# Assessing the impact of buildings and construction across scales using the Australian Industrial Ecology Lab

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**Abstract –**
*As global population and urbanization increase, so do the direct and indirect environmental impacts of cities around the world. Counter-acting efforts toward low-impact buildings are needed in order to mitigate the effects of building construction and use. Embodied energy and greenhouse gas (GHG) emissions of buildings are becoming more important with the successes in improving the operational performance of buildings. The calculation of embodied impacts requires rigorous, flexible and comprehensive assessment tools. We present the Australian Industrial Ecology Virtual Laboratory (IELab) as one such tool, discussing its structure, scope and function and a case study application to assess a building component. The input-output analysis at the core of the IELab is mathematically comprehensive in the assessment of direct and indirect impacts and the tool can be applied at a range of scales from building component, to precincts and cities, and to the construction industry. IELab uses a flexible formalism that enables consistent harmonisation of diverse datasets and tractable updating. The emissions and energy database supporting IELab has detailed data for several decades, aligning with economic accounts and data on labour, water, materials and waste that enrich assessment across other dimensions of sustainability. In the case study, we demonstrate how data from the IELab can be combined with product-specific life-cycle inventory (LCI) data to analyse the embodied GHG emissions of a domestic aluminium-framed window. IELab is a comprehensive, flexible and robust assessment tool well positioned to respond to the challenge of assessing and aiding the design of a low-impact built environment.*

Keywords: input-output analysis, embodied energy, embodied emissions, environmental footprint, low-impact buildings, building component

# 1. Introduction

## 1.1. Environmental performance of the construction sector

At the global scale, the construction sector is responsible for 30-40% of greenhouse gas (GHG) emissions (Ibn-Mohammed et al. 2013), 40% of primary energy and natural resources consumption, 25% of waste generation and 15% of fresh water use (Ding 2014). In Australia, it is also the construction industry which plays a dominant role in contributing to GHG emissions (Yu et al. 2017) and materials consumption (Teh et al. 2017b), manifesting far-reaching implications on energy use, natural resource depletion and waste generation (Krausmann et al. 2009).

These significant environmental impacts of the construction sector paired with increasing global population and urbanisation over the next decades emphasise the need to aim for the most environmentally-friendly solutions possible, focusing on low-impact projects (Krausmann et al. 2017). This is all the more important as construction projects have a long lifetime, thus potentially locking in impacts for decades to come.

GHG emissions mitigation in the built environment – a major part of the environmental impacts – is at the heart of a number of initiatives: parallel to the Paris Agreement, the Global Alliance for Buildings and Construction was launched in December 2015, with its principal aim being the alignment of the worldwide buildings and construction sector with the goal of limiting global warming below 2°C (Global Alliance for Buildings and Constructions 2015). In Australia, the Green Building Council Australia (GBCA) recently published a Carbon Positive Roadmap for the Built Environment (GBCA 2017). Additionally the Federal Department of the Environment and Energy is releasing a National Carbon Offset Standard for buildings and precincts (Department of the Environment 2016a, 2016b) promoting net zero-carbon projects.

## 1.2. Significance of embodied emissions in whole life-cycle considerations

Several studies have suggested that a building's environmental impacts are predominantly attributable to its operational phase as they accumulate over the whole lifespan of the project (Kneifel 2010, You et al. 2011, Moussavi Nadoushani et al. 2015). The majority of Australian regulations and rating tools therefore emphasise reducing environmental impacts from the operational phase of a building (Iyer-Raniga 2012). However, reducing operational impacts alone will not result in the significant environmental improvements that are needed. The impacts embodied in the supply chain of the construction sector are increasingly taking up a larger share, because plenty of new projects are constructed every year, making the embodied impacts surge remarkably. The operational impacts conversely are becoming smaller, because of buildings transitioning from being conventional to passive, low-energy and nearly zero-energy buildings (Stephan et al. 2013, Crawford 2014, Stephan et al. 2014, Chastas et al. 2016).

On a national scale, GHG emissions embodied in the construction sector play a significant role: In Ireland, 11.7% of the total emissions could be attributed to the construction sector in 2005, with 71% of them coming from indirect sources (Acquaye et al. 2010). In China, the construction industry was responsible for 66.5% of the total GHG emissions in 2009, nearly all of them (96.6%) came from indirect sources (Chen et al. 2017). Australia's carbon footprint of the construction industry comprised 18.1% of the overall emissions in 2013. Electricity as well as the materials sector contributed most significantly (Yu et al. 2017).

The large majority of studies on carbon accounting in the built environment focus on the building scale and include both embodied and operational emissions. Recent reviews in the field reveal the increasing number of such studies (Ramesh et al. 2010, Sharma et al. 2011, Chau et al. 2015, Chastas et al. 2016). Depending on the chosen method as well as the energy efficiency of the building, the share of embodied emissions in a whole building life-cycle can vary widely. Crawford (2014), for example showed that it could be at least 55% of total life-cycle GHG emissions for a building, thus highlighting its significance.

### 1.3. The Australian Industrial Ecology Virtual Laboratory

The Australian Industrial Ecology Virtual Laboratory (IELab, https://ielab.info) is a collaborative online tool and research hub to compile and access large-scale environmentally extended multi-region input-output (EE-MRIO) data. These data can be used for a multitude of analyses for research questions at the interface of environmental, social and economic topics (Wiedmann 2017).

The IELab is built on detailed regional and sectoral data containing economic information, GHG emissions, energy use, waste, water use or land use. In a collaborative approach, data feeds from any IELab contributor can be used and shared within the IELab community, allowing for a rapid update of heterogeneous datasets (Lenzen et al. 2014, Lenzen et al. 2017). IELab provides the most comprehensive EE-MRIO data for Australia. Furthermore, the input-output (IO) analysis at the core of the IELab is mathematically comprehensive in the assessment of direct and indirect impacts due to an economy-wide system boundary.

