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Measuring Carbon for Urban Development Planning

Colin Beattie, Curtin University Sustainability Policy (CUSP) Institute, WA, Australia
Jessica Bunning, Curtin University Sustainability Policy (CUSP) Institute, WA, Australia
Joanne Stewart, Murdoch University, WA, Australia
Peter Newman, Curtin University Sustainability Policy (CUSP) Institute, WA, Australia
Martin Anda, Murdoch University, WA, Australia

Abstract: This paper examines a framework for calculating carbon dioxide equivalent (CO_2-e) emissions in urban developments, including emissions inherent in: materials, construction, operation, transport, water, and waste processes over the life cycle of a development. The paper takes a holistic approach to urban design, to include not only the CO_2-e emissions inherent in the individual buildings but also in the infrastructure and service provision of the community as a whole metabolic system. A range of carbon assessment tools is examined to assess their capacity for measuring CO_2-e emissions in terms of this framework. The tools are reviewed for their applicability to four case studies in Western Australia: Peri-urban development (greenfield), Urban redevelopment (brownfield), Mining camps, and Indigenous communities, which demonstrate the type of settlement patterns that carbon assessment tools must respond to. The case studies are also indicative of the challenges facing other urban developments around the world in cutting CO_2-e emissions and enhancing sustainability. The results of the study show that two tools are currently available that can measure and model carbon emissions and carbon consequences of variations of design in urban developments. The tools C^{CAP}Precint and e-Tool are highlighted in this paper as outstanding examples.

Keywords: Development, Carbon, Planning, Urban, Sustainability, Tool, Lifecycle Analysis, Climate Change, Infrastructure, Transport, Water, Waste, Energy

Introduction

THERE IS MUCH discrepancy over the degree of CO_2-e emissions emitted from urban developments. The World Energy Outlook 2008 report claims cities produce between 67% and 71% CO_2-e emissions, and the Clinton Climate Initiative states that cities are responsible for 80% of emissions (Dhakal, 2010a). However, figures from the International Panel on Climate Change (IPCC) indicate that cities produce between only 30% and 40% of CO_2-e emissions (Satterthwaite, 2010). The varying accounts imply uncertainty exists over the boundaries of where carbon is emitted and the responsibility for its production. For example, the majority of stationary energy (not fuel for transport) is typically generated outside city boundaries; a substantial amount of that power is still a direct response to the appetite for energy within the city boundary from residents, commerce and industry.

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There is an increasing move to measure the carbon impact of all urban developments and associated infrastructure (energy supply, transport, buildings, water and waste) (Satterthwaite, 2010), which contribute to the carbon consumption and production patterns of people's lifestyles (Dhakal, 2010b). Assessing the energy consumed within the following areas is the key to understanding what society is responsible for in terms of CO_2-e emissions: the material and construction processes involved in the built environment; usage of energy within buildings; mode and usage of transport; the operational energy required for distribution of electricity, gas and water; and the management of waste. Change in any of these areas through urban development policy can play a major role in reducing global CO_2-e emissions.

Governments are exploring low-carbon alternatives to improve urban design and infrastructure networks, as well as new tools to measure CO_2-e emissions that will enhance capacity to evaluate progress towards decarbonised development. This review is aimed at assisting the understanding of current carbon performance and how carbon assessment can be mainstreamed in urban development. In doing this the CO_2-e emissions associated with four case studies of urban developments in Western Australia (WA) are examined, reflecting how people interact with their environment, including their varying carbon profiles. The sources of CO_2-e emissions identified for development of four community types are integrated into a framework for measuring those emissions. This review is part of an ongoing Australian Research Council project called Decarbonising Cities and Regions. The issues discussed in this paper on calculating CO_2-e emissions for urban communities in WA are indicative of the challenges facing urban development world over, whether they be in big cities or in remote settlements. So lessons learned from this paper on appropriate tools for carbon governance can arguably be applied to similar locations around the globe. The four types of development consist of two urban and two regional types:

Urban

- Urban fringe development (greenfields)–where lifestyles are inherently more car dependent and consumption-oriented.
- Urban redevelopment (brownfield)–where lifestyles are more focussed on walkable and public environments rather than private consumption.

