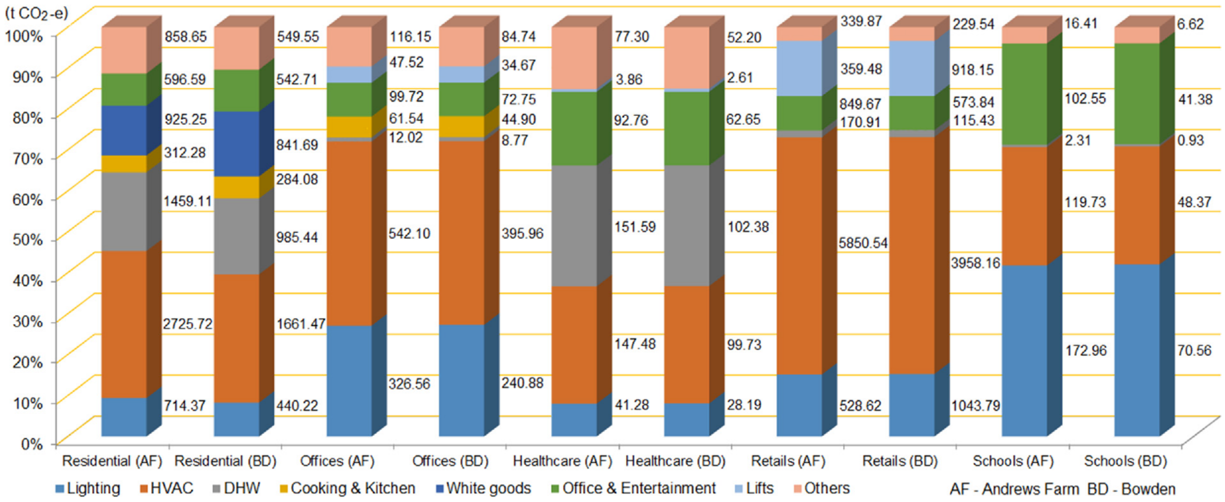

Fig. 9. Breakdown of precincts operational emissions.

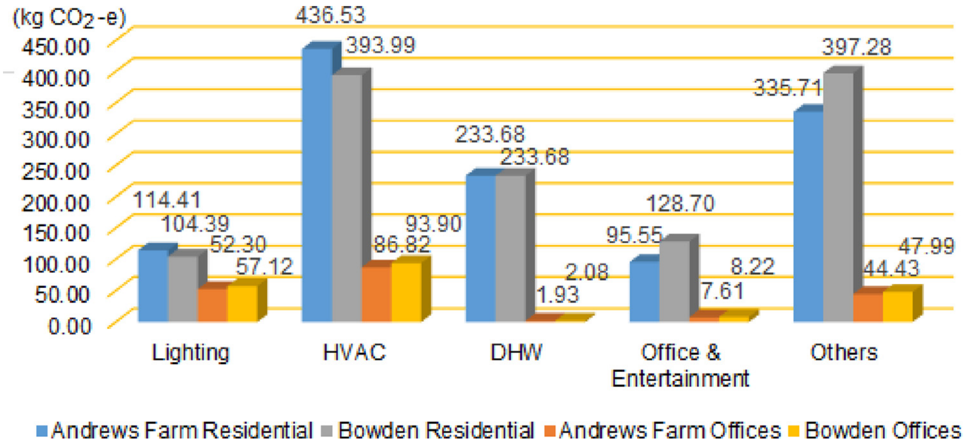

Fig. 10. Per capita annual operational carbon in residential and office use.

Fig. 10). However, there is only a marginal difference between the overall per capita operational emissions of dwellings and offices in these two precincts, i.e. Bowden is about 4.1% higher than Andrews Farm. This may be attributed to the fact that on average inner-suburban dwellings have less occupied hours during a day due to higher employment and therefore lower operational carbon in total, although such dwellings are normally more carbon intensive to operate. With respect to the carbon associated with office oper-

