Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 00 (2017) 000–000

Procedia Engineering

www.elsevier.com/locate/procedia

International High- Performance Built Environment Conference – A Sustainable Built Environment Conference 2016 Series (SBE16), iHBE 2016

The Carbon Footprint of Australia's Construction Sector

Man Yu[a]*, Thomas Wiedmann[a,b], Robert Crawford[c], Catriona Tait[d]

[a]Sustainability Assessment Program (SAP), School of Civil and Environmental Engineering, UNSW Australia, Sydney, NSW 2052, Australia
[b]ISA, School of Physics A28, The University of Sydney, Sydney, NSW 2006, Australia
[c]Faculty of Architecture, Building and Planning, University of Melbourne, Melbourne, VIC 3010, Australia
[d]Cardno, St Leonards, NSW 2065, Australia

Abstract

Australia accounts for just 0.33% of the world's population yet it is one of the highest emitters of greenhouse gas (GHG) emissions per capita in the world. The construction sector is a substantial area for mitigation efforts in Australia because of its economic importance and its involvement with indirect GHG emissions, i.e. those embodied in construction supply chains, including construction materials and electricity use. While the majority of policies and regulations focus on reducing direct emissions from buildings, more attention needs to be paid to the embodied emissions of the whole sector as these can take up anywhere between 10% and 97% of the whole life-cycle carbon emissions.

This study aims at unravelling the total carbon footprint of the construction sector in Australia from 2009 to 2013, identifying the key contributing supply chains, industries and products. An economy wide input-output (IO) analysis is performed using a collaborative, cloud-based data platform – the Industrial Ecology Virtual Laboratory (IELab). This allows for a detailed disaggregation of sectors and permits more refined analysis as well as benchmarking against other sectors in the economy.

Results for CO_2e emissions by final demand show the construction sector makes up 18.1% of Australia's carbon footprint, compared to only 1.9% of direct emissions in 2013. The largest contributors to these embodied emissions are electricity, water & waste and materials throughout the years. Results are also broken down by detailed construction activities in residential / non-residential, road & bridge, other heavy and civil engineering and construction services. Mitigation options for electricity supply and materials use in the Australian construction sector are suggested.

Peer-review under responsibility of the organizing committee iHBE 2016.

Keywords: construction sector; carbon footprint; embodied emissions; input output analysis; Australia

* Corresponding author. Tel.: +61-466-911-638.
E-mail address: man.yu@unsw.edu.au

1877-7058
Peer-review under responsibility of the organizing committee iHBE 2016.

1. Introduction

1.1. Greenhouse gas implications of the construction sector

The construction sector was directly and indirectly responsible for 18% of global greenhouse gas (GHG) emissions in 2010 [1], and it was the largest consumer of materials in 2005 with far-reaching implications on energy use and GHG emissions [2]. Among various major emitting industries, the construction sector offers large abatement opportunities for emission reduction in the short-term due to its economic importance and involvement with GHG emissions embodied in construction supply chains [3]. While the majority of policies and regulations focus on reducing direct emissions from buildings, more research over recent years has paid attention to the indirect or life-cycle GHG emissions of the whole sector [4]. A recent review of life-cycle energy in buildings found that embodied energy can take up anywhere between 5% and 100% of whole life-cycle energy consumption (equating to 10-97% of whole life-cycle carbon emissions) depending on building function, location, material use and assumptions about the service life and energy supply. This proportion tends to increase as buildings transition from conventional to passive, low energy and nearly zero energy buildings [5].

Acquaye and Duffy [6] found that 11.7% of Ireland's national emissions were from the construction sector in 2005, and 71% of these from indirect sources. Meanwhile, Norway reported its GHG emissions from construction as 4.2 Mt CO_2e in 2003 and 5.3 Mt CO_2e in 2007, of which embodied emissions constituted the majority of total emission [7]. Chang et al. [8] found that the energy use in the construction sector accounted for nearly 50% of China's total energy use in 2007 and that the largest contributors to embodied energy in construction were materials, heating, fuels and electricity supply. Chen et al. [9], furthermore, concluded later that the construction industry, accounting for 66.5 % of Chinese total carbon emissions, was the largest carbon emitter among all industries in China in 2009, of which 96.6% were indirect (embodied) carbon emissions with the largest contribution coming from the electricity, gas & water supply sector.

The studies of Ireland and Norway's construction industry emissions and others identified future areas for emission mitigation through measures such as increasing the share of renewable energy, enhancing the maintenance of machinery and equipment, optimizing operations, reducing the amount of carbon-intensive materials used, limiting the distance for materials transportation [6, 8].

1.2. Australia's construction sector

Australia accounted for just 0.33% of the world's population yet it was one of the highest emitting countries in the world in terms of per-capita emissions [10]. Since the Paris Climate Change Agreement confirmed the global transition to zero net emissions well before the end of the century, Australia, as a signatory to the Agreement, should be aiming to achieve the net zero goal by about 2050 in order to stay within the recommended carbon budget of 1% of global total, concluded by Australian Climate Change Authority [11]. The same report found that if Australia's built environment sector reaches zero carbon emissions for the operation of residential and commercial buildings by 2050, it could contribute 28% to the country's 2030 emissions reduction target and save up to AU$20 billion [11].

