



Assessing the greenhouse gas mitigation potential of urban precincts with hybrid life cycle assessment

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ABSTRACT

As the critical link between individual building and city, precinct represents an important scale for urban planning, at which low-carbon strategies for urban built environment can be tested and measured. However, previous studies often failed to assess the life cycle greenhouse gas (GHG) emissions from the urban precincts comprehensively and reliably due to methodological and data-related limitations. This study is conceived to bridge this gap by applying a case-specific hybrid life cycle assessment (LCA) to a typical residential precinct including buildings, open spaces, network, on-site energy units and occupant-related mobility. Meanwhile, the corresponding conventional process-based LCA is conducted alongside to quantify the impact of applying different LCA approaches. For the whole precinct, the life cycle GHG emissions from hybrid LCA is 16% higher than its corresponding process-based LCA result, reaching 16.6 t CO₂e/inhabitant/year. Embodied emissions, operational emissions and occupant-related transport emissions take up 28%, 32% and 40% of the life cycle GHG emissions, respectively, and the biggest difference between these two LCA approaches is seen in embodied emissions (22%), followed by transport emissions (17%) and operational emissions (11%).

Assuming no technology innovation and substantial changes in economic structure, precinct design and lifestyle are involved, twelve GHG emissions mitigation measures are quantified. While process-based LCA suggests a mitigation potential of 35%, hybrid LCA results in a reduction of 31%. The most effective measures are related to reducing transport emissions and operational emissions, but for the embodied emissions, instead of reducing them, the combination of all measures brings about a slight increase both absolutely and relatively. From base case to mitigated case, the differences between two LCA approaches are enlarged and the biggest difference is always seen in embodied emission. This implies the process-based LCA would further underestimate the life cycle GHG emissions in mitigated case, therefore, the use of hybrid LCA is more favourable for the purpose of providing a comprehensive and reliable assessment.

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1. Introduction

Globally, the urban built environment is responsible for more than 70% of energy consumption and greenhouse gas (GHG) emissions, mainly attributed to housing and transport activities of urban dwellers (International Energy Agency, 2018; The World Bank, 2010). This number is likely to increase because the share of population living in urban areas is expected to reach 68% by 2050 (United Nations, 2019). In order to inform the decarbonization of

the built environment, numerous studies have been conducted for decades to analyse the GHG emissions from the built environment across scales (Newton et al., 2019).

While the GHG emissions have been studied extensively at both the building as well as the city scale (Chen et al., 2019; Ottelin et al., 2019), this cannot be said for the interim level of urban precincts (Huang et al., 2017b; Sharifi and Murayama, 2013). At this scale, individual buildings as well as other built environment objects and flows including open spaces (road, green spaces), networks (water, sewerage, electricity, gas, telecommunications) and mobility can be assessed holistically to present a more comprehensive and accurate GHG emissions profile (Lotteau et al., 2015; Thomson et al., 2019). Similar to building-level assessment, life cycle assessment (LCA) is

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the predominantly adopted methodology to assess the GHG emissions from an urban precinct for the whole duration of its lifecycle (Newton, 2019; Xing et al., 2019). But on the other hand, a comprehensive precinct-level assessment should have a much broader scope encompassing three distinct but inter-linked components: 1) embodied emissions that are associated with the construction, maintenance and end-of-life treatment of all precinct objects; 2) operational emissions that are generated from the operation of all precinct objects; 3) occupant-related transport emissions that are generated from daily commuting, business trips and personal travels (Huang et al., 2017a, b; Stephan et al., 2013).

By examining the studies and tools made for precinct-scale emissions assessment, several methodological challenges have been identified which can significantly affect the comprehensiveness, comparability and reliability of the assessment (Xing et al., 2019). Firstly, the scope definition is depending on the selection of precinct objects (i.e. buildings, open space, networks and mobility), the contributing elements of each object (e.g. road and footpath of open space), and the life cycle stages (i.e. construction, operation, maintenance and end-of-life). Very few studies have taken all precinct objects, elements and life cycle stages into account, which may potentially result in unfair contribution analysis (Lotteau et al., 2015; Rasmussen et al., 2018). Secondly, as an integral part of LCA, the availability of representative, complete, consistent and transparent data inputs for life cycle inventory (LCI) analysis has always been a challenging task. Most studies choose to collect or use background LCI data from a mixture of sources including precinct assessment tools (e.g. Mutoxia, PrecinX, eTool, etc), LCI databases (e.g. Ecoinvent, Environmental Product Declarations, ICE, ELCD, BEES, etc.), government guidelines and literatures, which can rarely represent the precinct under study consistently and transparently (Optis and Wild, 2010; Resch and Andresen, 2018; Rojas-Arevalo et al., 2017). Thirdly, the most widely conducted LCA is a process-based approach relying on the collection of energy and resources required as well as the wastes and emissions coming out of each life cycle stage of each precinct element. Inherently, this type of approach would underestimate the life cycle GHG emissions to various extents because the required data cannot be exhaustively collected, especially for auxiliary processes, services and upstream supply chain products. Therefore, there is a need to complement this process-based LCA approach with a top-down environmentally-extended input-output approach (EEIOA) forming a hybrid LCA approach to reach a more complete system (Crawford, 2008; Crawford et al., 2018; Junnila, 2006; Lenzen and Treloar, 2002; Stephan et al., 2019; Suh et al., 2004).

With the aim of providing a comprehensive and reliable assessment on the life cycle GHG emissions for urban precincts, this study addresses the methodological challenges outlined above by developing and applying a case-specific hybrid LCA approach to a typical residential precinct located at the outer suburb of Adelaide, Australia. Following the Introduction, Section 2 provides descriptions of the hybrid LCA model, the case study precinct, the goal and scope of this assessment as well as the selected emissions mitigation measures. In this assessment, the system comprehensiveness can be ensured as all precinct objects, elements and life cycle stages have been taken into account. More importantly, all background LCI data required for each life cycle stage of each precinct element (e.g. building materials manufacturing, electricity consumption, passenger car transportation, etc.) are derived from the newly developed up-to-date Australian-specific hybrid LCI database which can represent the precinct completely, consistently and transparently. In Section 3, detailed contribution analysis gives an indication of major emitting hotspots, from which twelve mitigation measures are quantified to explore the precinct-scale

emission mitigation potential. Since the life cycle GHG emissions and emission mitigation potential may vary significantly between conventional process-based LCA and hybrid LCA due to the variance in system completeness, this study also investigates the magnitude of the differences by conducting the same assessment using process-based approach side by side. Finally, the main results and implications are concluded in Section 4 together with the identification of limitations and future studies.