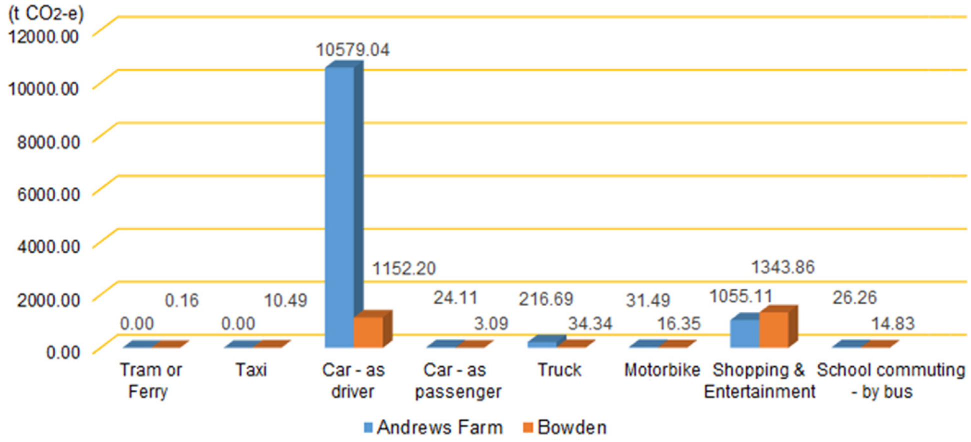

Fig. 11. Breakdown of precincts annual travelling emissions.

ations, it is indicated that inner-suburban occupants apparently contribute more because of a higher occupancy of office buildings.

Occupants' travelling is another major contributor to precinct life-cycle carbon, especially for an outer suburb like Andrews Farm. Despite this suburb having a potential for TOD, the inefficient local access to the public transport system makes the occupants in Andrews Farm highly dependent on travelling in their cars and thus produce a significant amount of travelling carbon (as shown in Fig. 11). Fig. 11 also illustrates that, with a more efficient use of public transport system, Bowden has less than 68.3% of the travelling carbon related to private car use (the annual per capita carbon contributed by private car use in Andrews Farm is 1.87 t CO_2-e, while that in Bowden is just 0.59 t CO_2-e). In addition, it is worth acknowledging that Bowden also has lower travelling embodied carbon than Andrews Farm due to the lower ownership of private cars. Therefore, both availability and utilization of public transport are of great importance in affecting the carbon performance of a precinct.

1.10 Scenario analysis

In this study, it is noted that occupants' travelling carbon, affected by travel mode choices, contributes a significant amount to the precinct carbon balance for both inner and outer suburbs, while renewable energy usage such as solar harvesting has the potential to offset precinct emissions by a significant amount. Therefore, scenario analysis is applied to examine how significantly results and subsequent recommendations of the assessment respond to the following changes in the assumptions and the parameters applied to travel mode choices and coverage of residential PV installations for future planning purposes:.

- *Private car users switching to public transport is increased by 35%*: At present, public transport (bus, tram, train and ferries) carries about 12% of motorised trips in South Australia, which is predicted to experience an average annual growth of 0.55% by 2030 [57]. Therefore a 35% shift to public transport is applied considering a 60-year precinct lifespan.
- *A growth of 90% residential PV installation within the expected precinct lifespan*: A National survey conducted by Australian PV Institute indicates that between 2001 and 2010 the growth in the Australian market for solar PV is around 15% [58]. A period of extremely rapid growth occurred between 2010 and 2013. Therefore a conservative estimation of 90% increase is employed in this scenario analysis.

Based on the assumed scenarios, the model suggests that shifting 35% of travelling from using private cars to using public/alternative transport modes and increasing residential PV installation ratio to 90% could lead to an overall annual carbon reduction up to 9.0% in Andrews Farm and 2.2% in Bowden (see Fig. 12). Increasing the use of public transport to 35% would contribute about 15.1% reduction to travelling carbon in Bowden, while in Andrews Farm such a reduction would be as significant as 30.4% (15.3% higher than that of Bowden). Meanwhile, a growth of 90% in residential PV installation would contribute to the carbon offsetting of up to 81.7% in Andrews Farm and 75.7% in Bowden, despite that this would cause 1.1% and 0.7% increase in embodied carbon for the respective precincts. This could be attributed to the relatively lower solar potential in a high-density inner suburb. The overall results also indicate that outer-suburban living can be potentially more carbon efficient, with the increase of renewable energy use and the decrease of car dependence.