It is of great significance to track emissions where possible in construction sector because of its important economic position in Australia. According to the ABS Trend Chain Volume Measures for Value of Construction Work Done [12], the total construction work demonstrated an overall increasing trend from 2008 to 2014, and in the first quarter of 2016, the construction industry shared 7.64% of GDP, which made it the second highest industry behind mining [13]. Although the total value fell in recent years due to substantial reduction in heavy & civil engineering construction, the Australian Construction Industry Forum (ACIF) [14] estimated that construction will remain at this level for a few years because of the increasing residential building construction at the moment and predicted rise in non-residential building construction in the following years.

An early study conducted by the Australian Bureau of Statistics (ABS) [15] found that the construction sector within Australia had comparably small direct emissions from fuel combustion (4.6 Mt CO_2e in 1994/95) but significantly more embodied emissions from other sectors (21.4 Mt CO_2e in 1994/95). Taking embodied emissions into account reveals the impact of the construction as the fourth largest indirect emitting sector (excluding direct residential emissions) behind manufacturing (71 Mt CO_2e), electricity, gas, water & waste services (56.5 Mt CO_2e) and transport (22.3 Mt CO_2e). Wood and Dey [16] also identified construction sector as one of the key indirect emitters apart from electricity and direct residential emissions, and confirmed a substantial shift in emissions from primary industry (agriculture and manufacturing) towards secondary or tertiary industries (electricity generation, construction, transport, trade, repair and services) when embodied emissions were considered. The significant variance between direct and embodied emissions infers the importance to identify and track carbon footprint as a potential for emissions reduction.

1.3. Quantifying embodied GHG emissions

In contrast to direct emissions, it is more difficult to quantify embodied emissions due to the challenges in assigning the responsibilities of GHG generation.

Life-cycle assessments of building case studies, complete construction sectors or construction materials have been conducted in many regions since the early 1980s [17]. These studies use a range of methods, and it is concluded that a comparison between studies, even within a nation, is unrealistic due to the broad variation in data availability and assumptions made [18]. Nevertheless, a commonly acknowledged finding was the process-based assessment might underestimate the embodied supply-chain emissions of construction sector [19]. Therefore, input-output analysis (IOA) has been routinely applied to evaluate the carbon footprint (or embodied emissions) and embodied energy consumption of construction sector. As early as 1993, Oka et al. [20] had utilized IOA to estimate the embodied energy consumption and carbon emissions of six office buildings in Japan. After that, in 2001 and 2003, IOA on Australian buildings had been conducted by Treloar et al. [21] and Crawforad and Treloar [22] respectively to validate this approach.

IOA is a macroeconomic technique that uses inter-industrial monetary transactions to represent the complex interdependencies of industries in modern economy [16]. When coupling economic data with environmental data, environmentally extended IO model is created to assess the carbon emissions associated with each sector in relation to itself and other sectors [23]. It is the interest of this study as it is superior in evaluating emissions from an entire sector or nation. The consumption-based approach assumes each sector produces a homogenous set of goods or services, and the homogeneity can be minimized by disaggregating industrial sectors. Multi-Regional Input-Output (MRIO) models are extensions of the IO models and are emerging as a method to assess the global supply chain. These models aid in avoiding the need to assume domestic production technologies for imports and they can be set up to accommodate the purpose of the study with available data [24].

1.4. Aims of this study

Due to the absence of detailed disaggregated data concerning embodied emissions in individual areas within Australian construction sector, the ability to implement effective emission reductions is negatively affected. This study is conducted with the aim of filling this gap. Inventories of the carbon footprint of the Australian economy including specific construction areas are presented from 2009 to 2013 to identify the key contributing supply chains, industries and products. A two-region, globally closed model of Australia and the Rest of World (RoW) is employed. The carbon footprint as adopted in this paper comprises GHG emissions embodied in final demand for construction sector products (i.e. buildings and infrastructure). The embodied emissions are either emitted within Australia or embodied in imported goods and services required by Australian domestic final demand for construction products.

2. Methods and data

2.1. Environmentally extended input-output model and data

While economic data can be derived from national IO tables compiled by the ABS, and direct GHG emissions data can be retrieved from Australian Greenhouse Emissions Information System (AGEIS), these data sources are not adopted directly because they are not sufficiently detailed for refined analysis and they do not cover corresponding data for the RoW. Instead, a new, two-region input-output model has been constructed where both Australia and the RoW and their trade matrices are represented.