2. Methods and data

2.1. Hybrid life cycle assessment model

Based on the methodology presented in Yu and Wiedmann (2018), a hybrid LCA model has been used combining the AusLCI process coefficient matrix (Australian National Life Cycle Inventory Database, <http://www.auslci.com.au>) and the Australian EEIO coefficient matrix for the accounting year of 2014/15. This hybrid LCI matrix features process-based LCI data for 4463 AusLCI products/processes and they are complemented by an upstream cut-off matrix representing those inputs from the EEIO system that are missing in the process-based system (Suh, 2004). Those missing inputs are derived by adding columns of inputs from the EEIO system (in monetary units) to matching products/processes (after scaling to the functional unit of the product/process) and subsequently removing those EEIO inputs that are already represented in the process coefficient matrix. This last step involves a conversion of process-based inputs from physical to monetary units and is necessary to avoid double counting (Suh et al., 2004; Wiedmann et al., 2011). The hybrid GHG emissions intensities (GELs) of all AusLCI products/processes (expressed as kg CO₂e per unit of product/process, meaning the GHG emissions embodied in that product/process starting from the extraction of raw materials, transport, refining, processing, to the ready-to-use final product) are calculated using Equation (1) of Yu and Wiedmann (2018). By inactivating the upstream cut-off matrix, the process coefficient matrix is disconnected from EEIO coefficient matrix, resulting in a complete set of process-based GELs. With these two sets of GELs, hybrid LCA and process-based LCA can be conducted in parallel to demonstrate how the assessment would be influenced by applying different LCA approaches. It is the first time that the hybridisation being semi-automatically and simultaneously implemented on all products/processes of a national LCI database. This gives the hybrid LCI database the full capacity so that it can be used in the same way as the conventional process-based databases.

2.2. Precinct background and profile

A typical residential precinct based on an outer suburb of Adelaide, Australia, is selected to demonstrate the application of the hybrid LCA approach and to highlight the impacts of different LCA approaches on assessment results.

Found in 1991 with a constructed land size of 2.73 km², this precinct, mainly comprising single-storey detached houses, two-storey townhouses and three-storey apartments, is about 30 km away from the city centre where local bus services are provided every 300–400 m along the main roads (Fig. 1 and Table 1). According to the 2016 Australian Census, this precinct accommodated 8043 persons forming 2890 private dwellings and on average, each dwelling had 1.8 motor vehicles. 35.8% of the population were students and 45.6% were employed either full-time or part-time. Among the employees, 82.1% travelled to work by car as driver or passenger while the rest travelled by public transport or worked at home (ABS, 2017).

Unlike the stand-alone buildings, morphological parameters of a

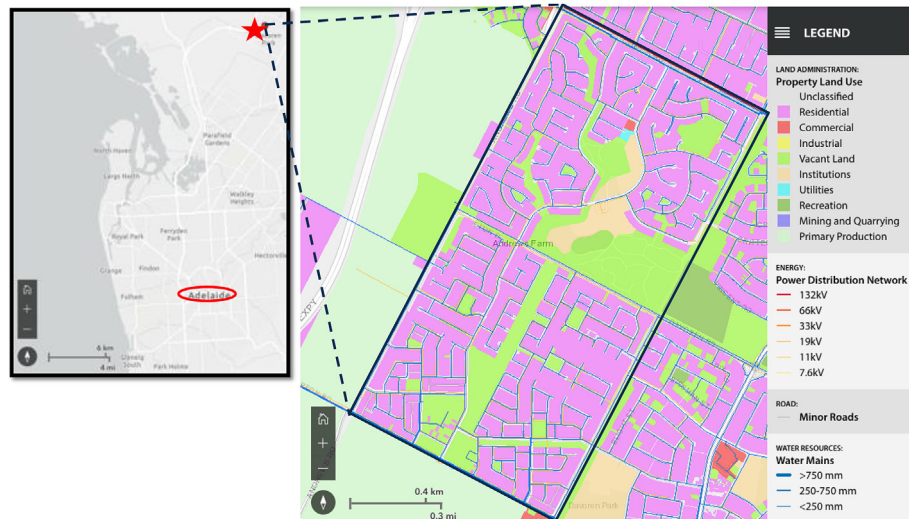


Fig. 1. The case study precinct, including its geographical location, property land use (residential buildings, commercial buildings and educational institutions), open spaces (road, recreation and vacant land) and networks (electricity distribution network and water mains). Retrieved from <http://www.aginsight.sa.gov.au> on 12 May 2019.

Table 1
Buildings, open spaces, networks and on-site renewable energy units in the precinct.

Residential buildings	Average floor area (m ²) ^a	Quantity ^b	Total area (m ²)
Detached house	214	2723	582722
Townhouse	194	153	29682
Apartment	152	14	2128
Non-residential buildings			Total area (m²)^c
Retail			2380
School			82670
Open spaces			Total area (m²)^c
Road			480177
Driveway			101150
Footpath			274387
Networks			Total length (m)^c
Water main			66635
Sewer main			71283
Electricity distribution cable			20211
On-site renewable energy units		Quantity^d	Total rated output (kw)^d
Solar PV panel system		818	2454
Solar water heater		307	

^a Source: [ABS, CommSec \(2017\)](https://www.commsec.com.au/content/dam/EN/ResearchNews/ECOREport.20.11.17_Biggest%20homes_size-fall.pdf). Australian home size hits 20-year low: CommSec Home Size Trends Report. Commonwealth Securities Limited, https://www.commsec.com.au/content/dam/EN/ResearchNews/ECOREport.20.11.17_Biggest%20homes_size-fall.pdf.

^b Source: [ABS, 2017](https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC40026?opendocument). 2016 Census QuickStats. https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC40026?opendocument. (Accessed 28 April 2019).

^c Measured and calculated from <https://maps.sa.gov.au/SAPPA/>.

^d Retrieved and extrapolated from <https://nationalmap.gov.au/renewables/> and <http://www.cleanenergyregulator.gov.au/RET/Forms-and-resources/Postcode-data-for-small-scale-installations>.

precinct, such as the urban form and building heights, should be considered as they would change the precinct orientation and obstruction angle, affecting the lighting, cooling, heating requirements and solar access of buildings (Hviid et al., 2008; Ratti et al., 2005; Steemers, 2003; Wong et al., 2011). In addition, the occupant-related transport emissions would be influenced as well by the urban density (Dujardin et al., 2012; Norman et al., 2006; Perkins et al., 2009). To account for the effects of these morphological factors on precinct's life cycle GHG emissions for more contextualised and accurate assessment, a few morphological coefficients (μ_i , μ_h , μ_c , μ_t , μ_s) are calculated according to Rodríguez-Álvarez (2016) to adjust the baseline calculation (Table 2). To this end, the actual precinct geometry needs to be transformed into a

simpler and virtual notional grid that is composed of 665 orthogonal building blocks. Each block represents the average values of the precinct area retaining the critical information on key parameters list in Table 2.

2.3. Goal and scope definition

The primary aim of this paper is to provide a detailed life cycle GHG emissions assessment of the precinct described above by applying both process-based LCA and hybrid LCA. Based on that, various emissions mitigation measures targeting embodied, operational and occupant-related transport emissions can be identified and quantified to understand the overall precinct-scale mitigation

potential as well as the most effective measures. Since this paper only focuses on the built environment, emissions associated with other expenditures such as food, clothing, goods, other activities and services (e.g. financial services, education services, medical and health services, etc.) are not taken into account, although they can significantly contribute to the precinct's GHG emissions from the consumption's perspective (Lotteau et al., 2015; Stephan and Stephan, 2016).

The service life of the precinct is set to be 50 years according to Australian National Construction Code and the absolute (kt CO₂e), spatial (kg CO₂e/m² floor area/year) and per capita (t CO₂e/inhabitant/year) functional units are adopted allowing comparison with other studies. Fig. 2 depicts the boundary selected for this study. Extended from building-level assessment, precinct-level assessment has covered a wide range of objects including buildings, open spaces, networks, on-site energy units and mobility, and the life cycle GHG emissions are classified into:

- embodied emissions that are associated with the manufacturing and transportation of products for each object, on-site construction and installation, maintenance and replacement of these objects over 50 years, and their end-of-life treatment;
- operational emissions that are associated with the heating, cooling, lighting, hot water use, cooking, appliance and other energy use for buildings over 50 years, as well as the energy required for the operation of other precinct objects over the same period. For on-site energy units, in particular, the operational emissions are negative representing the emissions offset by harvesting the solar energy;
- occupant-related transport emissions that are generated from daily commuting, business trips and personal travels over 50 years.