Regional

- Mining camps–where lifestyles are focused on daily fluctuations of intensive on-site high energy use, and then long periods where workers are off-site at their mines.
- Remote Indigenous communities–where lifestyles are simple but the settlement is often dependent on energy intensive infrastructure and services and can have large fluctuations in population size.

The term urban development is used to represent all four of these settlement types which, in this paper, are a combination of buildings and shared infrastructure in a town site.

A Framework for Sources of CO_2-e Emissions in Urban Development

For each case study six sources of CO_2-e emissions are set out in Table 1. These have been examined in the ARC Linkage project Decarbonising Cities and Regions to determine the overall carbon footprint. By quantifying and analysing these sources of CO_2-e emissions across various developments ranging from current practice to those that appear more sustainable, a benchmark can be achieved for optimising reduced carbon development against baseline, business as usual (BAU) alternatives.

Table 1: Framework for Sources of CO_2-e emissions in Urban Development

a) Material The CO_2-e emissions associated with the extraction and/or farming of raw materials and the manufacture of assemblies used in buildings and infrastructure including the variations when regional and recycled materials are used;
b) Construction The CO_2-e emissions used in the demolition, site preparation, and construction processes including transport fuels, power and water to site, site waste management and variations with different approaches;
c) Operational The CO_2-e emissions associated with building/development operations from electrical power and natural gas including the differences with different building types and variations when provided from centralised or distributed sources;
d) Transport The CO_2-e emissions from transport fuels used in the on-going use of the area by residents including the variations with different urban and remote area designs;
e) Water The CO_2-e emissions produced in the full water cycle (pumping water in and out) including emissions linked to different forms of water infrastructure (centralised or distributed); and
f) Waste The CO_2-e emissions associated with the solid waste generated by the community and its variations when there is more re-use and recycling.

The framework is further represented in Figure 1. The diagram illustrates how the sources within the metabolism (resource inputs and waste outputs) of the development are interrelated with each component depending on the others. The determination of carbon metrics for the sources can enhance understanding on which responses are best suited for a particular development and the impact and trade-offs that might occur to CO_2-e emissions through these actions. For example, an action that could be implemented which directly targets the reduction of potable (drinking) water usage is to install a 'third pipe' system for recycling grey water. This would reduce the amount of potable water required, therefore reducing CO_2-e emissions associated with pumping the water. The effects of this strategy will bear on the following elements of the framework:

a) Material.
Additional embodied emissions associated with the additional pipes that would be required and in the recycled water treatment plant itself.
c) Operational.
Emissions associated with pumping water to and/or from the recycled water treatment plant and treating the water (this could be a positive or a negative impact).

The same concept of impacts and trade-offs can be applied to transport. Land use patterns like density and mixed-use have a big impact on how much private car use is associated with a development (Newman and Kenworthy, 1999). By not considering the transport carbon implications in urban design developments is to miss a major contributor to CO_2-e emissions. Some technologies that are highly effective at reducing CO_2-e emissions for example co-generation and public transport are highly dependent on the density of population and jobs, hence the design and assessment tool needs to include consideration of multiple factors (Beattie and Newman, 2011). Obviously any carbon assessment tool will need to recognise the interdependencies that occur between the many design and infrastructure options.