Australian IO and direct GHG emissions data for 112 industry / product sectors in 2009 were derived from the Industrial Ecology Virtual Laboratory (IELab, https://ielab.info) [25] to form the 2009 Australian Supply and Use Table (SUT), among which the construction industry is represented in five sectors: residential building construction, non-residential building construction, road & bridge construction, other heavy & civil engineering construction and construction services [26]. RoW data was aggregated from all countries in the Eora global MRIO in its simplified form of 26 sectors (Eora: worldmrio.com) [27, 28] and added to the Australian SUT. The procedure adopted was described in the Supplementary Information of Wiedmann et al, 2015, page 4 [29], resulting in a two-region environmentally extended input-output model for 2009. In order to make this model balanced and consistent with national accounts data, a RAS iterative scaling technique was adopted. The RAS method bi-proportionally scales the original unbalanced IO matrix using the fixed total input and output of each industry / product obtained from the 2009 national accounts into the final balanced IO model [30, 31].

Since IELab and Eora currently have no available data for years of 2010-2013, the two-region IO models for these years were created based on the 2009 model. The total inputs and total outputs in 2010 ABS IO table were used as the basis for the creation of 2010 and 2011 Australian SUTs [32]. Similarly, the total inputs and outputs in 2013 ABS IO table were used as the basis for the creation of 2012 and 2013 Australian SUTs [33]. In addition, national GHG emissions data from 2010 to 2013 by economic sector from AGEIS (excluding land use, land-use change and forestry (LULUCF) and residential emissions) were disaggregated and adopted to accommodate the need for emissions data in the model [26, 34]. Global GHG emissions data for years of 2010-2013 from World Bank (excluding LULUCF emissions, residential emissions, and Australian emissions) were disaggregated and adopted as the scaling factors for the calculations of RoW emissions in corresponding years. Likewise, global GDP data (excluding Australian GDP) from World Bank for these years were disaggregated and adopted as the scaling factors for the calculations of the RoW transaction matrix in corresponding years. In the end, the RAS method as described above was conducted for the model in each year to obtain balanced IO models.

2.2. Carbon mapping from industries to products

A "carbon map" is a table of GHG emissions that shows from which industries in an economy these emissions originate and in which finally demanded products these emission become embodied in [29]. This enables an analysis of intermediate emissions permitting the identification of the largest contributing sectors to embodied emissions within an industry. Converting the two-region IO model into a carbon map involves several matrix calculations, which were described in detail in [29].

For the purpose of illustrating results, the 112 disaggregated sectors supplied by the IELab are aggregated depending on the level on which the study is focusing. For the Australia-wide analysis, the sectors are aggregated following the Input-Output Industry Groups (IOIG) in accordance with Australian and New Zealand Standard Industrial Classification (ANZSIC) [26]. For the construction sector-wide analysis, the sectors are aggregated into “Materials”, “Agriculture”, “Coal, Oil & Gas”, “Machinery & Equipment”, “Electricity, Gas & Water”, “Construction”, “Transport”, “Services” and “Other”. For the assessment of emissions in further detail, a few of sectors in the construction sector level analysis are disaggregated further. For instance, the “Materials” category is disaggregated and re-aggregated into different types of materials such as “Iron & Steel”, “Timber”, “Cement, Concrete, Brick, Plaster, Ceramic and Limestone”, etc.

2.3. Assumptions and limitations

One key assumption in input-output analysis is the proportionality between physical and financial flows, i.e. embodied emissions are allocated in proportion to financial transactions between sectors. However, the effect of this assumption on the results is limited, since our analysis is conducted at a relative aggregated sectoral level (112 sectors) at which price fluctuations within one year are sufficiently equalized. Other limitations arise from areas specific to the data. This includes the non-availability of national IO accounts for years of 2011 and 2012, as well as the fact that the financial transactions made in a year do not necessarily indicate the work done in that year (due to depreciation of investments). The latter issue is alleviated by analysis of time series data offered in this work.

3. Results and discussion

Before getting to the construction sector level analysis, Australia's emissions in 2013 are initially presented both from a territorial (direct industry emissions) and from a carbon footprint (consumption-based) perspective, enabling a comparison between this study and previous studies. The carbon footprint (CF) of Australia's construction sector is then presented for 2013 and analyzed in detail to illustrate the specific contributing supply chains, industries and products within each sub-sector. Following that, a time series analysis ranging from 2009 to 2013 demonstrates the trends and changes occurring in recent years.

3.1. Australia's GHG emissions in 2013

National direct emissions in 2013 were 495 Mt CO_2e, while the national CF was calculated in this study as 499 Mt CO_2e (both excluding LULUCF and residential emissions). Imported goods and services contributed 23.6% to the CF.

In 2013, Figure 1 demonstrated the largest contributors to national CF in Australia were "services" (26.0%), "electricity, gas & water" (18.2%) and "construction" (18.1%). The results identified an 854% increase in emissions when considering embodied emissions from construction compared to the direct emissions from this sector. This was the largest percentage in increase of all sectors shown in Figure 1 and was much larger than the 365% identified in the 2001 ABS study [15].