The primary reasons that use (B1), repair (B3) and refurbishment (B5) of these objects over 50 years are excluded from this assessment are due to the unavailability of data and the emissions associated are considered negligible. B1 stage captures emissions released from the precinct objects throughout their lifetime, B3 stage takes into account the emissions arising from the unpredictable repair processes, and B5 stage relates to the emissions associated with alteration or improvement to the physical characteristics of the precinct objects. Excluding these emissions would not prevent the assessment from meeting the professional

guidelines, and this is commonly applied in other similar studies (Huang et al., 2017a, b; RICS, 2017; Robati et al., 2019; Schmidt et al., 2020; Stephan et al., 2013; Stephan and Stephan, 2016).

Due to the involvement of a large number of variables and the complexity of interactions and constraints, four assumptions are made to reasonably simplify the modelling and calculation. These assumptions are provided separately in the [Supplementary Material](#).

As discussed previously, the precinct-level life cycle GHG emissions are the summation of embodied emissions, operational emission and occupant-related transport emissions. Mathematical formulations for each component and the data required are provided separately in the [Supplementary Material](#) as well.

2.4. Selected emissions mitigation measures

In order to quantify the overall precinct-scale emissions mitigation potential, common measures targeting embodied, operational and occupant-related transport emissions of urban precincts are identified and selected based on existing scientific studies, visions and pathways of local development, characteristics of the specific precinct under study, and the availability of required data (Akbarnezhad and Xiao, 2017; Antonín et al., 2017; ASBEC and ClimateWorks Australia, 2018; Beyond Zero Emissions, 2013; Campisi et al., 2018; ClimateWorks Australia, 2013; COAG Energy Council, 2018; Crawford et al., 2016; Gieseckam et al., 2014; Government of South Australia, 2014; Malmqvist et al., 2018; Moussavi Nadoushani and Akbarnezhad, 2015; Newton and Tucker, 2011; Pomponi and Moncaster, 2016; SDSN and IDDRI, 2014; Stephan et al., 2017; Stephan and Stephan, 2016; Stock et al., 2018).

Neither disruptive technology innovation nor substantial changes in economic structure, precinct/building design and life-styles are introduced in these measures, so that the estimated emissions mitigation potential is conservative and easily achievable. In other words, the implementation of all selected measures only represents one possible integrated way to mitigate the precinct-scale emissions to a certain extent. This is deemed sufficient in this study as the main intentions are to comprehensively and reliably quantify the mitigation potential under a prescribed circumstance and to evaluate the differences caused by applying different LCI methods. These measures are organised and prioritised following the three steps strategy, which is 1) reduce the demand and/or consumption; 2) use renewable or infinite sources

Table 2
Morphological parameters and coefficients of the precinct.

Morphological parameters ^a				
Orientation of buildings (%)	East	West	South	North
	24.5	23.25	25.85	26.4
Total perimeter on main orientation (north-south, m)				37151
Total perimeter on second orientation (east-west, m)				48894
Average height of buildings (m)				4.64
Population density (persons/acre)				11.92
Orientation ratio				0.76
Obstruction angle in the north-south axis (degree)				7.31
Obstruction angle in the east-west axis (degree)				9.64
Morphological coefficients ^b				
Average lighting coefficient (μ_l)				1.16
Average heating coefficient (μ_h)				1.1
Average cooling coefficient (μ_c)				0.98
Average transport coefficient (μ_t)				1.94
Average solar potential coefficient (μ_s)				0.87

^a Obtained and calculated from the precinct modelling.

^b Calculated according to Rodríguez-Álvarez, J., 2016. Urban Energy Index for Buildings (UEIB): A new method to evaluate the effect of urban form on buildings' energy demand. *Landscape and Urban Planning* 148, 170–187.

Legend:		Product			Construction		Use								End of Life			
		A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	B8	C1	C2	C3	C4
		Raw material supply	Transport to manufacturer	Manufacturing	Transport to precinct site	Construction and installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use/generation	Operational water use	Transportation in use	Demolition	Transport	Waste processing	Disposal
Buildings	Detached house																	
	Townhouse																	
	Apartment																	
	Retail																	
	School																	
Open spaces	Road including public lighting																	
	Driveway																	
	Footpath																	
Networks	Water main																	
	Sewer main																	
	Electricity distribution cable																	
On-site energy units	Solar PV panel system without battery storage																	
	Solar water heater																	
Mobility	Train																	
	Bus																	
	Car																	
	Truck																	
	Motorbike																	
	Airplane																	

Fig. 2. System boundary selected for life cycle GHG emissions assessment of the precinct. Extended and modified from BSI (2011).

and 3) use finite resources as efficiently and wisely as possible (Bueren et al., 2012) (Table 3).

3. Results and discussion

3.1. Life cycle greenhouse gas emissions of the base case precinct

For the whole precinct, the process-based LCA suggests a life cycle GHG emissions of 5747 kt CO₂e, equivalent to 42 kg CO₂e/m² of the precinct/year, 187 kg CO₂e/m² of the residential area/year and 14.3 t CO₂e/inhabitant/year. In hybrid LCA, the results are increased by 16%, reaching 6679 kt CO₂e (49 kg CO₂e/m² of the precinct/year, 217 kg CO₂e/m² of the residential area/year and 16.6 t CO₂e/inhabitant/year). Both sets of results are higher than those from international studies (Lotteau et al., 2015) and local studies (Crawford, 2011; Newton and Tucker, 2011; Perkins et al., 2009) which concluded a wide range from 11 to 124 kg CO₂e/m² of the residential area/year and from 0.6 to 8.6 t CO₂e/inhabitant/year. This is mainly due to the wider coverage of precinct objects and life cycle stages in this study, as well as the more complete system offered by hybrid LCA. For example, very few previous studies have included the manufacturing and operation of vehicles in their analysis, whereas in this study, the manufacturing of vehicles alone is taking up more than 40% of the life cycle embodied emissions and the emissions caused by vehicle fuel consumption are responsible for more than 12% of the life cycle operational emissions.

Occupant-related transport emissions represent the largest

share of the life cycle GHG emissions, followed by operational emissions and embodied emissions, and this is in agreement with previous studies (Lotteau et al., 2015; Norman et al., 2006; Stephan et al., 2013). For occupant-related transport emissions, private-car commuting and air travel are the two predominant contributors, and this echoes the national statistics which reported cars are responsible for almost half of the transport emissions (AGEIS, 2018). As a low-density outer-suburban precinct, the access to and use of public/active transport are limited, therefore more than 80% of the employees from this precinct rely on private cars for commuting. For operational emissions, Heating, Ventilating, and Air Conditioning (HVAC) is the largest contributor, followed by appliance use, lighting, vehicle operation, road operation, domestic hot water use and others. The biggest change (+43%) from process-based LCA to hybrid LCA is associated with the vehicle operation, which raises the relative contribution of vehicle operation to 15.5%, thus all other components are showing slightly declining relative contributions. As for the embodied emissions, vehicle manufacturing is the largest contributor, followed by primary construction materials (such as concrete, asphalt, steel, etc.), other construction materials and construction activities (Fig. 3).