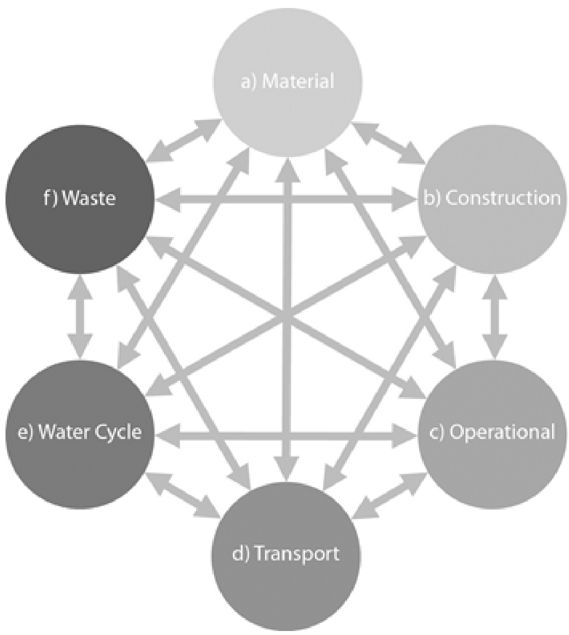

Figure 1: Sources of CO_2-e Emissions in Urban Development

An assessment tool that considers the carbon metrics for all the sources of CO_2-e emissions in an urban development is important for a number of reasons. It is necessary to have a tool that can facilitate quick assessments by professionals who are seeking to create new reduced carbon development that is cost effective. It is also crucial to have the data to understand the carbon metrics and associated costs to enable traction with state and local government in their assessment processes that increasingly require reduced carbon outcomes (e.g. COAG 2009). This knowledge provides a mechanism for change versus set targets, as it provides a sophisticated approximation of CO_2-e emissions. The framework for the six sources of CO_2-e emissions can enhance decision-making and allow authorities to benchmark emissions and build a portfolio of strategies to represent best practice for reduced carbon. If a tool can be both a design and an assessment tool it will enable carbon management to be mainstreamed in urban development.

Establishing Boundaries

Boundaries need to be set for the effective assessment of any project or plan. Figure 2 illustrates the construction and operating carbon impacts that ought to be assessed. The diagram is a high level, generic depiction. The specifics of how these boundaries apply to the four case studies will vary, sometimes significantly, across each case.