Several Australian construction-related studies using IELab have been conducted to assess the emissions footprint of construction materials and sectors (Wiedmann 2017). This includes the production of warm-mix asphalt mixtures (Rodríguez-Alloza et al. 2015), construction materials, goods and services in Gold Coast City (Ely 2015), the production of cement and different concrete types (Teh et al. 2017a), construction material replacement scenarios using engineered wood products instead of reinforced concrete (Teh et al. 2017b), and the entire Australian construction sector (Yu et al. 2017).

## 1.4. Applicability across scales

When it comes to quantifying and assessing GHG emissions in the built environment, consistency across scales is very important. The nested emissions accounting framework in IELab (Figure 1) allows for a comprehensive and consistent evaluation of GHG emissions at different scales. Each cell, or "node" in the nested table represents an emissions value (e.g. in kt $CO_2$e) that can be attributed to an industry in a region where the emission originates and one product (group) in a region where the emission becomes embodied. Because of this origin-destination link this framework has also been termed a "carbon map" (Wiedmann et al. 2016).

A nested emissions accounting framework enables completeness and consistency across the scales and attribution of emissions to any producing or consuming activity. These characteristics are important when it comes to emission reduction targets, carbon pricing and carbon neutrality because they allow for an unambiguous and complete allocation of emissions that can be aligned with various GHG accounting standards. Wiedmann et al. (2016) present an example of a 'carbon map' for Greater Melbourne and use it to identify the scopes 1, 2 and 3 as defined by the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) (WRI et al. 2014). Within the same carbon map, both the direct territorial emissions as well as the emissions footprint of a region can be identified.

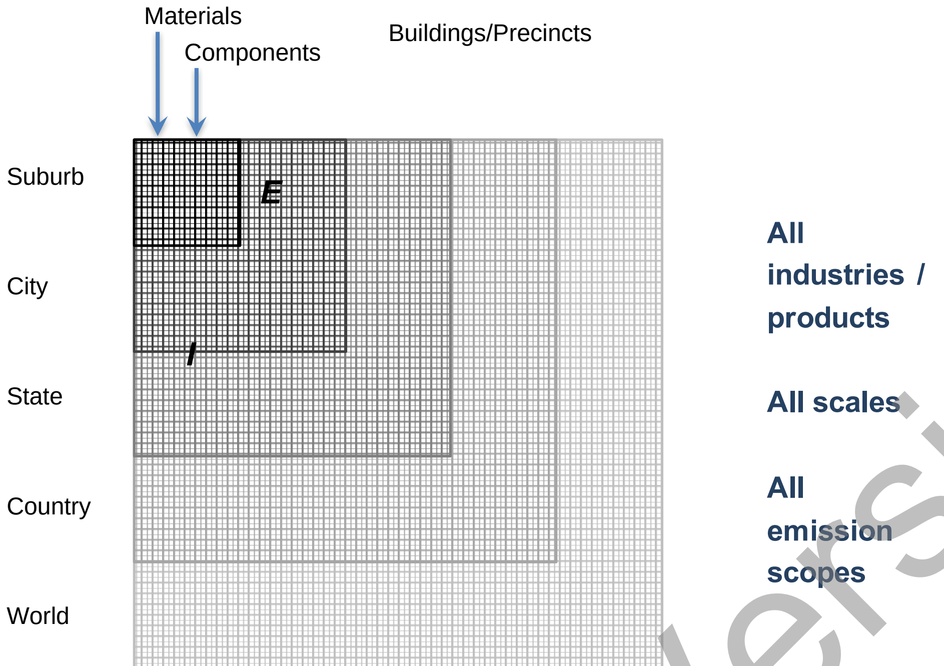


*Figure 1: Nested emissions accounting framework where all scopes of emissions from all product groups in an economy are represented in cells belonging to one of the geographical scales. Imports (I) to any scale are located in columns, exports (E) in rows. Embodied emissions from entities below the suburban scale (buildings and precincts) are accounted for by adding their constituent materials and components (from Wiedmann et al. (2013)).*

Whereas IO tables are complete in their economy-wide representation, they do not inherently have high spatial resolution. Downscaling IO tables is limited by the availability of suitable data to act as proxies for fine spatial estimations. IELab developers have constructed sub-national MRIO tables that include regions with as little as 10,000 inhabitants (Lenzen et al. 2014). Data that enable this spatial breakdown include household census data, employment data and business register data which are all available at SA2 level – refer to the later section on Data and the Supplementary Information (SI).

However, none of these data are available at precinct or street level and it would not make sense to try and construct IO tables at this scale because such small spatial units cannot be represented as economies with inter-industry transactions in a meaningful way. Instead, buildings and precincts are modelled bottom-up from the materials and components they are made of. Emissions footprint calculations with the IELab allow a derivation of life-cycle GHG inventories for these products. In some cases, data from bottom-up process analysis (LCA) can be used to improve the accuracy of the results and/or convert the units from a monetary basis to a physical unit basis (Teh et al. 2017b).

Several forms of input-output-based hybrid LCA are enabled by the IELab (Heijungs et al. 2002, Suh et al. 2004, Suh et al. 2005, Suh et al. 2007b). The term "hybrid LCA" is generally used for a marriage of bottom-up engineering process analysis and top-down economic IO analysis, combining the advantages of both – specificity and completeness (Bullard et al. 1978, Moskowitz et al. 1985). This is the most comprehensive method by which decision-makers can assess the energy or emissions footprint of different designs or planning alternatives across the upstream supply chain, and across all scales of the nested emissions accounting framework.

Depending on the specific LCA type, under- or overestimation of the overall emissions may occur (Säynäjoki et al. 2017). Dixit (2017) shows that a purely process-based LCA can lead to underestimation and an input-output LCA to overestimation. An IO-based hybrid approach, specified with more precise bottom-up data from relevant processes, is usually necessary in order to achieve the most precise results. Notable examples that use hybrid life-cycle inventories for the quantification of embodied energy and/or emissions in buildings include, inter alia, Treloar et al. (2000a), Treloar et al. (2001b), Treloar et al. (2001a), Crawford et al. (2005), Crawford (2014), Crawford et al. (2016) and Stephan et al. (2016a).