3.2. Process-based LCA versus hybrid LCA for base case precinct

Compared with process-based LCA, hybrid LCA clearly generates higher life cycle GHG emissions due to the method's more complete system coverage. At the individual component level, the differences

Table 3
Selected emissions mitigation measures and the associated calculation details.

Strategy	Description	Specific measures	Calculation details
Life cycle embodied emissions			
Recover	Substitute emissions intensive materials with recovered wastes and/or by-products	- Substitute ordinary Portland cement with blended cement containing supplementary cementitious materials (SCM) ^a	The embodied emissions intensity of concrete (EEI_{ij}) is reduced by 27%
Recycle	Substitute virgin materials with recycled materials	- Substitute steel with recycled steel	The embodied emissions intensity of steel (EEI_{ij}) is reduced by 10%
Prefabricate	Improve the construction efficiency and reduce the waste through prefabrication	- Replace reinforced concrete ribs by prefabricated ribs	- The quantity of steel in the slabs (M_{ij}) is reduced by 22% - The waste rate of steel and concrete (τ_{ij}) from onsite construction are reduced from 5% to 10%, respectively, to 0.5% - The onsite construction emissions intensity (EL_{c-i}) is reduced by 15%
Life cycle operational emissions			
Lean	Reduce energy demand through passive design	- Upgrade the insulation (ceiling: from R2 to R4; wall: from R1.5 to R3) - Upgrade the window from single glazing to double glazing	- The annual operating hours of heating (H_{h-i}) and cooling (H_{c-i}) are reduced by 23% - The annual operating hours of heating (H_{h-i}) and cooling (H_{c-i}) are reduced by 47% - The quantities of extra insulation and glazing materials per floor area (M_{ij}) are increased by 3 times and 2.5 times, respectively
Green	Generate renewable energy from on-site sources	- Add battery storage to current solar PV system - Expand the solar PV system to the whole precinct - Expand the SWH system to the whole precinct	- The overall energy efficiency of solar PV system (η_{pv}) is increased by 3.8% - The overall area of PV panels (A_{pv}) is increased by 2.3 times - The quantities of solar water heaters (M_{swh}) is increased by 7.8 times; - The additional batteries, PV panels and solar water heaters would increase the life cycle emissions embodied in on-site energy units
Clean	Reduce energy consumption through the improvement of energy efficiency	- Replace the existing energy inefficient appliances to alternatives with higher energy ratings - Replace CFL lighting with LED lighting	- The operational emissions intensities of appliances ($OEI_{ap-i,t}$) are reduced by 30% on average - The operational emissions intensities of lighting (OEI_{l-i}) is reduced by 25%
Life cycle occupant-related transport emissions			
Avoid	Avoid or reduce travel demand	- Reduce travel demand by 15%	- The average daily travel distance ($TD_{u,v}$) is reduced by 15% - This would also reduce the life cycle operational emissions of mobility by 15%
Shift	Shift from emissions intensive travel modes to low emitting modes	- Shift 25% normal car to electric car - Shift 25% car travel to bus travel	- The total travel distance of normal car is reduced by 50% and evenly shifted to electric car travel and bus travel - The additional electric cars would increase the life cycle emissions embodied in mobility
Share	Use car travel as efficiently as possible	- Share 25% private car travel with carpool	- The total travel distance of private car is further reduced by 25% and shifted to carpool

^a In this case, concrete 40 MPa is replaced with concrete 40 MPa 30% fly ash.

between process-based LCA and hybrid LCA vary significantly from one to another. For example, in this case study, the embodied emissions in plasterboard differ by 90%. Such a significant difference in calculated emissions highlights the narrow scope of consideration that process-based LCA applies. Alternatively, hybrid LCA considers the systemic nature of real world environmental impacts, accounting for a greater range of emissions deemed 'insignificant' (Greenhouse Gas Protocol, 2011) from the perspective of process-based LCA. Additionally, the difference in results between process-based LCA and hybrid LCA re-orders the emissions footprint of some precinct components. For example, in Fig. 4, vehicle operation switches ranking with lighting operation from processed-based LCA to hybrid LCA. Since mitigation strategies for each of these components require a very different strategic approach, hybrid LCA provides decision makers a more comprehensive assessment to inform priority areas for targeted emissions mitigation.

Of the three emissions categories, embodied emissions represent the largest disparity between process-based LCA and hybrid LCA (22%), followed by transport emissions and operational emissions at 17% and 11%, respectively. The relative differences in the disparity of results occur due to embodied emissions being generated from a wide range of products, processes and services whose process-based life cycle inventory data are more complex and

dominated by higher upstream inputs. Therefore embodied emissions contain less completed inventories than those of transport and operational emissions where the share of direct emissions is larger.

3.3. Emissions mitigation potential and analysis

Transport represents the most emissions intensive category of the precinct, followed by operational emissions and embodied emissions. Mitigation measures for each of these categories are outlined in Table 3. Ideally, implementing all mitigation measures would see the greatest reduction in overall emissions for the precinct. However, in reality, budgetary and regulatory constraints as well as engrained cultural and political structures necessitate a more nuanced approach to transitioning to a lower emissions precinct. Therefore, to assist the decision making process, the mitigation potential of each precinct category is quantified and further discussions on each emissions category explore the implications of transition for policy makers, precinct residents and industry representatives.

3.3.1. Mitigation potential of transport emissions

Transport is the most significant contributor to the life cycle GHG emissions of the studied precinct; it also represents an area of

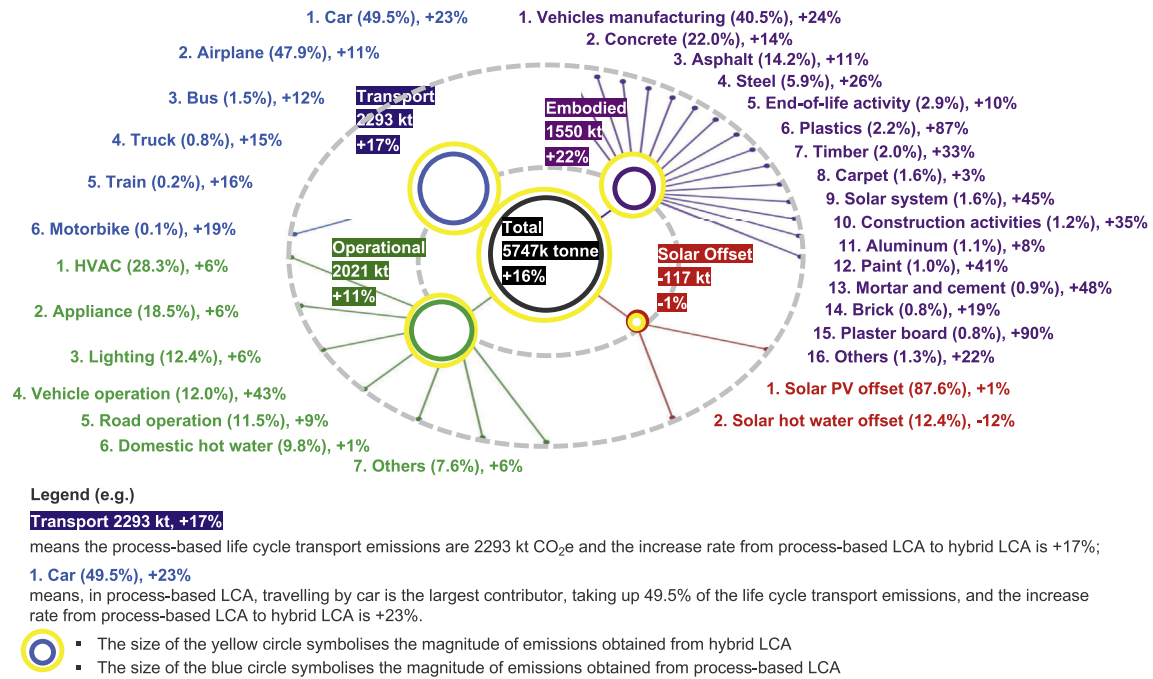


Fig. 3. Life cycle greenhouse gas emissions of the base case precinct.