These results confirmed the emission shift from primary industries when assessing direct emissions to secondary and tertiary industries when taking a consumption-perspective, which was also identified in the literature [16]. Primary industries, like agriculture, coal mining and oil extraction, involve emissions intensive sectors. Secondary and tertiary industries however utilize the commodities produced or collected by the primary industries. The implication of this on construction sector, as a secondary industry, is an increase in the responsibility for upstream emissions from suppliers (mostly construction materials) with a widening in scope for potential emission reductions.

Another observation found when comparing the 2001 ABS study [15] with this study was that the change of CF in the construction sector over the years between 1995 and 2013 is considerably larger than the change in the sector's direct emissions. The direct emission found in 2001 ABS study was 4.6 Mt CO_2e in 1995 and the embodied emission 21.4 Mt CO_2e [15], while in this study, these values were increased by 107% and 322%, respectively. Even though slightly different models and assumptions were used in the two studies, it was sufficiently evident to conclude the embodied emissions from construction increased significantly faster than the corresponding direct emissions over the years.

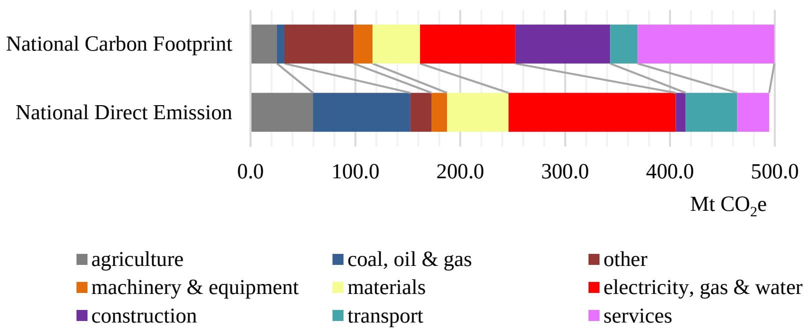

Fig.1. Australia's GHG emissions in 2013 from a consumption (CF) and a territorial (direct/industry) perspective.

3.2. Construction sector emissions in 2013

Direct GHG emissions from the construction industry in Australia were found to be 9.5 Mt CO_2e in 2013 and the CF was 90.3 Mt CO_2e, making up 1.9% and 18.1% of Australia's total emissions, respectively (Figure 1).

As shown in Figure 2, residential building construction was responsible for 23.8 Mt CO_2e emissions, non-residential building construction embodied 16.8 Mt CO_2e, 9.8 Mt CO_2e were embodied in road and bridge construction, and 47.3 Mt CO_2e were embodied in other heavy & civil engineering construction, making it the largest area of embodied construction emissions. Meanwhile, only 0.02 Mt CO_2e were embodied in construction services and imports for construction had 2.3 Mt CO_2e of embodied emissions. The reasons why "other heavy & civil engineering construction" had the highest embodied emissions were, first, because the largest amount of investment was made to this type of construction in 2013, and second, that this sub-sector emitted the highest amount of CO_2e (0.42 kg CO_2e) per dollar of final demand indicating it involved more GHG emissions intensive processes than other types of construction.

The sectors that contributed most significantly to construction sector CFs were "electricity, gas & water" (40.4%) and "materials" (20.7%). It was also noted that the "construction" itself contributed significantly to the industry's embodied emissions (8.3%). This included direct emissions from construction activities and machinery and also emissions related to construction services (see section 3.2.3 below). The next three sections broke down the results further in order to identify which industries / products contributed the most to embodied emissions in construction.

3.2.1. Embodied emissions from electricity

"Electricity, gas & water" as defined by ANZSIC includes all aspects of the electricity generation, delivery of electricity and gas through mains services, water, drainage, sewage systems as well as the collection treatment and disposal of wastes [26].

The breakdown (Figure 3a) revealed that electricity generation and transmission contributed 65.2% of the embodied electricity emissions to construction sector. This was due to the fact that the Australian electricity generation mix is dominated by fossil fuels (87%) [35]. Water & waste contributed 12.3%; imported electricity, gas & water contributed 22.5%; while gas supply contributed negligible embodied emissions.

Within the construction sector, "other heavy & civil engineering construction" was the sector with the largest amount of embodied emissions from electricity (Figure 2), confirming that this type of construction used the largest amount of electricity among all construction sectors in 2013.

As the largest contributor, electricity is evidently an area for considerable emission reductions, and the transition to near-zero-carbon electricity supply is required if the Paris Agreement is to be achieved. Among various renewable energy technologies, geothermal electricity has the highest CF intensity, while run-of-river hydropower has the lowest one; the CF intensities of solar photovoltaic and wind power lie in between, which can give some insights into the formulation of emission abatement polices [36].