6. Conclusions and future research

This paper presents a model for the integrated assessment of precinct carbon performance which takes into account carbon offsetting as well as interplays among precinct objects, precinct morphology, and resident life-styles. The application of the model is demonstrated through comparative case studies and scenario analysis to examine the carbon performance of urban precincts under various contexts. The following indicative results summarised from this study can serve to inform and provide a basis for further studies in precinct carbon assessment and future planning for precinct development:

- The advantage of having predetermined carbon intensity data is that it enables a quick assessment and does not require a user to possess expert knowledge. Furthermore, the process-based intensity data can also represent carbon profiles of precinct objects in a straightforward manner. However, the use of intensities in modelling is limited by their availabilities, especially for those service related data which is difficult to be measured and represented by processes. In addition, the overall carbon intensities of precinct objects are often affected by the accumulative errors from the substantial variations in demand/quantity and intensity data of building materials. Therefore, in future studies an improved data strategy and statistical analysis are suggested to enhance the quality of intensity data as well as the evaluation of results.
- The findings from case studies indicate that occupants' travelling remains a major contributor of outer suburban carbon emissions. Despite being planned with a potential for TOD, Andrews Farm is still largely characterised as a highly car-dependent precinct. This may be related to both the life styles of the occupants preferring

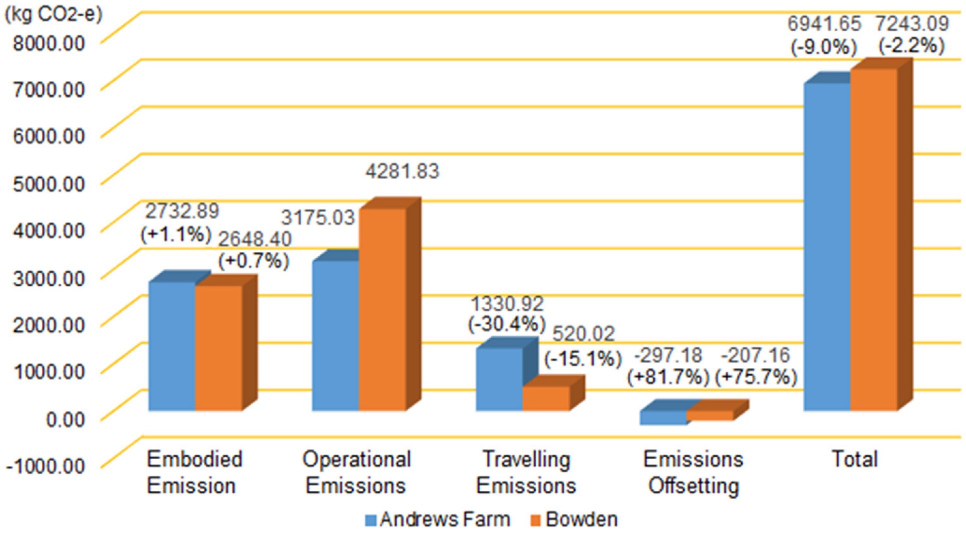

Fig. 12. Precincts per capita annual emissions (with changes in travel and SHU profiles).

to drive and the inefficient access to public transport systems for mobility. Therefore, significant effort and investments for behavioural changes and improved local public transport infrastructure and services are crucial for an outer suburb like Andrews Farm to achieve carbon reduction.

- On a per capita basis, the case studies extrapolate that outer-suburban occupants have higher embodied and travelling carbon but lower operational carbon than inner-suburb counterparts. While improving efficiency and coverage of public transport systems is critical for low carbon living in outer suburbs, for inner suburbs an optimal plan to moderate inter-building effects for abating the energy use for artificial lighting and HVACs and increasing solar harvesting is of great importance to carbon reduction. Also, the preliminary results indicate only a slight increase in total per capita emissions for the outer compared with inner suburban case studies. Given that highly densified inner suburbs are generally believed to be more sustainable than low-density outer suburbs, this tentative finding suggests some further research to validate the results is required, including a sensitivity analysis when different data methods and data sources are applied.
- The scenario analysis suggests that solar harvesting using solar water heating systems and PVs can offset precinct carbon emissions by a significant amount. Optimal planning on precinct morphology can support an increased efficiency of solar harvesting as well as deployment of renewable energy systems. A further point raised from the scenario analysis is that changes in travel modes and PV installations disproportionately benefit outer low-density suburbs in lowering their carbon emissions (per capita). This suggests that the carbon performance of these suburbs can be significantly improved without major redevelopment and densification. In addition, outer suburbs have the potential to be more carbon efficient with a more extensive adoption of renewable energy and a stronger shift to public transport utilisation.