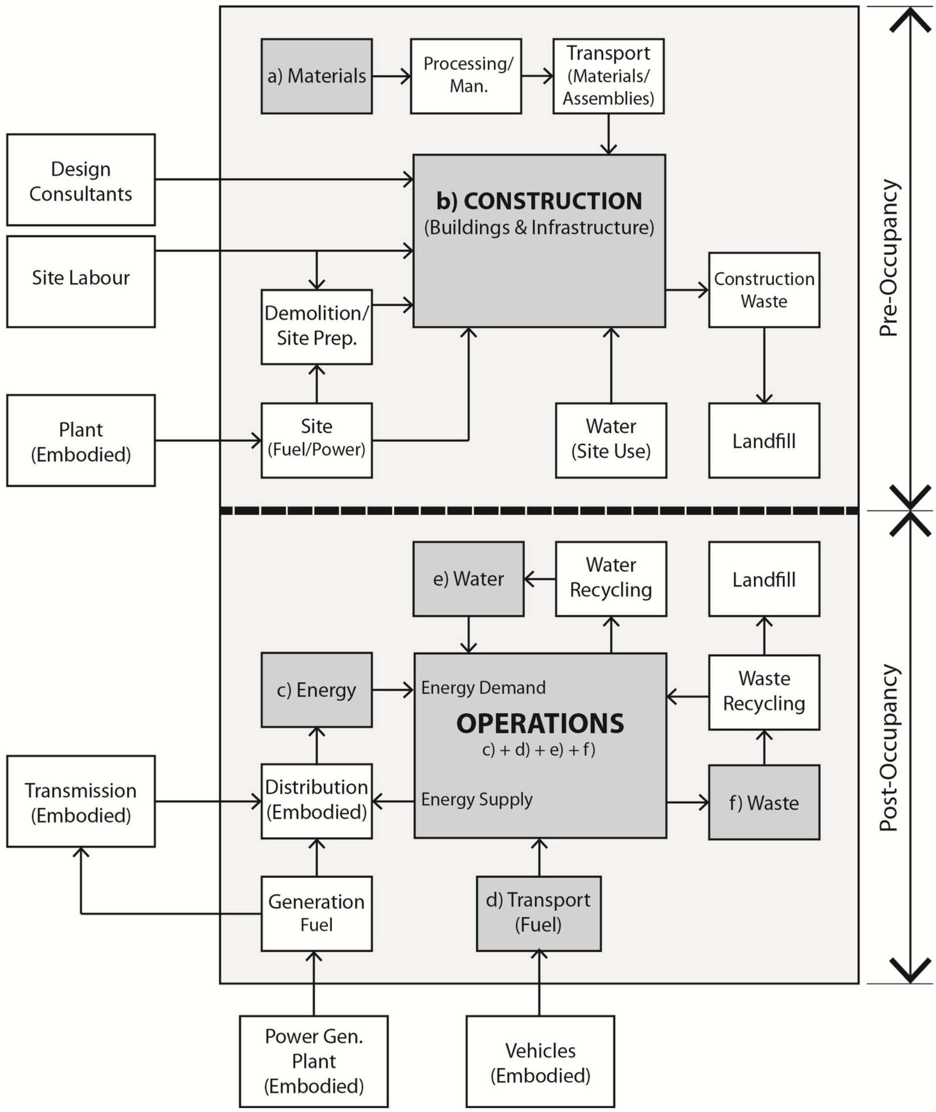

Figure 2: System Boundary for the "a) to f)" Framework

Selection and Application of Appropriate Tools

A literature review was conducted to examine a range of tools available and their capacity to provide a carbon metric and thus measure the CO_2-e emissions produced over the lifecycle of the four case studies. Examples of the references used include AILA (2010), Assefa et al (2010), BFRL (2007), Danish Building Research Institute (2006), Hamilton et al (2009), Kinesis (2011), NSW Department of Planning (2002) The Athena Institute (2010), US Department of Transportation (2007). Of the 34 tools reviewed, the majority considered CO_2-e emissions in their particular frameworks but did not provide the functionality to calculate the actual CO_2-e emissions produced throughout the lifecycle of a development. C^{CAP}Precinct and eTool were the tools that performed best in terms of being applicable to the highest number of carbon sources as defined by the framework, thus satisfying four of the six sources.

In order to assist in choosing the right tools it is necessary to see the qualitative differences between settlement types. The Urban Fringe and Urban Redevelopment cases are mostly considering large scale urban developments in the order of thousands of residents. The Regional cases that will be examined are in the order of 50 to 1000 residents. Small urban developments could potentially use either tool depending on the level of detail that they require and the purpose of the study. The definition of 'small' in this case is really down to the end user and how much time is available to assess a project.

C^{CAP}Precinct (Kinesis, 2011) can be applied to a project of any scale at an early stage, even before road layouts have been planned, by using the in-built algorithm that calculates road types and lengths including services distribution networks based on the available area. As the design unfolds, further iterations of the model can be assessed, providing greater detail and potentially allowing better design decisions to be made at an earlier stage. The eTool software cannot predict the allocation of roads and services before the design of a development is formalised, rather it models the energy details of the buildings, energy systems and water systems separately so it is inherently more useful for a small development. C^{CAP}Precinct covers the infrastructure associated with a large scale development based on existing knowledge of standard road construction methods and what development uses they are applicable to.

The urban metabolism is considered to be quite different for urban developments compared to small-scale remote communities, as the latter have quite different housing densities, occupancy rates, transport modes and configurations, and energy and water grid supplies. C^{CAP}Precinct is driven by databases derived from existing urban areas that provide a baseline for fundamental information relating to energy, water and transport and is therefore an appropriate choice for the large-scale urban developments. The flexibility of eTool for single and grouped housing, small community buildings and off-grid energy and water systems make it particularly useful for the remote small-scale settlements of mining camps and Indigenous communities. The open nature of the eTool software and depth of information available for a range of energy and water sources is essential for assessing regional communities–as these are neither connected to grid supply systems nor designed with standard urban layouts. The eTool software can also be used for small-scale urban housing assessments.

Reviewing the Tools

C^{CAP} Precinct

The C^{CAP}Precinct tool is made up of five modules that examine: energy; embodied CO_2-e; the water cycle; land-use and transport and cost-benefit. The modules are connected and when the relevant data are entered into each one, they inform one another and calculate the following four key performance indicator (KPI) total outputs (metrics shown in brackets):

- Embodied Emissions(kg CO_2-*e*/per person)
- Energy and Greenhouse Gases(kg CO_2-*e*/per person/year)
- Potable Water(kl H_2O/per person/year)
- Vehicle Hours Travelled(hours/per person/week)
- Cost and Total Affordability($/per dwelling/year)