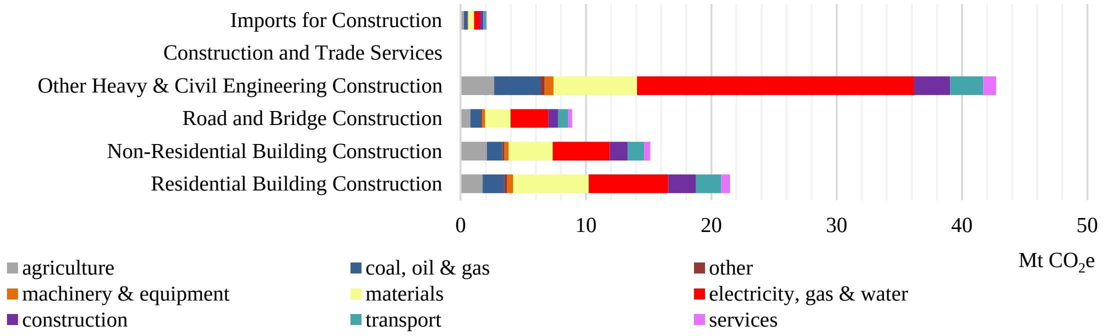

Fig.2. Carbon footprint of Australia's construction sector in 2013.

3.2.2. Embodied emissions from materials

It is well known that materials play a key role in contributing embodied emissions to the construction sector. This study found that cement, concrete, plasterboard, limestone, brick and other ceramics accounted for the largest embodied emissions (39.2%), other minerals accounted for 24.2%, iron & steel and timber contributed similar amount at around 9.8% and 9.3% respectively, other metals 9.2% and plastic, polymer and rubber 6.0% (Figure 3b).

Similar to the results of this study, several previous studies found that concrete and steel were the largest contributors to embodied emissions in construction projects as they were very energy intensive. Yan et al. [37] found 94-95% of embodied material emissions was form concrete or reinforced steel in Hong Kong and Giesekam et al. [38] showed 44% of industrial emissions arisen from steel and cement in UK construction industry.

A variety of options have been provided to reduce the carbon emissions coming out of materials used in construction industry. The first and most obvious option is to use alternative materials with lower environmental impacts. Ibn-Mohammed et al. [39] mentioned replacing energy-intensive materials by wood will significantly reduce the embodied emissions in buildings. A parallel study from our research team confirms this in quantitative terms. If 100% reinforced concrete is replaced by Engineered Wood Products (EWPs) in constructing all new residential buildings in Australia, a saving of 26 Mt CO_2-e can be achieved by 2050. When sequestration is taken into account, the saving would become to 119 Mt CO_2-e [40]. Secondly, materials use can be reduced through improved design and extended lifetime of existing structures [38]. The third approach is to take measures to reuse and recycle the materials. Currently, the recycling rate in Australia is much lower than other OECD countries, and construction industry has paid little attention to the paradigms of environmental sustainability. Practices, such as using waste from old buildings to construct new buildings or retrofit existing buildings, should be encouraged and widely implemented [41].

3.2.3. Embodied emissions from other construction sectors

In basic terms, the implication of embodied emissions within construction sector arose as a result of the monetary transactions between different construction companies.

It was found that 54.8% of embodied emissions came from construction services with the remaining 14.6%, 11.8%, 9.9%, 4.7% and 4.2% arising from residential building construction, other heavy & civil engineering construction, non-residential building construction, imports for construction and road & bridge construction, respectively (Figure 3c).

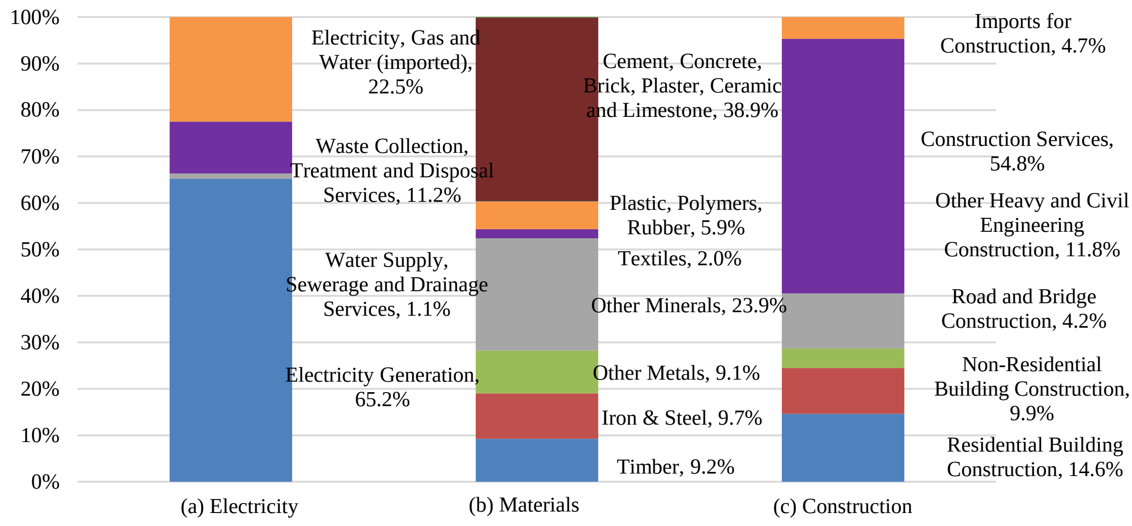

Fig.3. (a) Electricity; (b) Materials; (c) Construction-related emissions embodied in Australia's construction sector in 2013.