With the development of energy storage technologies, off-grid energy storage systems such as batteries and phase change material (PCM) based systems, there is potential application in renewable energy storage for households. Energy storage at a precinct scale can contribute to the cost reduction of grid upgrade and maintenance, which would correspondingly boost the installation of SHUs. Future studies will focus on the carbon performance evaluation of off-grid energy storage systems. Moreover, the proposed model can be applied to compare precinct scenarios in different studies and reduce the overall carbon emissions by supporting optimal redevelopment of urban precincts. Therefore, further scenarios will be examined for a comprehensive understanding of precinct carbon performance, which might contribute to the optimal planning of urban precincts. Meanwhile, due to the lack of in-detail and sufficient data, the operational carbon of infrastructure (such as water and waste) as well as the influence of occupant behaviours on infrastructure deployment and operations at the precinct level are not covered in depth at the current stage. These aspects also remain as part of the focus for further research and model refinement.

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Appendix A. Embodied carbon contents and features of rooftop STW systems

(Based on references [53] and [59])

Description	Embodied carbon (kg CO2-e)	System features
Solar thermal collector	143.59	Two-panel system with the solar collector area of 2.13 m^2 and the water tank capacity of 160L for a four-people family.
Insulation	24.52	
Glass	7.35	
Copper pipes	41.42	
Galvanized steel sheet	13.88	
Rubber sealant	2.67	Lifespan of the STW system: 15 years Maintenance cycle: 4–5 years Overall system efficiency: 30–40%
Black paint	0.64	
Casing paint	1.94	
Screws	0.00	
Copper absorber	12.38	
Add 10% contingencies	10.48	
Waste rate (about 27%)	28.3	
Water tank (160 L)	289.08	
Copper pipe	17.63	
Steel frame	68.59	
Transport	45.99	
Installation	20.21	
Maintenance	87.38	
Disposal	1.55	

Appendix B. Embodied carbon content of rooftop PV systems

(Based on references [28] and [60])

Description	Embodied carbon (kg CO2-e/m2)	Lifespan (years)
PV panel production	151.01	30
Extraction and refining	0.80	30
Silicon purification & processing	83.57	30
Casting & wafer production	25.93	30
Chemical attack & texturing	2.14	30
Film formation	5.77	30
Electrical contacts, passivation & arc	5.23	30
Panel assembling	27.57	30
BoS system (no battery)	92.49	60
Support structure	47.30	60
Inverter & transformer	7.81	30
Battery	10.88	5–7
Overall waste, cables etc.	29.57	60
Installation	47.30	60
System operation and maintenance	29.57	4–5

References

[1] S. Barles, Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues, J. Environ. Plann. Man. 53 (2010) 439–455.

[2] CO_2 Emissions from Fuel Combustion Highlights, International Energy Agency, Paris, 2015.

[3] Australia Government Report, Annual Report 2011- 2012, 2012 (Canberra).

[4] A. Druckman, T. Jackson, Analyse the carbon footprint of UK households 1990–2004: a socio-economically disaggregated quasi-multi-regional input-output model, Ecol. Econ. 68 (2009) 2066–2077.

[5] Methodology Determinations, Department of the Environment, Canberra, 2014.

[6] F.H. Abanda, J.H.M. Tah, F.K.T. Cheung, Mathematical modelling of embodied energy, greenhouse gases, waste, time-cost parameters of building projects: a review, Build. Environ. 59 (2013) 23–37.

[7] A.F. Marique, S. Dujardin, J. Teller, S. Reiter, School commuting: the relationship between energy consumption and urban form, J. Transp. Geogr. 26 (2013) 1–11.

[8] B. Huang, K. Xing, S. Pullen, Life-cycle energy modelling for urban precinct systems, J. Clean. Prod. 142 (2017) 3254–3268.

[9] G.P. Gerilla, K. Teknomo, K. Hokao, An environmental assessment of wood and steel reinforced concrete housing construction, Build. Environ. 42 (2007) 2778–2784.

[10] P. Newton, D. Marchant, J. Mitchell, J. Plume, S. Seo, R. Roggema, Performance Assessment of Urban Precinct Design: a Scoping Study, CRC for Low Carbon Living, 2013.

[11] R. Trubka, S. Glackin, O. Lade, C. Pettit, A web-based 3D visualisation and assessment system for urban precinct scenario modelling, ISPRS. J. Photogramm. 117 (2016) 175–186.