In general, the precision and completeness of a hybrid approach has a price. Enriching the nested emissions accounting framework with process data draws on disparate data sources that need expert disciplinary guidance for integration with the IELab. However, the nested structure and the formal data-handling of the IELab are well suited to minimizing this overhead of hybrid LCA. Recently, Crawford et al. (2017) have shown that a significant level of automation can be achieved for such hybridisation tasks. The nested emissions accounting framework, enabled by the IELab, allows for a progressive and staged replacement of spatially coarse IO data as more precise or disaggregate physical data becomes available.

### 1.5. Article structure

Subsequent to this section, we discuss the mathematical basis for our approach and how data are brought together in the IELab. Section 3 presents an applied case study for a specific building component and in section 4 we present an overview of further environmental impacts that can be assessed with the IELab. Section 5 concludes and provides an outlook for further work.

## 2. Methods and Data

### 2.1. Methods

Typically, LCA considers processes involved in the production of a "functional unit" (for example, an aluminium-framed window) and some proximate suppliers of materials and other inputs into this functional unit. IO data are employed for evaluating the remainder of the upstream supply chain, thus rendering the assessment complete in terms of supply-chain coverage. The layer of first-order (direct) supplies may be specified by physical processes and flows (as in our later case study) or on the basis of engineering cost data $\tilde{\mathbf{y}}$. The remaining layers are entirely enumerated using IO data. The latter are:

- a $N \times N$ matrix, $\mathbf{T}$ of intermediate transactions with elements $T_{ij}$ describing the supply of commodities produced by industry sectors $i$=1,…,$N$ for further use by industry sectors $j$=1,…,$N$;
- a $N \times K$ matrix of final demand $\mathbf{y}$ with elements $y_{jk}$ describing the final demand of commodities sold by industry sectors $j$=1,…,$N$ to agents $k$=1,…,$K$ (households, the government, the capital sector, stockpiles, and foreign consumers);
- and a $1 \times N$ matrix, or satellite account $\mathbf{Q}$ of energy use and GHG emissions (and other environmental performance data) by industry sectors $i$=1,…,$N$.

Adding intermediate and final demand yields total output $\mathbf{x} = \mathbf{T}\mathbf{1}^{\mathbf{T}} + \mathbf{y}\mathbf{1}^{\mathbf{y}}$ (determined as row-wise sums across $\mathbf{T}$ and $\mathbf{y}$, denoted using summation operators $\mathbf{1}^{\mathbf{T}}$ and $\mathbf{1}^{\mathbf{y}}$). The life-cycle energy and emissions embodied of the functional unit can then be determined through Leontief's demand-pull formulation $\mathbf{F} = \mathbf{Q}\hat{\mathbf{x}}^{-1}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\tilde{\mathbf{y}}$, where $\mathbf{q} = \mathbf{Q}\hat{\mathbf{x}}^{-1}$are energy and emissions coefficients, $\mathbf{L} = (\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}$is called the Leontief inverse, $\mathbf{I}$ is a $N \times N$ identity matrix with $I_{ij}$ = 1 for $i$=$j$ and 0 otherwise, $\mathbf{F}$ holds energy and emissions embodiments, and the hat symbol denotes vector diagonalization[1].

Energy and emissions embodiments can be broken down by sector of energy use and GHG emissions, and by type of input into the functional unit: $\mathbf{F}^{\mathrm{ps}} = \widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}(\mathbf{I} - \mathbf{T}\hat{\mathbf{x}}^{-1})^{-1}\hat{\tilde{\mathbf{y}}}$. Here, $\mathbf{F}^{\mathrm{ps}}$ is a $N \times N$ matrix, with elements $F_{ij}^{\mathrm{ps}}$describing the energy used or emissions emitted by

[1] Note that we assume that the engineering cost $\tilde{\mathbf{y}}$ for the aluminium-framed window are part of final demand. This is true if the aluminium-framed window is for a household, the government, or part of a capital investment, or purchased by a foreigner. This would not be true if the window were part of an intermediate input into the production of another sector.

sector $i$ to directly or indirectly enable the input of commodity $\tilde{y}_{\boldsymbol{j}}$. In addition, energy and emissions embodiments can be decomposed by supply-chain stage (Waugh 1950, Suh et al. 2007a): $\mathbf{F}^{\mathrm{ps}} = \widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}(\mathbf{I} + \mathbf{T}\hat{\mathbf{x}}^{-1} + (\mathbf{T}\hat{\mathbf{x}}^{-1})^2 + (\mathbf{T}\hat{\mathbf{x}}^{-1})^3 + \cdots)\hat{\tilde{\mathbf{y}}}$. For the example of an aluminium-framed window:

- $\widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}\hat{\tilde{\mathbf{y}}}$ representing 0th-order or direct embodiments (for example the energy or emissions associated with operating machinery in the window production factoryearth),
- $\widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}\mathbf{T}\hat{\mathbf{x}}^{-1}\hat{\tilde{\mathbf{y}}}$ representing 1st-order embodiments (for example the energy or emissions associated with assembling the machinery equipment that is used in the factory),
- $\widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}(\mathbf{T}\hat{\mathbf{x}}^{-1})^2\hat{\tilde{\mathbf{y}}}$ representing 2nd-order embodiments (for example the energy or emissions associated with manufacturing steel components for the machinery equipment that is used in the factory),
- $\widehat{\mathbf{Q}\hat{\mathbf{x}}^{-1}}(\mathbf{T}\hat{\mathbf{x}}^{-1})^3\hat{\tilde{\mathbf{y}}}$ representing 3rd-order embodiments (for example the energy or emissions associated with smelting iron ore into basic iron and steel shapes used for manufacturing steel components for the machinery equipment that is used in the factory), and so on.

As a case study we determine the embodied emissions of a domestic aluminium-framed window using the Path Exchange method. This hybrid LCA method combines top-down IO data with bottom-up process data, by first running a structural path analysis (Defourny et al. 1984, Treloar 1997) on the IO sector that comprises the product under consideration, and then replacing individual structural paths that are not well represented by aggregate IO data with superior data from process databases such as EcoInvent (Wernet et al. 2016). The

Path Exchange method consists of substituting input-output nodes with the corresponding physical process data, where available.