Construction services is a broad sector including more specific areas of construction that are not associated directly with the other four defined construction sectors. The large amount of embodied emissions from this sector comes from a broad range of activities, such as concreting, demolishing existing buildings, erecting and maintaining utility lines within subdivisions, building waterproofing and so on and so forth. The allocation of embodied emissions from the work done by other construction companies depends on the definition of the emitting construction projects. It was found that most of the emissions from construction services were embodied in residential building construction and other heavy & civil engineering construction (Figure 2).

3.3. CF of Australia's construction sector 2009-2013

National direct industry emissions and national total carbon footprint showed little variation in the time period 2009-2013, with a slight drop for the CF in later years and in the direct (territorial) emissions for 2013 only (Figure 4). The latter has been attributed to the introduction of a carbon tax by the Labor government in 2012 [42]. Both metrics are also similar in size, with the CF being the same or slightly higher than national emissions. This indicates that the amount of emissions embodied in imports and exports are very close to each other for Australia.

As was the case for 2013 (Figure 1) the major contributors to the national direct emissions were "electricity, gas & water", "coal, oil & gas", "agriculture" and "materials" for all years. Similarly, the largest contributors to national carbon footprint consistently remained into "services", "electricity, gas & water", "construction" and "other manufacturing". In addition, while the national direct emissions and national CF decreased by 2.9% and 0.6% respectively from 2009 to 2013, the direct construction emissions and construction CF increased by 9.6% and 10.6% respectively, indicating higher contribution of emissions from construction sector to national GHG emissions throughout the years. The construction CF peaked in 2012 with 93 Mt CO_2-e (Figure 5).

A breakdown by sub-sector (Figure 5) confirmed that "other heavy & civil engineering construction" contributed most to the total construction CF throughout the years. For 2012 and 2013 in particular, the contribution of this type of construction became even larger with decreased contribution arisen from building constructions. However, this trend has been reversed in 2013 and it is thought that emissions embodied in heavy construction might decline further in upcoming years since less investment has been made in this sector since 2014 [14].

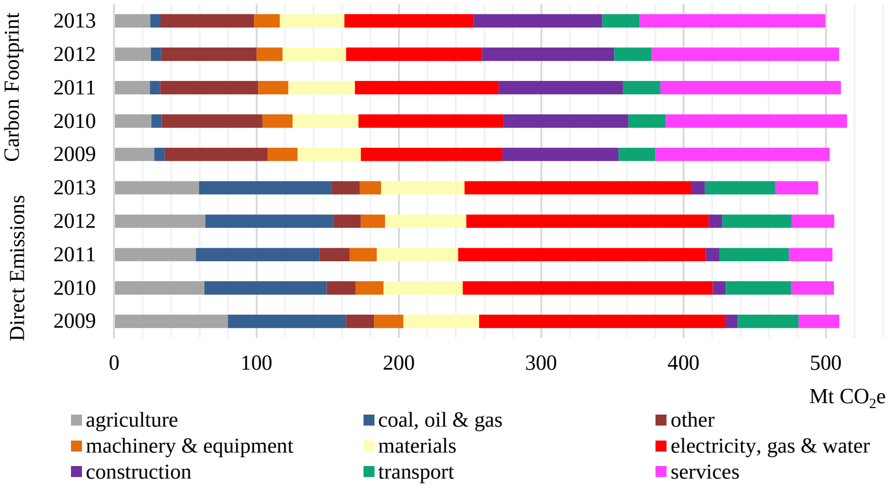

Fig.4. Australia's GHG emissions from a consumption (CF) and a territorial (direct/industry) perspective from 2009 to 2013.

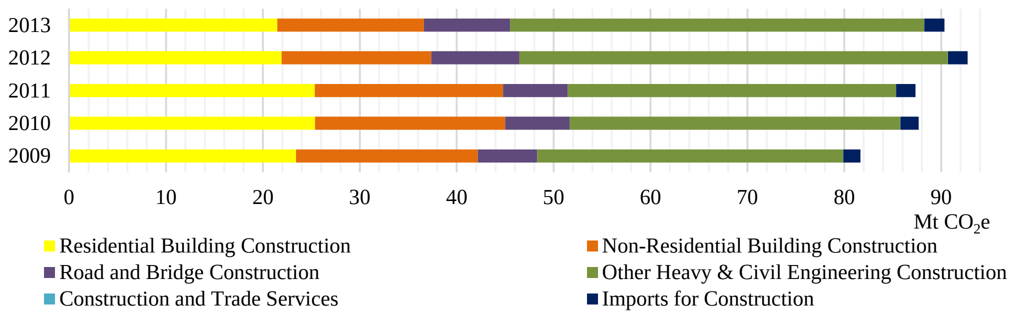

Fig.5. Carbon footprint of Australia's construction sector from 2009 to 2013.