[12] B. Huang, K. Xing, S. Pullen, Energy and carbon performance evaluation for buildings and urban precincts: review and a new modelling concept, J. Clean. Prod. (2015) 1–12, http://dx.doi.org/10.1016/j.jclepro.2015.12.008.

[13] ISO (International Organization for Standardization), ISO 14040: Environmental Management–Life Cycle Assessment–Principles and Framework, 2006.

[14] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs embodied emissions in buildings —a review of current trends, Energy Build. 66 (2013) 232–245.

[15] M. Karimpour, M. Belusko, K. Xing, F. Bruno, Minimising the life cycle energy of buildings: review and analysis, Build. Environ. 73 (2014) 106–114.

[16] J. Monahan, J.C. Powell, An embodied carbon and energy analysis of modern methods of construction in housing: a case study using a lifecycle assessment framework, Energy Build. 43 (2011) 179–188.

[17] M.J. González, J.G. Navarro, Assessment of the decrease of CO2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact, Build. Environ. 41 (2006) 902–909.

[18] M. Wallhagen, M. Glaumann, T. Malmqvist, Basic building life cycle calculations to decrease contribution to climate change e case study on an office building in Sweden, Build. Environ. 46 (2011) 1863–1871.

[19] D. Bourgeois, C. Reinhart, I. Macdonald, Adding advanced behavioural models in whole building energy simulation: a study on the total energy impact of manual and automated lighting control, Energy Build. 38 (2006) 814–823.

[20] Navigating the Numbers: Greenhouse Gas Data and International Climate Policy, World Resource Institute, Washington, DC, 2009.

[21] J.K. Stanley, D.A. Hensher, C. Loader, Road transport and climate changes: stepping off the greenhouse gas, Transport. Res. A-Pol. 45 (2011) 1020–1030.

[22] Australia's National Greenhouse Accounts: National Greenhouse Gas Inventory Accounting for the Kyoto Target, Department of Climate Change and Energy Efficiency, Canberra, 2009.

[23] M. Lenzen, Total requirements of energy and greenhouse gases for Australian transport, Transport. Res. D-Tr. E. 4 (1999) 265–290.

[24] A. Perkins, S. Hamnett, S. Pullen, R. Zito, D. Trebilcock, Transport, housing and urban form: the life cycle energy consumption and emissions of city centre apartments compared with suburban dwellings, Urban Policy Res. 27 (2009) 377–396.

[25] T. Beer, T. Grant, D. Williams, H. Watson, Fuel-cycle greenhouse gas emissions from alternative fuel in Australian heavy vehicles, Atmos. Environ. 36 (2002) 753–763.

[26] S. Dujardin, F. Pirart, F. Brévers, A.F. Marique, J. Teller, Home-to-work commuting, urban form and potential energy savings: a local scale approach to the regional statistics, Transport. Res. A-Pol. 46 (2012) 1054–1065.

[27] J. Kanters, M. Horvat, Solar energy as a design parameter in urban planning, Enrgy. Proced. 30 (2012) 1143–1152.

[28] I. Nawaz, G.N. Tiwari, Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level, Energ. Policy 34 (2006) 3144–3152.

[29] S. Kalogirou, Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters, Sol. Energy 83 (2009) 39–48.

[30] A. Stoppato, Life cycle assessment of photovoltaic electricity generation, Energy 33 (2008) 224–232.

[31] P.W.G. Newman, J.R. Kenworthy, Gasoline consumption and cities: a comparison of US cities with a global survey, J. Am. Plann. Assoc. 55 (1989) 24–37.

[32] K. Steemers, Energy and the city: density, buildings and transport, Energy Build. 35 (2003) 3–14.

[33] J. Ma, Z. Liu, Y. Chai, The impact of urban form on CO_2 emission from work and non-work trips: the case of Beijing China, Habitat Int. 47 (2015) 1–10.

[34] J. Zhang, et al., Evaluating environmental implications of density: a comparative case study on the relationship between density, urban block typology and sky exposure, Automat. Constr. 22 (2012) 90–101.

[35] M. Raynolds, R. Fraser, M.D. Checkel, The relative mass-energy-economic method for system boundary selection Part 1: a means to systematically and quantitatively select LCA boundaries, Int. J. Life Cycle Ass. 5 (2000) 37–46.

[36] M.K. Dixit, C.H. Culp, J.L. Fernández-Solís, System boundary for embodied energy in buildings: a conceptual model for definition, Renew. Sustainable Energy Rev. 21 (2013) 153–164.