Input-output-based LCA has been used before for assessing building and construction applications, notably by Treloar, Crawford and colleagues (Treloar 1997, Treloar et al. 2000b, Crawford 2008, Lenzen et al. 2009). The particular innovation in the present work is that:

a) the IO data and related embodiment calculations were performed in, or integrated with, the IELab, a collaborative research platform maintained in a high-performance computing cloud, by researchers from 8 different institutions, all jointly developing and sharing data and analytical tools, and
b) the specific analysis of the aluminium-framed window is undertaken at unprecedented detail (see section 3 Case Study).

Achievement b) is made possible precisely by the collaboration described under a), because the IELab's data and tool sharing environment, procedural standardisation and automation, and workflow streamlining harnesses a wealth of data, enabling enhanced joint research efficiency (Lenzen et al. 2014, Lenzen et al. 2017).

## 2.2. Data

There are more than 100 environmental performance data integrated into the IELab and it is worthwhile expanding on how this data is handled and harmonised to a single consistent data set. IELab uses a so-called "root classification", which is a disaggregation of the MRIO tables at very high sectoral and regional detail. For the Australian IELab, the root classification encompasses 2214 regions within Australia, and 1284 economic sectors and products for *each* of these regions (refer to the SI for more detail).

All raw data integrated into the IELab data repository are accompanied by a mapping to this root classification. Raw data are not automatically mapped and disaggregated to this classification, but there is always codified meta information (downscaling methods or proxies) on how these data sets *would* be mapped to the root classification. This meta information is saved together with the original raw data, which remains unchanged. The root classification is more detailed than any raw data set that has so far been incorporated into the IELab framework. Further, the root classification also represents the highest level of disaggregation for any MRIO table that is constructed with the IELab. This standardized system that insists on a means to map any data used to a high level of resolution, also allows a high degree of automation and choice regarding source data sets for constructing MRIO tables and doing analysis with them.



## 3. **Case Study – Domestic aluminium-framed window**

To illustrate the potential of the IELab, embodied GHG emissions of a domestic aluminium-framed window are calculated using the Path Exchange hybrid method (Lenzen et al. 2009). This demonstrates how high-resolution IO data from the IELab can be combined with available process data to generate more comprehensive system boundaries and avoid truncation errors.

### 3.1. Case study description

Windows are an essential component of buildings and they typically comprise different materials for their frame, glazing and seals. This makes a window an ideal case study as it is easy to relate to, yet provides sufficient complexity to cover a range of materials and processes. A single-glazed, aluminium-framed window with rubber seals is used as a case study as it is the most common type of window used in Australian domestic buildings. This is the functional unit of the process analysis and its material composition is presented in **Error! Reference source not found.**.

*Table 1: Material composition for 1 $m^2$ single-glazed aluminium-framed window*

| Material | Quantity per $m^2$ of window |
|---|---|
| Clear float glass (4 mm) | 13 kg |
| Powder coated aluminium | 6.1 kg |
| Rubber seals | 0.03 kg |
| Hardwood timber reveal | 10.8 kg |

Note: figures based on Building Products Innovation Council (2017)

### 3.2. Scope of analysis

This cradle-to-gate analysis takes into account GHG emissions that are associated with the production of the window, covering raw material extraction, processing, transportation, material manufacture and window production. Recurrent and demolition-related GHG emissions are not considered. While important in the life-cycle environmental performance of a window system, they are not essential in order to demonstrate the application of IELab in calculating embodied GHG emissions.

### 3.3. Method and data sources

The Path Exchange hybrid method combines top-down IO data with bottom-up process data (see Methods and Data) beginning with a structural path analysis on the IO sector responsible for producing aluminium windows, i.e. *'22230010 Aluminium/aluminium framed doors (incl roller/concertina) & windows (incl glass)'* - refer to SI for expanded list of sectors and building products. This identifies embodied GHG emissions by sector required to produce one AUD worth of outputs from this sector. This emission intensity is multiplied by the cost of 1 $m^2$ of window (AUD262 in 2009 terms), the functional unit of the process data. Process data comprises the physical processes required to produce 1 $m^2$ of window and is extracted from available process databases relevant to Australia (Grant 2016, Building Products Innovation Council 2017). Specific data used for the case study are indicated in **Error! Reference source not found.**. Table 2 in the SI represents the top ten IO nodes for window production and the process values for the processes/emissions source with which they have been substituted.

*Table 2: Data sources used for the case study – BP LCI refers to Building Products LCI (2017)*

| Type of data | Flow | Source | Year | Comments |
|---|---|---|---|---|
| Input-output | Greenhouse gas emissions | IELab | 2009 | Aluminium/aluminium framed doors (incl roller/concertina) & windows (incl glass); door/window frames; roller grilles |
| Process | Material and energy inputs, direct GHG | BP LCI | 2009 | Product: Aluminium framed window (Powdercoated Aluminium Framed, Single Glazed, |

| | | | | |
|---|---|---|---|---|
| | emissions | | | Annealed Glass) |
| Process | GHG emissions | AusLCI/ ecoinvent | Varies | Product: Powdercoated aluminium extruded profile (ecoinvent data modified for Australian energy mix) |

3.4. GHG emissions of case study window

The resulting GHG emissions of the 1 $m^2$ single-glazed, aluminium-framed window are 212.2 kg $CO_2$-e. This is higher than previously reported figures which rely solely on process data (e.g. 124.5 kg $CO_2$-e by Citherlet et al. (2000)). With IO data accounting for 35% of the total emissions, this demonstrates the importance of using hybrid analysis to ensure a comprehensive analysis of environmental flows. Without the use of IO data, up to one third of all emissions would have been unaccounted for. The strength of the Path Exchange approach is that the combination of IO data from the IELab and process data from other sources results in a comprehensive system boundary while maintaining specificity and reliability through the use of bottom-up process data. Figure 2 shows an overview of the hybridisation process with respective emissions values.