The tool also quantifies and reports on the results that sit behind these KPIs, including electricity and gas consumption at a building and precinct level, resident vehicle kilometres travelled and mode split, and the capital and recurrent costs of green infrastructure. C^{CAP}Precinct was reviewed to assess how it considers each source of CO_2-e emissions in the framework:

- CO_2-e Emissions used in Materials
  The model considers a single snapshot of the development project, which reflects the embodied CO_2-e emissions at the time of modelling however, the tool is designed to be iterative so as data becomes more specific the model can be altered and the results recalculated. Embodied emissions associated with mixed-use, retail and commercial buildings are not calculated.
  The model includes internationally recognised lifecycle databases from the SimaPro LCA software and allows a selection of basic building assemblies across single, detached and multi-unit dwellings, as shown in Figure 3. A source of materials and locations can be chosen for fourteen common building materials. A clear limitation is that the model does not allow for a mix of designs with respect to materials. For example, all detached dwellings can only be modelled with a single set of materials and assemblies.

EMBODIED CO2 INPUTS

DWELLING ASSEMBLY

	Detached Dwellings	Attached Dwellings	Multi-Unit Dwellings
Roof	Timber Frame, Terracotta Tile Roof	Timber Frame, Terracotta Tile Roof	Concrete Slab, Synthetic Rubber Membrane Roof
External Walls	Cavity Clay Brick Wall	Cavity Clay Brick Wall	200mm Hollow Core Precast Concrete Wall
Internal Walls	Timber Stud Wall	Timber Stud Wall	150mm Tilt-Up Precast Concrete Wall
Upper Floor	Elevated Timber Floor (Upper Level)	Elevated Timber Floor (Upper Level)	110mm Elevated Concrete Floor
Ground Floor	110mm Elevated Concrete Floor	110mm Concrete Floor Slab on Ground	110mm Elevated Concrete Floor
Party Wall	NO WALL	Cavity Clay Brick Wall	Cavity Concrete Block Wall
Carparking	110mm Concrete Floor Slab on Ground	110mm Concrete Floor Slab on Ground	110mm Concrete Floor Slab on Ground
Windows	Standard Aluminium Single Clear	Standard Aluminium Single Clear	Standard Aluminium Single Clear
External Doors	Solid hardwood external door	Solid hardwood external door	Solid hardwood external door
Internal Doors	Foam-cored wood-surfaced internal door	Foam-cored wood-surfaced internal door	Foam-cored wood-surfaced internal door

MATERIALS

GHG sequestered from wood products? FALSE

	Dwellings	Infrastructure
Clay Brick Cladding	Standard Clay Brick (RER)	
Cement Block Cladding	Solid Cement Block (DE)	
Structural Concrete	20 Mpa Concrete	20 Mpa Concrete
Bulk Insulation	Glasswool Blanket (CH)	
Steel	Rolled Structural Steel (AU)	Rolled Structural Steel (AU)
Structural Hardwood	Standard Struct Hardwood (AU)	
Structural Softwood	Standard Struct Softwood (AU)	

	Dwellings	Infrastructure
Aluminium	Standard Aluminium (AU)	Standard Aluminium (AU)
Plasterboard	Gypsum Plasterboard (CH)	
Glass	Standard Glass, 0% Recyc (AU)	
Paint Finish	Water-based Acrylic (RER)	
Paving	Light Clay Brick (DE)	Light Clay Brick (DE)
Aggregate	Gravel (AU)	Gravel (AU)
Binding	Lime Mortar (CH)	Lime Mortar (CH)