[37] S. Suh, et al., System boundary selection in life-cycle inventories using hybrid approaches, Environ. Sci. Technol. 38 (2004) 657–664.

[38] W. Leontief, Environmental repercussions and the economic structure: an input-output approach, Rev. Econ. Stat. 52 (1970) 262–271.

[39] G.J. Treloar, Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method, Econ. Syst. Res. 9 (1997) 375–391.

[40] M. Lenzen, Errors in conventional and input-output-based life-cycle inventories, J. Ind. Ecol. 4 (2000) 127–148.

[41] G. Majeau-Bettez, A.H. Strømman, E.G. Hertwich, Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues, Environ. Sci. Technol. 45 (2011) 10170–10177.

[42] R.H. Crawford, Validation of a hybrid Life–Cycle inventory analysis method, J. Environ. Manage. 88 (2008) 496–506.

[43] A. Stephan, R.H. Crawford, K.D. Myttenaere, A comprehensive assessment of the life cycle energy demand of passive houses, Appl. Energy 112 (2013) 23–34.

[44] J. Norman, H.L. MacLean, C.A. Kennedy, Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions, J. Urban Plann. Dev. 132 (2006) 10–21.

[45] B. Brekke, E.H. Hansen, Energy saving in lighting installations by the utilization of daylight, Proc. Right Light 3 (1995) 875–886.

[46] R. Embrechts, V.C. Bellegem, Increased energy savings by individual light control, In: proceedings of Right Light 4, Copenhagen (1997) 179–182.

[47] D.R.G. Hunt, Improved daylight data for predicting energy savings from photoelectric controls, Light. Res. Technol. 41 (1979) 261–283.

[48] M. Bodart, A.D. Herde, Global energy savings in offices buildings by the use of daylighting, Energy Build. 34 (2002) 421–429.

[49] A. Tzempelikos, A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand, Sol. Energy 81 (2007) 369–382.

[50] R. Pacheco, J. Ordóñez, G. Martínez, Energy efficient design of building: a review, Renew. Sustain. Energy Rev. 16 (2012) 3559–3573.

[51] Intergovernmental Panel on Climate Change, Publications and Data, 2006, http://www.ipcc.ch/publications_and_data/publications_and_data.shtml.

[52] Australian Energy Update, Department of Industry and Science, Canberra, 2015, http://www.industry.gov.au/Office-of-the-Chief-Economist/Pages/default.aspx.

[53] F. Ardente, G. Beccali, M. Cellura, V.L. Brano, Life cycle assessment of a solar thermal collector, Renew, Energy 30 (2005) 1031–1054.

[54] J. Rodríguez-Álvarez, Urban Energy Index for Buildings (UEIB): A new method to evaluate the effect of urban form on buildings' energy demand, Landsc. Urban Plan. 148 (2016) 170–187.

[55] Live Solar Potential Tool, Australia PV Institute, 2016, http://pv-map.apvi.org.au/potential.

[56] Australian Bureau of Statistics, ABS. Stat BETA. B31 Dwelling Structure, 2011 (http://stat.abs.gov.au/).

[57] Transport and Regional Economics, Public Transport Use in Australia's Capital Cities: Modelling and Forecasting (Report 129), Bureau of Infrastructure, Canberra, 2013.
[58] W. Johnston, R. Egan, PV in Australia Report 2015, APVI (Australia PV Institute), 2016.
[59] R. Battisti, A. Corrado, Environmental assessment of solar thermal collectors with integrated water storage, J. Clean. Prod. 13 (2005) 1295–1300.
[60] A.F. Sherwani, J.A.U. Varun, Life cycle assessment of solar PV based electricity generation systems: a review Renew, Sustainable Energy Rev. 14 (2010) 540–544.
[61] M. Bilec, R. Ries, H.S. Matthews, A.L. Sharrard, Example of a hybrid life-Cycle assessment of construction processes, J. Infrastruct Syst 12 (2006) 207–216.
[62] N. Howard, Environmental assessment/rating–Have we lost the plot? in: SBE16 International High-Performance Built Environment Conference, Sydney, November 17–18, 2016.
[63] S. Junnila, A. Horvath, A.A. Guggemos, Life-cycle assessment of office buildings in Europe and the United States J. Infrastruct. Syst. 12 (2006) 10–17.