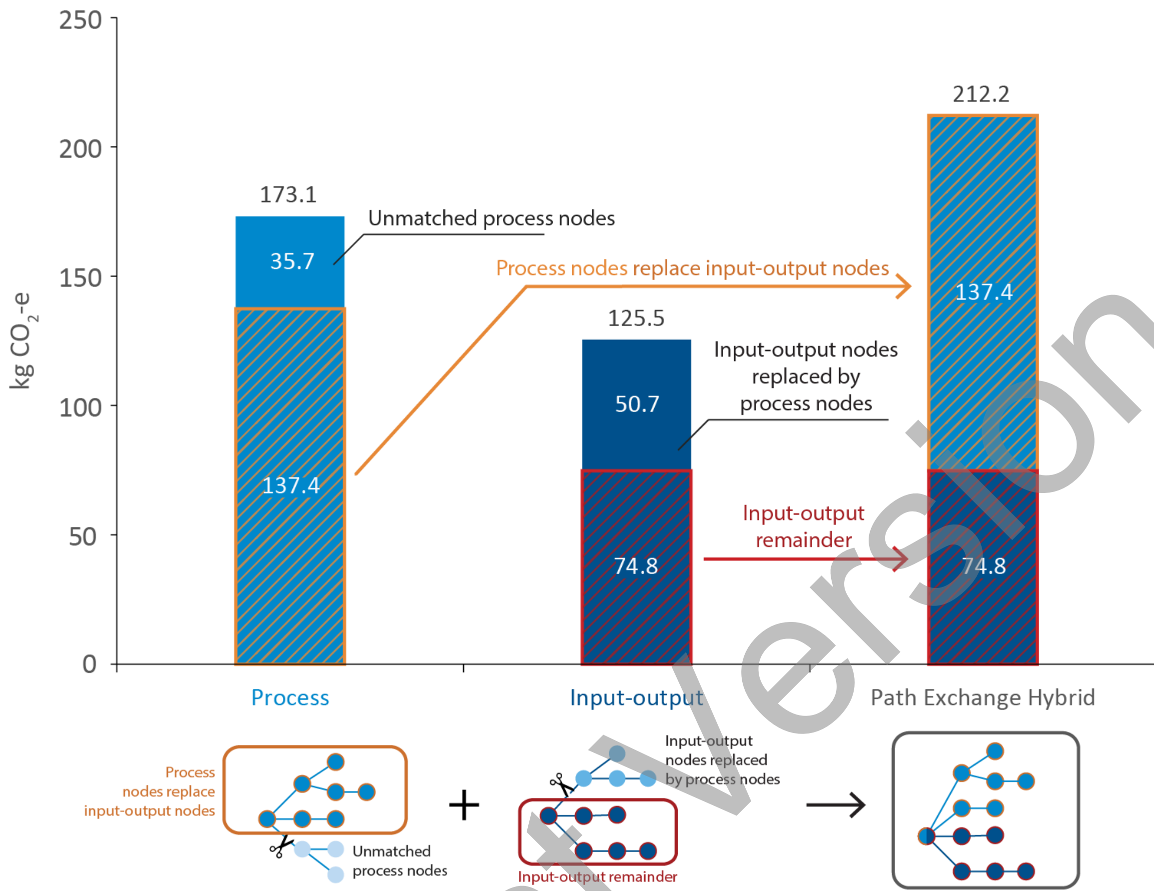


*Figure 2: Overview of hybridisation process for calculating embodied GHG emissions of case study window.*

Figure 3 shows the embodied GHG emissions of the case study window, by element and LCI data type. Aluminium is the most emissions-intensive element of the window, mainly due to the large amount of electricity used in its production. The 'IO remainder' includes emissions attributable to minor elements of the window where physical quantities were not available (e.g. plastic end caps, silicon, fittings, screws), as well as non-material-related emission sources such as the provision of services (e.g. insurance, finance, communication) to the window manufacturer needed to support their activities.

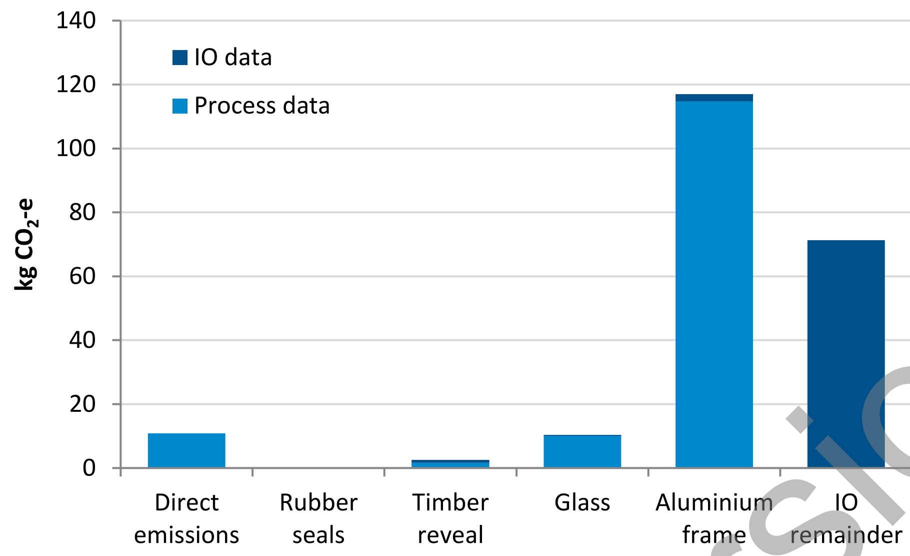


*Figure 3: Embodied GHG emissions of 1 m² window, by element and LCI data type.*



### 3.5. Limitations

The analysis of the case study provides a demonstration of how the IELab can be used for hybrid LCA. However, the results presented should be used with caution due to a number of limitations associated with the data and approach used. Factors such as the data type, source, age, aggregation level, relevance and reliability, as well as material quantities, manufacturing processes, and life-cycle scope can all affect the results.