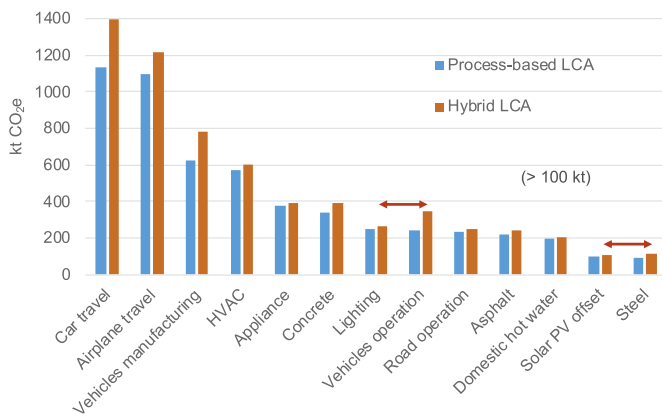


Fig. 4. Greenhouse gas emissions generated from the top contributing components (>100 kt).

high mitigation potential. Four measures targeting transport emissions are identified in Fig. 5. According to the results of both LCA methods, the greatest mitigation potential is achieved if the car travel is replaced by car-pooling, the travel distance is reduced, the car travel shifts to bus travel, and the electric vehicle is deployed.

Each of these mobility shifts necessitates vastly different transition pathways, representing a number of opportunities and challenges for decision makers. For instance, reducing travel distance could be achieved through remote working or by choosing active mobility solutions, like cycling and walking where possible. In contrast, a number of issues significantly impact on the ability to achieve the full potential of this mitigation measure. Both poor land use planning and dominant car based mobility regimes contribute to urban sprawl, reduce perceptions of safety for active transport users and lock in private car dependency (Moradi and Vagnoni, 2018; OECD/IEA/NEA/ITF, 2015). One way to combat this is to work remotely, however this shift will inevitably increase the

operational emissions of the precinct due to the increased energy demand of running a home office. Public transportation via bus travel represents an area of high mitigation potential for the precinct, although mobility change to public transport experiences its own challenges. These include perceptions that public transport is slower, infrequent and expensive (Laakso, 2017); in comparison private mobility is seen as fast, efficient and relatively inexpensive, noting these feelings do not factor in the total cost of vehicle ownership. Many of these barriers will need to be overcome to influence the adoption of low emissions mobility, necessitating further behavioural change research for the precinct before strategies are deployed. An opportunity exists to explore the mitigation potential of rail transport, as the local railway becomes electrified over the coming years (Government of South Australia Department of Planning, 2017), and if accessibility is considered, this option could link multi-modal transport options. A mobility shift in the direction of bicycle-rail transport would further reduce congestion issues that may be experienced by road dependant travel modes such as bus travel and car-pooling.

3.3.2. Mitigation potential of operational emissions

Operational emissions are the second largest contributor to the life cycle GHG emissions of the studied precinct; they also represent an area of high mitigation potential given the energy efficiency focus of the building and construction regulatory requirement. Fig. 5 presents the mitigation potential of five measures; three measures with high potential for rapid mobilisation are discussed further in this section. Little difference is observed between process-based LCA and hybrid LCA mitigation calculations, this is because emissions are largely related to energy consumption and this is accounted for adequately in both methods.

The most effective measures are observed in solar PV and solar water heating system expansion, upgrading windows to double-glazing, using more energy efficient appliances or lighting systems, and upgrading building insulation material. Considering the

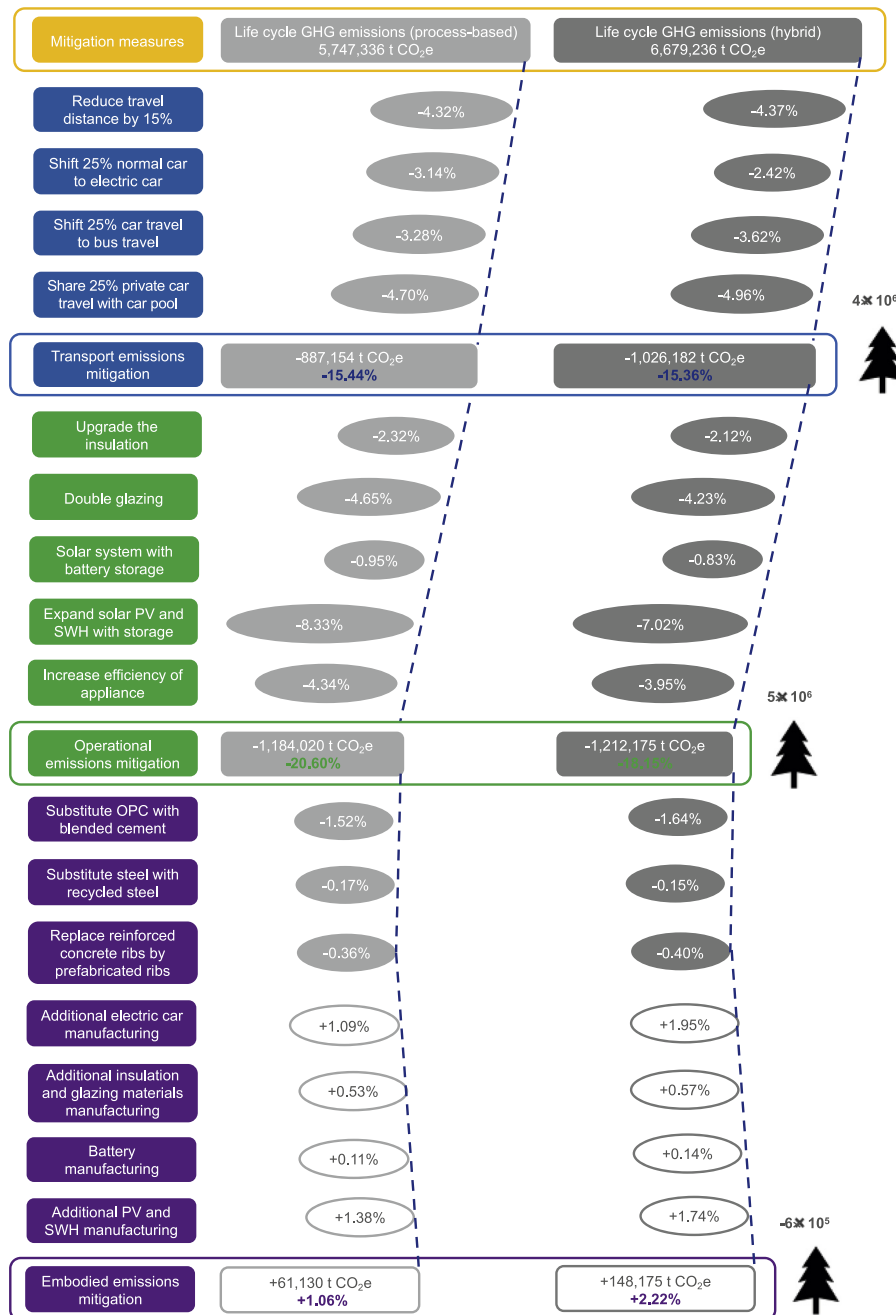


Fig. 5. Emissions mitigation potential of the precinct (note: the size of the ellipse is proportional of the magnitude of the mitigation; the value above each tree is the number of the trees whose effect on emissions savings is equivalent to the overall effect of mitigation measures of each category).