Figure 3: Partial Screenshot of C^{CAP}Precinct Embodied CO_2-e Inputs

- CO_2-e Emissions in the Construction Process
  The energy used in the construction and assembly of the buildings and infrastructure that form part of the development is not included in the tool. The significance of construction energy to the overall CO_2-e emissions is not presently known.
- Operational Energy
  This module takes the form of a ledger recording the ongoing operational demand of a precinct on an hourly basis, in terms of gas and electricity consumed and potentially, exported. Importantly, it considers the thermal energy loads from residential and non-residential hot water systems, and space heating and cooling.
- Transport Fuels
  The transport fuel used in the construction process has been considered in a) above, where sources of materials and country of origin can be selected, as shown in Figure 3. In terms of the ongoing use of the area, the tool provides an analysis of the movement of residents in and around the development based on private vehicle use and public transport options.
- CO_2-e Emissions in the Water Cycle
  Both of the water modules (potable and storm) adopt an hourly account of demands and supplies measured against the reference model, which uses data from the Water Authority that is broken down by postcode. Non-residential water use is also covered by the same data set. The hourly modelling can demonstrate periods of high water use (e.g. from irrigation or heat rejection) and reconcile these with appropriate alternative supplies. Flow rates and consumption can be converted to CO_2-e emissions by calculating the amount of energy required to pump the water around.
- Waste
  CO_2-e emissions associated with solid waste are not covered by C^{CAP}Precinct.

In summary, the tool provides an automatically generated report including results as a percentage change against BAU, but more importantly the KPI's monitored generate specific metrics.

Example – Cockburn Coast, WA

The Cockburn Coast site to the South of Fremantle, WA is being redeveloped as part of a District Structure Plan (DSP) proposed by the Western Australian Planning Commission and Landcorp. The site covers just over 200ha and will have 4850 new dwellings, 10,000 residents and 6800 jobs, which aligns with the state development plan, *Directions 2031*. The DSP set some sustainability targets expressed as percentage improvements against the per capita average including:

- 20% waste reduction
- 60% wastewater reuse
- 30% reduction in scheme water consumption
- 40% reduction in stationary greenhouse gas emissions

The C^{CAP}Precinct tool was used to assess carbon as part of the planning design process, comparing parameters set by the DSP and a high performance alternative with the Perth

Metropolitan average. It was very quickly established that the targets set by the DSP were easily achievable with relatively simple approaches, some of which would be expected in new developments anyway. So, the bar was raised by modelling the proposal using a number of additional technologies that are associated with improved performance. Table 2 shows the approaches taken to meet the DSP targets and the higher performance strategies applied to the model.

Table 2: Strategies Applied to Reduce CO_2-e Emissions based on those Set by the Planning Agency and those Developed by the Researchers out of the C^{CAP}Precinct Tool

	District Structure Plan	**High Performance**
ENERGY AND GREENHOUSE		
Thermal Performance	NatHERS 7 star	NatHERS 7 star
Hot Water, Heating and Cooling	Residential: Solar (gas boost) hot water, 5 star heating and cooling Non-residential: conventional hot water, heating and cooling	Residential detached and attached: Solar (gas boost) hot water, 5 star heating and cooling Residential multi-unit and non-residential: tri-generated hot water, heating and cooling
Renewable and Low Carbon Energy	None	1.5kWe solar PV (residential detached and attached) 1,500kWe tri-generation plant (residential multi-unit and non-residential)
WATER		
Fixture Efficiency	Residential: standard irrigation, standard practice (3 star WELS) Non-residential: economic best practice (efficiency measures with two year payback)	Residential: efficient irrigation (30% efficiency improvement) and fixture efficiency (≈4.5 star WELS) Non-residential: high efficiency (greater than two year payback)
Appliance Efficiency	Residential: ≈2 star WELS	Residential: ≈4.5 star WELS
Alternative water Supply	None	Residential and non-residential wastewater reuse scheme (third pipe) for irrigation, toilet, laundry and heat-driven chiller heat rejection
TRANSPORT		
Public transport Access	Nearest major transport node (bus) of 400m and weekday peak frequency of 15 minutes	Nearest major transport node (light rail) of 400m and weekday peak frequency of 10 minutes

Car Parking Rates	Detached: 2 car spaces per dwelling Attached: 1 car space per dwelling Multi-unit: 1.4 car spaces per dwelling	Detached: 1 car space per dwelling Attached: 1 car space per dwelling Multi-unit: 1 car space per dwelling
Car Share	None	Available for detached, attached and multi-unit dwellings. Expected take-up rate is approximately 12% of residents.