## 4. Extensions

The nested-emissions framework demonstrates the range of scales where IELab has application and the preceding case study provides an example of how the IELab can deliver a specific analysis on one indicator (GHG emissions). It also has wide topical scope: it is able to assess a range of environmental impacts and to incorporate environmental "satellite accounts" including non-GHG emissions, water, land use, energy, waste, and material flows (refer also to SI Table 3). As explained in Section 2.2, satellite data are represented with consistent sectoral and regional structure with the financial core of the MRIO. These diverse environmental accounts within the IELab have many other applications. Here we comment on the significance and applications of the IELab in the domain of environmental-intensity indicators per unit of economic output. We also discuss the potential for using the IELab to address interconnections of these materials within the economy.

### 4.1. Environmental intensity of the economy

A range of benchmarking methods, spanning interconnections of natural resource flows with economies are emerging globally. These range across scales: cities (EIU 2010); states (Queensland 2012); and nations (PMSEIC 2010, World Bank 2017). Most current analysis of environmental intensities in economies is limited to assessment of overall nations. The indicators used for benchmarking performance generally focus on GHG emissions, energy, and water use per unit of economic production (See SI Table 3). The IELab is well positioned for more detailed analysis because it: (i) is capable of analysing these intensities at high spatial and sectoral resolution; (ii) multiple accounts are incorporated in an internally-consistent structure and; (iii) time-series of many indicators are now in place. This is expected to be of high value not only for comparison of options (from products to economies), but to help understand how economic sectors, regions or countries are decoupling economic growth from consumption of natural resources. As analysis and indicators of economic performance improves, further attention will be required to improve the energy, water and natural resources efficiency of buildings due to their significant consumption of these resources.

### 4.2. Interconnections of water and energy

In making choices about emissions-intensive building products (such as an aluminium-framed window) impacts on water can also be significant, for example, in the production of the aluminium directly, or in the provision of energy to alumina refineries. Embodied water flows through buildings and cities are approximately ten times the direct water flows (Kenway et al. 2008, Lenzen 2009), and water use by the energy sector is captured in the IO model through the water satellite data. The IELab creates the potential for appreciating region-specific direct and indirect water impacts and the same principle applies for all other environmental satellite accounts within the IELab.

A "grand sustainability challenge" for buildings, and the cities that they collectively comprise, is to reduce inputs of water, energy, and materials while maintaining living standards (Newman 1999). Understanding interconnections of water, energy, materials and waste is vital to this challenge and to avoid problem-shifting (externalising), rather than problem-solving across the interconnected issues. One key to avoiding problem-shifting is the use of tools that span multiple topics and datasets at the scale and resolution of the IELab.

### 4.3. Material Flows and Waste

Materials are often the carriers of embedded energy emissions (notably in cement and steel) and we can also arrange data on material inputs and waste flows in the satellite data. The material flows data in the IELab is the same as in the CSIRO Material Flows Database (West et al. 2013) and a waste flows database has been constructed from various sources (Fry et al. 2015). Using the IELab apparatus and these data we can report the (direct and indirect) material footprint of the entire residential building construction sector in Australia: 60.4 Mtons/year at 2009. Given the total output from that sector (AUD 61.4

billion), the total material intensity was 0.98 kg/AUD. This latter figure accounts for materials in the complete supply chain leading to residential construction, including any materials consumed during the extraction of raw materials from nature and their transport. Likewise, we can report the waste flow footprint was 4.98 million tons/year and the total waste intensity 0.08kg/AUD.

## 5. **Conclusions and Outlook**

Using virtual laboratory technology hosting an input-output model hybridized with LCA methodology, we demonstrate that environmental impact assessment of the built environment can be specific (to products and/or regions), complete (the scope of the whole economy) and comprehensive (including direct and embodied impacts and multiple indicators) at the same time. In our case study (an aluminium framed window) we combined the precision of LCA and the scope of (multi-region) IO data to calculate direct and embodied emissions in the complete supply chain leading to this final product. This information and many other environmental performance measures reside in the one framework: the Australian IELab. With the IELab, decision-makers can assess performance of a product, a building, a precinct or a larger entity across the full supply chain network and against multiple environmental, economic and social measures. Data supporting this effort is integrated through a formal procedure that harmonises all inputs to a sectoral and regional classification of high resolution.

Variations certainly exist between building types and site location and, even for similar buildings, there may be different prices for materials and supply chains involved, and subsequently differentiated impacts.  Yet, the scope and flexibility of IELab and the structured and consistent way it can employ detailed, bottom up or top-down data, permits an investigation into such variations.

When aspiring to low or zero carbon buildings, precincts and cities, not only the operational emissions, but also the embodied emissions should be taken into account. No policy yet exists in Australia specifically aimed at reducing the embodied resource flows and emissions associated with buildings. The upcoming National Carbon Offset Standard for Buildings and Precincts proposes to include embodied emissions in a future version. IELab is a comprehensive, flexible and robust assessment tool well positioned to respond to the challenge of assessing and aiding the design of a low-impact built environment.

The IELab depends on, and enables, a powerful collaboration platform, which also presents an opportunity for Australian Cooperative Research Centres, such as those for Low Carbon Living and Water Sensitive Cities as users. Further development of the IELab to include international supply chains and regions is underway and this enlarges both the capacity of the IELab and the scope for yet more collaboration.

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## References


Acquaye, A. and Duffy, A. (2010). Input-output analysis of Irish construction sector greenhouse gas emissions. Building and Environment 45(3): 784-791.

Anderson, J. E., Wulfhorst, G. and Lang, W. (2015). Energy analysis of the built environment—A review and outlook. Renewable and Sustainable Energy Reviews 44(0): 149-158.

Australian Government - Department of the Environment and Energy (2016). Draft National Carbon Offset Standard for Precincts. Canberra, Commonwealth of Australia, Department of the Environment and Energy, http://www.environment.gov.au/system/files/resources/677ae66c-8854-4899-a3b9-9cfc47018ada/files/draft-precincts-standard.pdf.

Building Products Innovation Council (2017). Building Products Life Cycle Inventory. Australia, http://www.bpic.asn.au.