real-world environment, upgrading window glazing, insulation material and household appliances could all be achieved simultaneously with any building renovation or new building construction. In contrast to this opportunity, energy efficiency regulation in Australia lags international best practice in terms of aligning policy with Net-Zero 2050 pathways (Berry and Marker, 2015), and an evaluation of energy efficiency standards by the CSIRO determined that most buildings were being designed to minimum Australian standards (CSIRO, 2013), locking in sub-par performance (Moore et al., 2019). ASBEC and ClimateWorks Australia (2018) estimates the optimal NatHERS (Nationwide House Energy Rating Scheme) efficiency rating for a home in Australia is about 7 stars, whereas current regulation stipulates a 6-star minimum. Given that the

South Australian government has committed to a net-zero emissions 2050 target (Government of South Australia, 2014), regulatory reform will need to address best practice gaps and align strategically with net-zero emissions pathways. The NatHERS rating tool currently only considers the building envelope, which excludes important energy contributors such as water heaters, air conditioners and home appliances. Therefore, any energy efficiency measures adopted in addition to minimum standards, including solar water heaters and solar PV, are at the whim of market preferences. Based on the issues outlined above, a number of barriers significantly impact the adoption of the operational mitigation measures identified. In response, NatHERS regulation should increase the minimum energy efficiency standard and expand to

consider the performance benefits of solar PV and solar water heating systems (ASBEC and ClimateWorks Australia, 2018); this will enable a more rapid implementation of these home upgrades and contribute to the substantial emissions mitigation potential outlined in Fig. 5.

3.3.3. Mitigation potential of embodied emissions

Embodied emissions identified in the precinct study equate to almost one third of the total life cycle GHG emissions; in addition, the suggested mitigation measures incur an increase in emissions rather than a reduction. This is because measures aiming at reducing transport emissions and operational emissions would indirectly increase the embodied emissions, which are often neglected in previous studies. These measures, such as deploying electric cars, upgrading insulation and glazing of houses, expanding solar PV and solar water heating units with battery storage, all come with emissions embodied in their manufacturing stage, transportation and installation stage, use stage and end-of-life stage. Herein we establish the substantial value that hybrid LCA offers over process based LCA. Using the electric vehicle as a focus mitigation strategy, if transport emissions mitigation potential is considered solely, both process-based LCA and hybrid LCA calculations are roughly the same. However, when the emissions embodied in electric vehicle manufacturing are considered, hybrid LCA calculations are double that of process-based LCA results. Based on this difference, the mitigation potential of an electric vehicle strategy for the precinct equates to almost 120,000 tonnes CO₂e from a process-based LCA perspective, but only 30,000 tonnes CO₂e according to hybrid LCA. Therefore, from a hybrid LCA point of view, process-based LCA overestimates the mitigation potential of electric vehicles, due to a narrower scope of consideration.

The identification of embodied emissions in other mitigation strategies allows for a more informed decision making process at all levels, highlighting the important contribution of this study for consumers, industry and decision makers alike. Embedding embodied emissions information into regulatory instruments would further influence a reduced dependency on high emissions materials with a low mitigation potential, such as steel; encourage consideration of alternative building materials not included in this study, such as sustainably managed Engineered Wood Products (Shanableh et al., 2017; Teh et al., 2017); and encourage circular economy practices that utilise recycled materials wherever possible.

4. Conclusion

As the critical link between individual building and city, precinct represents an important scale for urban planning, at which low-carbon strategies and technologies for urban built environment can be tested and measured (Bunning et al., 2013; Newton et al., 2019). This study is conceived to enable a comprehensive and reliable precinct-scale GHG emissions assessment by applying a case-specific hybrid life cycle assessment.

For the whole precinct, the hybrid LCA result is 16% higher than its corresponding process-based LCA result, reaching 16.6 t CO₂e/inhabitant/year. Embodied, operational and transport emissions take up 28%, 32% and 40% of the life cycle GHG emissions, respectively. Assuming no technology innovation and substantial changes in economic structure, precinct design and lifestyle are involved, hybrid LCA suggests the life cycle GHG emissions of the precinct can be reduced by 31%, and the most effective measures are related to reducing transport emissions and operational emissions. As for the embodied emissions, instead of reducing them, the combination of all measures brings about a slight increase both absolutely and relatively because measures targeting transport and operational

emissions come with emissions embodied in their manufacturing, transportation and installation, use and end-of-life stages. In order to further mitigate the overall life cycle GHG emissions, more attention should be paid to the assessment and reduction of embodied emissions.

Comparing process-based LCA and hybrid LCA, it is found that, at the individual component level, the differences between them vary significantly from one to another, which may provide potentially different implications on how life cycle emission are distributed among the contributing components. When the component-level results are aggregated into the three types of emissions, the biggest difference between them is seen in embodied emissions, because embodied emissions are generated from a wide range of products, processes and services whose process-based life cycle inventory data are more complex and dominated by higher upstream inputs, which are often truncated in process-based LCA. From base case to mitigated case, the differences between two LCA approaches for each type of emissions are enlarged, and the biggest difference is always seen in embodied emission. This implies the process-based LCA would further underestimate the life cycle GHG emissions in mitigated case, therefore, the use of hybrid LCA is more favourable for the purpose of providing a comprehensive and reliable assessment.

In this precinct-scale life cycle GHG emissions assessment, several limitations remain in providing a more accurate and insightful assessment. Firstly, some scope 3 emissions which are associated with household expenditures, such as food, clothing, goods, other activities and services are not taken into account, but they can significantly contribute to the precinct's GHG emissions from the consumption's perspective (Lotteau et al., 2015; Stephan and Stephan, 2016). Secondly, life cycle cost (especially with the solar PV system and electric vehicles) is an important factor to consider for the actual implementation of the mitigation measures, therefore, a life cycle costing analysis can be added in future research to identify the most cost-effective measures. Thirdly, some assumptions are made in this study to simplify the assessment, but ideally, the social-technical transitions in the built environment over the next decades should be taken into account to reflect the system dynamics, and the integration with complex systems approaches (e.g. agent-based modelling) is recommended.