4. Conclusion

This study set out with the purpose of identifying the key contributing sectors to the carbon footprint of the Australian construction industry. Using a 'carbon map' derived from a two-region input-output model, the construction sector has been analyzed at the economy-wide scale and in more detail than has been previously possible. The model provides insight on the carbon implications of the construction sector and identifies areas for the mitigation of GHG emissions.

The key findings from the model show that, in 2013, the carbon footprint in the construction sector makes up 18.1% of Australia's total CF, which is almost ten times more than the 1.9% of direct emissions contribution. The contribution of emissions from the construction sector to Australia's CF has increased in the last few years due to large amount of investment made to heavy & civil engineering work (partly due to the mining boom). This trend is not expected to last long though and further increases in emissions from the construction sector are likely to come from building construction in the coming years. Therefore, it is of great importance to track GHG emissions over time so that reduction efforts can be best targeted as the most significant sectors.

The largest contributors to the construction CF are "electricity, gas & water" and "materials" throughout the years. As the largest contributor, electricity is evidently an area for considerable emissions reductions. More renewable energy sources are suggested and energy consumed within construction processes needs to be sourced from these renewable technologies. With regard to the materials use, measures such as replacing carbon-intensive materials, reducing, reusing and recycling construction materials, are advised. New low-carbon materials, such as engineered wood products (EWPs) or geopolymer concrete, have the potential to replace the traditional materials of steel and Portland cement concrete, both of which are carbon-intensive. Several barriers, including perceptions of high cost, insufficient technical knowledge and skills, conservative industry culture and practices, and the limited availability of product and building-level data and tools for embodied carbon assessment need to be considered and overcome [3].

Acknowledgements

This research is funded by the Australian Research Council under the Discovery Project DP150100962. The authors gratefully acknowledge the funding support, and the suggestions and comments given by other two project members Paul-Antoine Bontinck and Dr. André Stephan. The Industrial Ecology Virtual Laboratory (IELab) is supported by the Australian Research Council, grant number LE160100066.

References

[1] Intergovernmental Panel on Climate Change, Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change, IPCC, Geneva, Switzerland, 2014.
[2] F. Krausmann, S. Gingrich, N. Eisenmenger, K.H. Erb, H. Haberl, M. Fischer-Kowalski, Growth in global materials use, GDP and population during the 20th century, Ecol. Econ. 68 (2009) 2696-2705.