Bullard, C. W., Penner, P. S. and Pilati, D. A. (1978). Net energy analysis - handbook for combining process and input-output analysis. Resources and Energy 1: 267-313.

Chastas, P., Theodosiou, T. and Bikas, D. (2016). Embodied energy in residential buildings - towards the nearly zero energy building: A literature review. Building and Environment 105: 267-282.

Chau, C. K., Leung, T. M. and Ng, W. Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. Applied Energy 143(0): 395-413.

Chen, J., Wu, Y., Yan, H. and Shen, L. (2017). An Analysis on the Carbon Emission Contributors in the Chinese Construction Industry. Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate. Y. Wu, S. Zheng, J. Luo et al. Singapore, Springer Singapore**:** 1197-1206.

Citherlet, S., Di Guglielmo, F. and Gay, J.-B. (2000). Window and advanced glazing systems life cycle assessment. Energy and Buildings 32(3): 225-234.

Crawford, R. H. (2008). Validation of a hybrid life-cycle inventory analysis method. Journal of Environmental Management 88: 496-506.

Crawford, R. H. (2014). Post-occupancy life cycle energy assessment of a residential building in Australia. Architectural Science Review 57(2): 114–124.

Crawford, R. H., Bartak, E. L., Stephan, A. and Jensen, C. A. (2016). Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. Renewable and Sustainable Energy Reviews 63: 435-451.

Crawford, R. H., Bontinck, P.-A., Stephan, A. and Wiedmann, T. (2017). Towards an Automated Approach for Compiling Hybrid Life Cycle Inventories. Procedia Engineering 180: 157-166.

Crawford, R. H. and Treloar, G. J. (2005). An assessment of the energy and water embodied in commercial building construction. Proceedings: 4th Australian Life-Cycle Assessment Conference, Sydney.

Defourny, J. and Thorbecke, E. (1984). Structural path analysis and multiplier decomposition within a social accounting matrix framework. Economic Journal 94: 111-136.

Ding, G. K. C. (2014). Life cycle assessment (LCA) of sustainable building materials: an overview. Eco-efficient Construction and Building Materials, Woodhead Publishing**:** 38-62.

Dixit, M. K. (2017). Embodied energy analysis of building materials: An improved IO-based hybrid method using sectoral disaggregation. Energy 124: 46-58.

EIU (2010). Asian Green City Index. Assessing the environmental performance of Asia's major cities, Economist Intelligence Unit, http://sg.siemens.com/city_of_the_future/_docs/Asian-Green-City-Index.pdf.

Ely, R. C., D.; Chen, G.; Wiedmann, T. (2015). Carbon Footprinting the Gold Coast City consumption of goods and built environment products. 23rd International Input-Output Conference. Mexico City, Mexico.

Fry, J., Lenzen, M., Giurco, D. and Pauliuk, S. (2015). An Australian Multi-Regional Waste Supply-Use Framework. Journal of Industrial Ecology 20(6): 1295-1305.

GBCA (2017). A carbon positive roadmap for the built environment / Discussion paper, Green Building Council Australia, https://gbca-web.s3.amazonaws.com/media/documents/a-carbon-positive-roadmap-v1-%28writable%29-distributed.pdf.

Global Alliance for Buildings and Constructions (2015). Putting the Buildings and Construction Sector on a below 2°C path - Common Statement. Le Bourget, Paris, http://www.globalabc.org/bundles/app/pdf/GABC%20common%20statement%20total%20signatures.pdf.

Grant, T. (2016). AusLCI Database Manual v1.26, Australian Life Cycle Assessment Society (ALCAS), http://auslci.com.au/Documents/AUSLCI_Manual%20V1.26.pdf.

Heijungs, R. and Suh, S. (2002). The computational structure of life cycle assessment. Dordrecht, Netherlands, Kluwer Academic Publishers.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. and Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. Energy and Buildings 66: 232-245.

Iyer-Raniga, U. (2012). Applying Black Swan theory for achieving sustainability in the built environment. International Journal of Environmental Science and Engineering Research Vol 3(3): 108-113.

Kenway, S. J., Turner, G., Cook, S. and Baynes, T. (2008). Water-energy futures for Melbourne: the effect of water strategies, water use and urban form. Canberra, CSIRO.

Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. Energy and Buildings 42(3): 333-340.

Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K.-H., Haberl, H. and Fischer-Kowalski, M. (2009). Growth in global materials use, GDP and population during the 20th century. Ecological Economics 68(10): 2696-2705.

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., et al. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proceedings of the National Academy of Sciences 114(8): 1880-1885.

Lenzen, M. (2009). Understanding Virtual Water Flows: A multiregion input-output case study of Victoria. Water Resources Research 45: 1-11.

Lenzen, M. and Crawford, R. H. (2009). The Path Exchange Method for Hybrid LCA. Environmental Science & Technology 43(21): 8251-8256.

Lenzen, M., Geschke, A., Malik, A., Fry, J., Lane, J., Wiedmann, T., et al. (2017). New multi-regional input-output databases for Australia – enabling timely and flexible regional analysis. Economic Systems Research 29: in press.

Lenzen, M., Geschke, A., Wiedmann, T., Lane, J., Anderson, N., Baynes, T., et al. (2014). Compiling and using input-output frameworks through collaborative virtual laboratories. Science of the Total Environment 485–486: 241–251.

Moskowitz, P. D. and Rowe, M. D. (1985). A comparison of input-output and process analysis. Health and Environmental Risk Assessment. P. F. Ricci and M. D. Rowe. New York, NY, USA, Pergamon Press: 281-293.

Moussavi Nadoushani, Z. S. and Akbarnezhad, A. (2015). Effects of structural system on the life cycle carbon footprint of buildings. Energy and Buildings 102: 337-346.

Newman, P. W. G. (1999). Sustainability and cities: extending the metabolism model. Landscape and Urban Planning 44(4): 219-226.

PMSEIC (2010). Challenges at Energy-Water-Carbon Intersections. Report of the PMSEIC Expert Working Group. Canberra, Prime Minister's Science, Engineering and Innovation Council.