CRediT authorship contribution statement

Man Yu: Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, preparation. **Thomas Wiedmann:** Funding acquisition, Conceptualization, Supervision, Validation, Writing - review & editing. **Sarah Langdon:** Formal analysis, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

ABS	Australian Bureau of Statistics
AGEIS	Australian Greenhouse Emissions Information System
AusLCI	Australian National Life Cycle Inventory Database
BEES	Building for Environmental and Economic Sustainability
BSI	British Standards Institution
CO ₂ e	Carbon Dioxide Equivalent
ICE	Embodied Energy and Carbon Footprint Database
IELab	Industrial Ecology Virtual Laboratory
EEIOA	Environmentally Extended Input Output Analysis
ELCD	European Life Cycle Database
GEIs	Greenhouse gas Emissions Intensities
GHG	Greenhouse Gas
HVAC	Heating, Ventilation and Air Conditioning
IO	Input-Output
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
NatHERS	Nationwide House Energy Rating Scheme
PV	Photovoltaic

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.123731>.

References

- Abs, 2017. 2016 Census QuickStats. https://quickstats.censusdata.abs.gov.au/census_services/getproduct/census/2016/quickstat/SSC40026?opendocument. (Accessed 28 April 2019).
- Abs, CommSec, 2017. Australian Home Size Hits 20-year Low: CommSec Home Size Trends Report. Commonwealth Securities Limited. https://www.commsec.com.au/content/dam/EN/ResearchNews/ECORReport.20.11.17_Biggest%20homes_size-fall.pdf.
- AGEIS, 2018. National Greenhouse Gas Inventory by Economic Sector. <http://www.environment.gov.au/climate-change/climate-science-data/greenhouse-gas-measurement/ageis>.
- Akbarnezhad, A., Xiao, J., 2017. Estimation and minimization of embodied carbon of buildings: a review. *Buildings* 7 (1), 5.
- Antonin, L., Marie, N., Stépán, M., Julie, Z., Jan, R., Ctislav, F., Jan, T., Petr, H., 2017. Design strategies for buildings with low embodied energy. *Proc. Instit. Civ. Eng. Eng. Sustain.* 170 (2), 65–80.
- ASBEC, ClimateWorks Australia, 2018. Building Code Energy Performance Trajectory Project Final Report - Built to Perform - an Industry Led Pathway to a Zero Carbon Ready Building Code. Australian Sustainable Built Environment Council. <https://www.asbec.asn.au/wordpress/wp-content/uploads/2018/10/180703-ASBEC-CWA-Built-to-Perform-Zero-Carbon-Ready-Building-Code-web.pdf>.
- Berry, S., Marker, T., 2015. Residential energy efficiency standards in Australia: where to next? *Energy Effic.* 8 (5), 963–974.
- Beyond Zero Emissions, 2013. Zero Carbon Australia Buildings Plan. Melbourne Energy Institute, The University of Melbourne. <http://media.bze.org.au/bp>.
- BSI, 2011. BS EN 15978: 2011 Sustainability of Construction Works. Assessment of Environmental Performance of Buildings: Calculation Method.
- Bueren, E.v., Bohemen, H.v., Itard, L., Visscher, H., 2012. Sustainable Urban Environments an Ecosystem Approach. Springer, Dordrecht.
- Bunning, J., Beattie, C., Rauland, V., Newman, P., 2013. Low-carbon sustainable precincts: an Australian perspective. *Sustainability* 5 (6), 2305–2326.
- Campisi, D., Gitto, S., Morea, D., 2018. An evaluation of energy and economic efficiency in residential buildings sector: a multi-criteria analysis on an Italian case study. *Int. J. Energy Econ. Pol.* 8 (3), 185–196.
- Chen, G., Shan, Y., Hu, Y., Tong, K., Wiedmann, T., Ramaswami, A., Guan, D., Shi, L., Wang, Y., 2019. Review on city-level carbon accounting. *Environ. Sci. Technol.* 53 (10), 5545–5558.
- ClimateWorks Australia, 2013. Tracking Progress towards a Low Carbon Economy: Buildings. www.climateworksaustralia.org/tracking-progress.
- COAG Energy Council, 2018. Report for Achieving Low Energy Homes. Commonwealth of Australia. <http://coagenergycouncil.gov.au/publications/trajectory-low-energy-buildings>.
- Crawford, R.H., 2008. Validation of a hybrid life-cycle inventory analysis method. *J. Environ. Manag.* 88 (3), 496–506.
- Crawford, R.H., 2011. Energy and Greenhouse Gas Emissions Implications of Alternative Housing Types for Australia. Australian Cities Research Network.
- Crawford, R.H., Bartak, E.L., Stephan, A., Jensen, C.A., 2016. Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. *Renew. Sustain. Energy Rev.* 63, 435–451.
- Crawford, R.H., Bontinck, P.A., Stephan, A., Wiedmann, T., Yu, M., 2018. Hybrid life cycle inventory methods – a review. *J. Clean. Prod.* 172 (Supplement C), 1273–1288.
- CSIRO, 2013. The Evaluation of the 5-Star Energy Efficiency Standard for Residential Buildings.
- Dujardin, S., Pirart, F., Brévers, F., Marique, A.F., Teller, J., 2012. Home-to-work commuting, urban form and potential energy savings: a local scale approach to regional statistics. *Transport. Res. Pol. Pract.* 46 (7), 1054–1065.
- Giesekam, J., Barrett, J., Taylor, P., Owen, A., 2014. The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy Build.* 78, 202–214.
- Government of South Australia, 2014. South Australia's Climate Change Strategy 2015–2050: towards a Low Carbon Economy. <https://www.environment.sa.gov.au>.
- Government of South Australia Department of Planning, T.a.I., 2017. THE 30-YEAR PLAN FOR GREATER ADELAIDE.
- Greenhouse Gas Protocol, 2011. Product Life Cycle Accounting and Reporting Standard.
- Huang, B., Xing, K., Pullen, S., 2017a. Carbon assessment for urban precincts: integrated model and case studies. *Energy Build.* 153, 111–125.
- Huang, B., Xing, K., Pullen, S., 2017b. Life-cycle energy modelling for urban precinct systems. *J. Clean. Prod.* 142, 3254–3268.
- Hviid, C.A., Nielsen, T.R., Svendsen, S., 2008. Simple tool to evaluate the impact of daylight on building energy consumption. *Sol. Energy* 82 (9), 787–798.
- International Energy Agency, 2018. World Energy Outlook 2018.
- Junnala, S.I., 2006. Empirical comparison of process and economic input-output life cycle assessment in service industries. *Environ. Sci. Technol.* 40 (22), 7070–7076.
- Laakso, S., 2017. Giving up cars – the impact of a mobility experiment on carbon emissions and everyday routines. *J. Clean. Prod.* 169, 135–142.
- Lenzen, M., Treloar, G.J., 2002. Differential convergence of life-cycle inventories toward upstream production layers implications for life-cycle assessment. *J. Ind. Ecol.* 6 (3/4), 137.
- Lotteau, M., Loubet, P., Pousse, M., Dufrasnes, E., Sonnemann, G., 2015. Critical review of life cycle assessment (LCA) for the built environment at the neighborhood scale. *Build. Environ.* 93, 165–178.
- Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdóttir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., Potting, J., 2018. Design and construction strategies for reducing embodied impacts from buildings – case study analysis. *Energy Build.* 166, 35–47.
- Moore, T., Berry, S., Ambrose, M., 2019. Aiming for mediocrity: the case of Australian housing thermal performance. *Energy Pol.* 132, 602–610.
- Moradi, A., Vagnoni, E., 2018. A multi-level perspective analysis of urban mobility system dynamics: what are the future transition pathways? *Technol. Forecast. Soc. Change* 126, 231–243.
- Moussavi Nadoushani, Z.S., Akbarnezhad, A., 2015. Effects of structural system on the life cycle carbon footprint of buildings. *Energy Build.* 102, 337–346.
- Newton, P., 2019. The performance of urban precincts: towards integrated assessment. In: Newton, P., Prasad, D., Sproul, A., White, S. (Eds.), *Decarbonising the Built Environment: Charting the Transition*. Springer Singapore, Singapore, pp. 357–384.
- Newton, P., Prasad, D., Sproul, A., White, S., 2019. Pathways to low carbon living. In: Newton, P., Prasad, D., Sproul, A., White, S. (Eds.), *Decarbonising the Built Environment: Charting the Transition*. Springer Singapore, Singapore, pp. 1–32.
- Newton, P.W., Tucker, S.N., 2011. Pathways to decarbonizing the housing sector: a scenario analysis. *Build. Res. Inf.* 39 (1), 34–50.
- Norman, J., MacLean, H.L., Kennedy, C.A., 2006. Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions. *J. Urban Plann. Dev.* 132 (1), 10–21.
- OECD/IEA/NEA/ITF, 2015. Aligning Policies for a Low-Carbon Economy. OECD Publishing, Paris.
- Optis, M., Wild, P., 2010. Inadequate documentation in published life cycle energy reports on buildings. *Int. J. Life Cycle Assess.* 15 (7), 644–651.
- Ottelin, J., Ala-Mantila, S., Heinonen, J., Wiedmann, T., Clarke, J., Junnala, S., 2019. What can we learn from consumption-based carbon footprints at different spatial scales? Review of policy implications. *Environ. Res. Lett.* 14 (9), 20.
- Perkins, A., Hamnett, S., Pullen, S., Zito, R., Trebilcock, D., 2009. Transport, housing and urban form: the life cycle energy consumption and emissions of city centre apartments compared with suburban dwellings. *Urban Pol. Res.* 27 (4), 377–396.
- Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment – what does the evidence say? *J. Environ. Manag.* 181, 687–700.
- Rasmussen, F.N., Malmqvist, T., Moncaster, A., Wiberg, A.H., Birgisdóttir, H., 2018. Analysing methodological choices in calculations of embodied energy and GHG emissions from buildings. *Energy Build.* 158, 1487–1498.
- Ratti, C., Baker, N., Steemers, K., 2005. Energy consumption and urban texture. *Energy Build.* 37 (7), 762–776.
- Resch, E., Andresen, I., 2018. A database tool for systematic analysis of embodied emissions in buildings and neighborhoods. *Buildings* 8 (8), 106.
- RICS, 2017. Whole Life Carbon Assessment for the Built Environment, RICS Professional Standards and Guidance, first ed. Royal Institution of Chartered Surveyors, London.
- Robati, M., Daly, D., Kokogiannakis, G., 2019. A method of uncertainty analysis for whole-life embodied carbon emissions (CO₂-e) of building materials of a net-