[3] J. Giesekam, J.R. Barrett, P. Taylor, Construction sector views on low carbon building materials, Build. Res. Inf. 44 (2015) 423-444.
[4] European Commission, Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee of the regions on resource efficiency opportunities in the building sector, 2014.
[5] P. Chastas, T. Theodosiou, D. Bikas, Embodied energy in residential buildings-towards the nearly zero energy building: A literature review, Build. Environ. 105 (2016) 267-282.
[6] A.A. Acquaye, A.P. Duffy, Input–output analysis of Irish construction sector greenhouse gas emissions, Build. Environ. 45 (2010) 784-791.
[7] L. Huang, R.A. Bohne, Embodied air emissions in Norway's construction sector: input-ouput analysis, Build. Res. Inf. 40 (2012) 581-591.
[8] Y. Chang, R.J. Ries, Y. Wang, The emobodied energy and environmental emissions of construction projects in China: An eocnomic input-ouput LCA model, Energy Policy. 38 (2010) 6597-6603.
[9] J. Chen, Y. Wu, H. Yan L. Shen, An Analysis on the carbon emission contributors in the Chinese construction industry, in: Y. Wu, S. Zheng, J. Luo, W. Wang, Z. MoL. Shan (Eds.), Proceedings of the 20th International Symposium on Advancement of Construction Management and Real Estate, Springer Singapore, Singapore, 2017, 1197-1206.
[10] DCCEE, Australia's emissions projections 2012, Department of Environment, Canberra, Australia, 2012.
[11] ASBEC, Low carbon, high performance: how buildings can make a major contribution to Australia’s emissions and productivity goals, 2016.
[12] ABS, ABS Trend Chain Volume Measures for Value of Construction Work Done, 8755.0, Australia, 2016.
[13] Trading Economics, Australia GDP from construction 1974-2016, 2016 [cited 30 May 2016].
[14] ACIF, May 2016 ACIF Forecasts: latest summary 2016 [cited 23 May 2016].
[15] D. Trewin, Energy and greenhouse gas emissions accounts, Australia 1992-93 to 1997-98, 4604.0 ABS, Canberra, 2001.
[16] R. Wood, C.J. Dey, Australia's carbon footprint, Econ. Systems Res. 21 (2009) 243-266.
[17] M. Buyle, J. Braet, A. Audenaert, Life cycle assessment in the construction sector: A review, Renew. Sust. Energ. Rev. 26 (2013) 379-388.
[18] M. K. Dixit, C.H. Culp, J. L. Fernandez-Solis, System boundary for embodied energy in buildings: A conceptual model for definition, Renew. Sust. Energ. Rev. 21 (2013) 153-164.
[19] X. Zhang, F. Wang, Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China’s building sector, Build. Environ. 104 (2016) 188-197.
[20] T. Oka, M. Suzuki, T. Konnya, The estimation of energy consumption and amount of pollutants due to the construction of buildings, Energ. Buildings. 19 (1993) 303-311.
[21] G. J. Treloar, P. E. D. Love, G. D. Holt, Using national input-output data for embodied energy analysis of individual residential buildings, Constr. Manage. Econ. 19 (2001) 49-61.
[22] R. H. Crawford, G. J. Treloar, Validation of the use of Australian input-output data for building embodied energy simulation, in Eighth International IBPSA Conference. (2003): Eindhoven, Netherlands.
[23] O. Ortiz, F. Castells, G. Sonnemann, Sustainability in the construction industry: A review of recent developments based on LCA, Constr. Build. Mater. 23 (2009) 28-39.
[24] J. C. Minx, T. Wiedmann, R. Wood, G. P. Peters, M. Lenzen, A. Owen, K. Scott, J. Barrett, K. Hubacek, G. Baiocchi, A. Paul, E. Dawkins, J. Briggs, D. Guan, S. Suh, F. Ackerman, Input-output analysis and carbon footprinting: An overview of applications, Econ. Systems Res. 21 (2009) 187-216.
[25] M. Lenzen, A. Geschke, T. Wiedmann, J. Lane, N. Anderson, T. Baynes, J. Boland, P. Daniels, C. Dey, J. Fry, M. Hadjikakou, S. Kenway, A. Malik, D. Moran, J. Murray, S. Nettleton, L. Poruschi, C. Reynolds, H. Rowley, J. Ugon, D. Webb J. West, Compiling and using input–output frameworks through collaborative virtual laboratories, Sci. Total. Environ. 485-486 (2014) 241-251.
[26] B. Pink, D. Trewin, Australian and New Zealand Standard Industrial Classification (ANZSIC), 2006 - Codes and Titles, 1292.0.55.002, ABS, Canberra, 28/02/2006 [cited 02/05/2016].
[27] M. Lenzen, D. Moran, K. Kanemoto, A. Geschke, Building Eora: A global multi-region input-output database at high country and sector resolution, Econ. Systems Res. 25 (2013) 20-49.
[28] M. Lenzen, K. Kanemoto, D. Moran, A. Geschke, Mapping the structure of the world economy, Env. Sci. Technol. 46 (2012) 8374-8381.
[29] T.O. Wiedmann, G. Chen J. Barrett, The concept of city carbon maps: A case study of Melbourne, Australia, J. Ind. Ecol. 2015.
[30] M. Lenzen, B. Gallego, R. Wood, Matrix balancing under conflicting information, Econ. Systems Res. 21 (2009) 23-44.
[31] ABS, Australian National Accounts: Input-Output Tables, 2008-09, 5209.0.55.001, ABS, Canberra, 10/09/2012 [cited 15/04/2016].
[32] ABS, Australian National Accounts: Input-Output Tables, 2009-10, 5209.0.55.001, ABS, Canberra, 20/09/2013 [cited 15/04/2016].
[33] ABS, Australian National Accounts: Input-Output Tables, 2012-13, 5209.0.55.001, ABS, Canberra, 25/06/2015 [cited 15/04/2016].
[34] AGEIS, National Greenhouse Gas Inventory by Economic Sector, Department of the Environment, Canberra, [cited 04/05/2016].
[35] Clean Eenergy Council, Clean energy Australia report 2013, CEC, Melbourne, Australia, 2013.
[36] P. Wolfram, T. Wiedmann, M. Diesendorf, Carbon footprint scenarios for renewable electricity in Australia, J. Clean. Prod. 124 (2016) 236-245.
[37] H. Yan, Q. Shen, L. C. Fan, Y. Wang, L. Zhang, Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong, Build. Environ. 45 (2010) 949-955.
[38] J. Giesekam, J. Barrett, P. Taylor, A. Owen, The greenhouse gas emissions and mitigation options for materials used in UK construction, Energ. Buildings. 78 (2014) 202-214.
[39] T. Ibn-Mohammed, R. Greenough, S. Taylor, L. Ozawa-Meida, A. Acquaye, Operational vs. embodied emissions in buildings - A review of current trends, Energ. Buildings. 66 (2013) 232-245.
[40] S. H. Teh, T. Wiedmann, J. Schinabeck, S. Moore, Replacement scenario for construction materials based on economy-wide hybrid LCA, in: International High-Performance Built Environment Conference - A Sustainable Built Environment Conference 2016 Series iHBE 2016, Sydney, Australia, 2016.
[41] K. Chiveralls, G. Zillante, J. Palmer, J. Zuo, L. Wilson, S. Pullen, Cleaning up the construction industry, 2011 [cited 05/06/2016].
[42] P.J. Burke, Undermined by adverse selection: Australia's direct action abatement subsidies, Crawford School of Public Policy, The Australian National University, 2016.