A feature of the tool that falls outside of the framework is to include both capital cost for applied strategies and annual savings in utility and transport costs. The reality is that cost is a key, if not *the* key indicator that determines what strategies are implemented, so the importance of this simple cost-benefit inclusion is obvious. And, for this particular case, the results demonstrated a compelling argument to explore the higher performance case, with an extra cost of AU$900/dwelling (average over all dwellings) capital cost over the DSP case, to achieve significantly better results in all the KPI's (Figure 4).

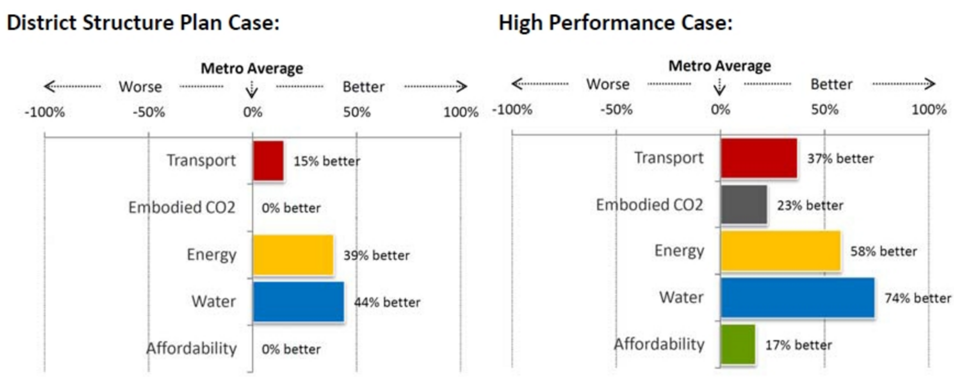

Figure 4: Screenshot of C^{CAP}Precinct KPI Outputs

eTool

eTool is a software program that calculates the embodied and operating energy and related CO_2-e emissions of buildings and small civil works (Haynes and Bruce, 2011). It has been released online (www.etool.net.au) and reviews of its pre-release version have indicated its suitability to small-scale urban developments. The tool is particularly suited to the remote small-scale villages of this study: mining camps and Indigenous communities, as it caters for housing, small community buildings and off-grid energy and water supply systems.

The tool employs a lifecycle analysis method providing calculations of: a building's lifespan; initial embodied energy of materials; recurring embodied energy in subsequent fit outs and maintenance; transport during construction and key aspects of operational energy.

Energy associated with end-of-life aspects, such as demolition or recycling of materials are not calculated.

The tool calculates metrics for primary energy use, CO_2-e emissions and operational costs of electricity supply including power used for water supplies and sewerage. These can be reported at a number of intensity levels including in total or per annum for each dwelling, per square metre or per occupant. Annual and total energy use and CO_2-e emissions are also aggregated for materials, transport during construction, recurring maintenance, assembly and operations.

The eTool was reviewed to assess how it considers each source of CO_2-e emissions in the framework:

- CO_2-e Emissions used in Materials
  Details of all the materials of construction required for the build including foundations, floors, walls, roof, finish and fittings, and service infrastructure can be selected from the database. The lifespan of each component can be entered so the recurring energy can be calculated over the design life of the building. Energy and carbon emissions associated with initial and recurring materials are aggregated and reported separately.
- CO_2-e Emissions in the Construction Process
  Within the construction process CO_2-e emissions from transport of materials from place of manufacture to distribution point and delivery to site are calculated. Hours of equipment use and its depot location can also be entered so its transport and operational energy use can be calculated.
- Operational Energy
  Energy supply data is provided for grid system and gas supplies. Customised Remote Area Power Supply (RAPS) can also be designed and each mega-joule (MJ) of supply calculated. Electricity demand for thermal control, refrigeration, lighting, water heating and appliances can be entered so loads on each supply system can be measured. An operating energy credit can be applied when renewable energy systems, such as photovoltaic panels, are planned to feed back into centralised energy systems, such as energy company grid supply.
- Transport Fuels
  Carbon emissions from transport fuels during the occupancy stage are not addressed.
- CO_2-e Emissions in the Water Cycle
  Energy associated with water supply and sewerage treatment and subsequent CO_2-e emissions are calculated based on mains or customised RAPS supply. Materials and construction processes for simple water supply and sewerage infrastructure can be assessed using the materials and assembly components of the tool.
- Solid Waste
  Carbon emissions from solid waste are not calculated, but the energy in emissions associated with the construction of simple waste treatment facilities can be measured using the materials and assembly components of the tool.