- zero energy building in Australia. *J. Clean. Prod.* 225, 541–553.
- Rodríguez-Álvarez, J., 2016. Urban Energy Index for Buildings (UEIB): a new method to evaluate the effect of urban form on buildings' energy demand. *Landsc. Urban Plann.* 148, 170–187.
- Rojas-Arevalo, A.M., Aye, L., Candy, S., 2017. Quantifying greenhouse gas emissions: a review of models and tools at the precinct scale. In: *World Sustainable Built Environment Conference (WSBE17)*, June 5–7 2017, Hong Kong, pp. 1042–1048.
- Schmidt, M., Crawford, R., Warren-Myers, G., 2020. Quantifying Australia's life cycle greenhouse gas emissions for new homes. *Energy Build.* 224.
- SDSN, IDDRI, 2014. Pathways to deep decarbonization: Australia chapter. In: Emmanuel Guérin, C.M., Waisman, Henri (Eds.), *Sustainable Development Solutions Network and Institute for Sustainable Development and International Relations*. <http://deepdecarbonization.org/>.
- Shanableh, A., Lu, H., El Hanandeh, A., Gilbert, B., Bailleres, H., Maalej, M., Barakat, S., Omar, M., Al-Toubat, S., Al-Ruzouq, R., Hamad, K., 2017. A comparative life cycle assessment (LCA) of alternative material for Australian building construction. *MATEC Web Conf.* 120.
- Sharifi, A., Murayama, A., 2013. A critical review of seven selected neighborhood sustainability assessment tools. *Environ. Impact Assess. Rev.* 38, 73–87.
- Steemers, K., 2003. Energy and the city: density, buildings and transport. *Energy Build.* 35 (1), 3–14.
- Stephan, A., Crawford, R.H., Bontinck, P.-A., 2019. A model for streamlining and automating path exchange hybrid life cycle assessment. *Int. J. Life Cycle Assess.* 24 (2), 237–252.
- Stephan, A., Crawford, R.H., de Myttenaere, K., 2013. Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. *Build. Environ.* 68, 35–49.
- Stephan, A., Jensen, C.A., Crawford, R.H., 2017. Improving the life cycle energy performance of apartment units through façade design. *Procedia Engineering* 196, 1003–1010.
- Stephan, A., Stephan, L., 2016. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Appl. Energy* 161, 445–464.
- Stock, P., Steffen, W., Bourne, G., Brailsford, L., 2018. *Waiting for the Green Light: Transport Solutions to Climate Change*. Climate Council of Australia. <https://www.climatecouncil.org.au>.
- Suh, S., 2004. Functions, commodities and environmental impacts in an ecological-economic model. *Ecol. Econ.* 48 (4), 451–467.
- Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Joliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. *Environ. Sci. Technol.* 38 (3), 657–664.
- Teh, S.H., Wiedmann, T., Schinabeck, J., Moore, S., 2017. Replacement scenarios for construction materials based on economy-wide hybrid LCA. *Procedia Engineering* 180, 179–189.
- The World Bank, 2010. *Cities and Climate Change: an Urgent Agenda*.
- Thomson, G., Newton, P., Newman, P., 2019. Sustainable precincts: transforming Australian cities one neighbourhood at a time. In: Newton, P., Prasad, D., Sproul, A., White, S. (Eds.), *Decarbonising the Built Environment: Charting the Transition*. Springer Singapore, Singapore, pp. 211–225.
- United Nations, 2019. *World Urbanization Prospects: the 2018 Revision (ST/ESA/SER.A/420)*.
- Wiedmann, T.O., Suh, S., Feng, K., Lenzen, M., Acquaye, A.A., Scott, K., Barrett, J.R., 2011. Application of hybrid life cycle approaches to emerging energy technologies - the case of wind power in the UK. *Environ. Sci. Technol.* 45 (13), 5900–5907.
- Wong, N.H., Jusuf, S.K., Syafii, N.I., Chen, Y., Hajadi, N., Sathyanarayanan, H., Manickavasagam, Y.V., 2011. Evaluation of the impact of the surrounding urban morphology on building energy consumption. *Sol. Energy* 85 (1), 57–71.
- Xing, K., Wiedmann, T., Newton, P., Huang, B., Pullen, S., 2019. Development of low-carbon urban forms—concepts, tools and scenario analysis. In: Newton, P., Prasad, D., Sproul, A., White, S. (Eds.), *Decarbonising the Built Environment: Charting the Transition*. Springer Singapore, Singapore, pp. 227–244.
- Yu, M., Wiedmann, T., 2018. Implementing hybrid LCA routines in an input–output virtual laboratory. *J. Econ. Struct.* 7 (1), 33.