Queensland Government - Department of Energy and Water Supply (2012). The 30-year electricity strategy. Directions paper. CS2052 12/12. Brisbane, Department of Energy and Water Supply, https://gci.uq.edu.au/filething/get/10293/QLD%20DEWS%2030yr-electricity-strategy-directions-paper.pdf.

Ramesh, T., Prakash, R. and Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings 42: 1592-1600.

Rodríguez-Alloza, A. M., Malik, A., Lenzen, M. and Gallego, J. (2015). Hybrid input–output life cycle assessment of warm mix asphalt mixtures. Journal of Cleaner Production 90: 171-182.

Säynäjoki, A., Heinonen, J. and Junnila, S. (2012). A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. Environmental Research Letters 7(3): 034037.

Säynäjoki, A., Heinonen, J., Junnila, S. and Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? Environmental Research Letters 12(1): 013001.

Sharma, A., Saxena, A., Sethi, M., Shree, V. and Varun (2011). Life cycle assessment of buildings: A review. Renewable and Sustainable Energy Reviews 15(1): 871-875.

Stephan, A. (2013). Towards a comprehensive energy assessment of residential buildings. A multi-scale life cycle energy analysis framework. ULB-BATir - Building, Architecture and Town planning and UoM-ABP - Architecture, Building and Planning. Brussels, Université Libre de Bruxelles and The University of Melbourne. Joint-PhD.

Stephan, A. and Athanassiadis, A. (2017). Quantifying and mapping embodied environmental requirements of urban building stocks. Building and Environment 114: 187-202.

Stephan, A. and Crawford, R. H. (2014). A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings. Architectural Science Review 57(1): 39-48.

Stephan, A. and Crawford, R. H. (2016a). The relationship between house size and life cycle energy demand: Implications for energy efficiency regulations for buildings. Energy 116, Part 1: 1158-1171.

Stephan, A., Crawford, R. H. and de Myttenaere, K. (2013). Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia. Building and Environment 68: 35-49.

Stephan, A. and Stephan, L. (2016b). Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Applied Energy 161: 445-464.

Suh, S. and Heijungs, R. (2007a). Power series expansion and structural analysis for Life Cycle Assessment. International Journal of Life Cycle Assessment 12(6): 381-390.

Suh, S. and Huppes, G. (2005). Methods for Life Cycle Inventory of a product. Journal of Cleaner Production 13: 687-697.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., et al. (2004). System boundary selection in Life-Cycle Inventories. Environmental Science & Technology 38(3): 657-664.

Suh, S. and Nakamura, S. (2007b). Five years in the area of input-output and Hybrid LCA. International Journal of Life Cycle Assessment 12(6): 351-352.

Teh, S. H., Wiedmann, T., Castel, A. and de Burgh, J. (2017a). Hybrid life cycle assessment of greenhouse gas emissions from cement, concrete and geopolymer concrete in Australia. Journal of Cleaner Production 152: 312-320.

Teh, S. H., Wiedmann, T., Schinabeck, J. and Moore, S. (2017b). Replacement Scenarios for Construction Materials Based on Economy-wide Hybrid LCA. Procedia Engineering 180: 179-189.

Treloar, G., Fay, R., Love, P. E. D. and Iyer-Raniga, U. (2000a). Analysing the life-cycle energy of an Australian residential building and its householders. Building Research & Information 28(3): 184-195.

Treloar, G., Love, P. E. D. and Holt, G. (2001a). Using national input-output data for embodied energy analysis of individual residential buildings. Construction, Management and Economics 19: 49-61.

Treloar, G., Love, P. E. D., Iyer-Raninga, U. and Faniran, O. O. (2000b). A hybrid life cycle assessment method for construction. Construction, Management and Economics 18: 5-9.

Treloar, G. J. (1997). Extracting embodied energy paths from input-output tables: towards an input-output-based hybrid energy analysis method. Economic Systems Research 9(4): 375-391.

Treloar, G. J., Fay, R., Ilozor, B. and Love, P. E. D. (2001b). An analysis of the embodied energy of office buildings by height. Facilities 19(5/6): 204-214.

Troy, P., Holloway, D., Pullen, S. and Bunker, R. (2003). Embodied and operational energy consumption in the city. Urban Policy and Research 21(1): 9-44.

Waugh, F. V. (1950). Inversion of the Leontief matrix by power series. Econometrica 18(2): 142-154.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. and Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21(9): 1218-1230.

West, J. and Schandl, H. (2013). Global Material Flow and Resource Productivity Dataset. CSIRO. Canberra, UNEP, Bangkok, http://www.cse.csiro.au/forms/form-mf-start.aspx.

Wiedmann, T. (2017). An input–output virtual laboratory in practice – survey of uptake, usage and applications of the first operational IELab. Economic Systems Research 29(2): 296-312.

Wiedmann, T., Crawford, R., Seo, S. and Giesekam, J. (2013). The Industrial Ecology Virtual Laboratory and its application to sustainability and environmental engineering – the case of low carbon living. Sustainable Engineering Society (SEng) 2013 Conference. National Convention Centre, Canberra, ACT.

Wiedmann, T. O., Chen, G. and Barrett, J. (2016). The Concept of City Carbon Maps: A Case Study of Melbourne, Australia. Journal of Industrial Ecology 20(4): 676-691.

World Bank (2017). Water productivity, total. IBRD. IDA Data. New York, http://data.worldbank.org/indicator/ER.GDP.FWTL.M3.KD.

WRI, C40 and ICLEI (2014). Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) - An Accounting and Reporting Standard for Cities, World Resources Institute, C40 Cities Climate Leadership Group and ICLEI Local Governments for Sustainability, http://ghgprotocol.org/city-accounting.

You, F., Hu, D., Zhang, H., Guo, Z., Zhao, Y., Wang, B., et al. (2011). Carbon emissions in the life cycle of urban building system in China—A case study of residential buildings. Ecological Complexity 8(2): 201-212.

Yu, M., Wiedmann, T., Crawford, R. and Tait, C. (2017). The Carbon Footprint of Australia's Construction Sector. Procedia Engineering 180: 211-220.