The operating cost associated with energy and water use is calculated based on the supply source chosen. Currently only grid sources have been included in the tool but costs related to off-grid options can be entered. Cost of materials, transport and assembly can also be entered to give a total approximate cost of the development, which informs the stakeholder of the cost-benefit of various options under consideration. Limitations of the tool include the inability to calculate carbon emissions attributable to the layout of an urban development such as, the occupants' transport fuel and waste emissions whereas these can be done with the C^{CAP}Precinct tool.

eTool Example

An example application of the eTool software and calculations is provided for a hypothetical community consisting of six three-bedroom two-bathroom dwellings with a one-room school, a store and off-grid energy and water supplies. The houses have an area of 160 m^2 with brick veneer walls, a concrete tile roof and a small steel verandah and a design life of 35 years. Components were selected for assembly, foundations, floors, walls, roof, services, finish and fittings based on a benchmark design included in the tool. For the example, operational energy was based on demand estimates calculated for a three-bedroom house with five occupants (an average value in these areas) in a remote Indigenous community (Beale, 2006). Two different energy options during occupancy were modelled. For the first option a 4.8 kW solar photovoltaic mono-crystalline system and solar hot water system with electric booster has been included in the design for each dwelling to provide most of the operational energy needs. It was assumed that energy for water supply is provided by a community diesel generator. The second option assumes a community diesel generator electricity supply with an electric boosted solar hot water system which is commonly used. The embodied energy of the solar hot water system is included but not the community diesel generator. The modelled primary energy use and CO_2-e emissions for the two options over the 35-year lifespan of the dwellings are provided in Table 3.

Table 3: Comparison of Energy Options for a 3 Bedroom House over a 35 Year Lifespan

Source	Solar PV		Diesel	
	Energy (GJ)	CO_2-e (t)	Energy (GJ)	CO_2-e (t)
Materials	6,316	442	4,590	353
Construction process (including transport)	880	48	867	47
Recurring materials, assembly and transport	3,046	161	2,207	115
Operations	7,975	-	17,944	1,043
Water systems	3,739	261	3,739	261
Total	21,956	912	29,348	1,819

The results from the tool show that the first option with a solar photovoltaic mono-crystalline system has higher embodied energy and construction requirements but uses much less primary energy once the settlement is occupied and operational. In total the solar option saves approximately 907 tonnes of CO_2-e, which is about half the emissions of the diesel option, over the lifespan of the buildings. That correlates to a saving of approximately 25.9 tonnes per year or, assuming a population of 30 people, 0.86 tonnes per capita per year. This shows a significant saving in emissions due to the installation of renewable energy options in communities.

Discussion

This paper has identified a framework for measuring the CO_2-e emissions involved in the lifecycle of a development with the ARC Linkage Project model. The literature review has shown that there are currently no tools available that meet all of the framework requirements. The solution will be a suite of tools so that the gaps identified in construction CO_2-e emissions and waste CO_2-e emissions can be calculated. The paper has contributed to this research topic on carbon emissions by identifying tools which could be used across all the case studies for collecting data and producing carbon assessment data though none of the tools are completely covering all carbon sources yet.

The importance of the linkages across the framework model (Figure 1) has to remain at the forefront of this research so that the holistic outcome, which is the objective behind the case study assessments, remains intact. However the two tools chosen to review in detail, C^{CAP}Precinct and e-Tool, are able to provide the means of measuring the majority of carbon emissions for assessment purposes.

Conclusions

If the process of urbanization is inevitable, then it is critical that society improves its understanding of the carbon consequences of urban development. This study has demonstrated that there is a very clear gap in the market for tools that provide a carbon metric to monitor CO_2-e emissions in urban development. The focus is on CO_2-e emissions because climate change demands an urgent response and that can only be achieved by establishing tangible, quantifiable data on CO_2-e emissions, to aid realistic and appropriate carbon reduction targets.

The next generation of carbon assessment tools needs to recognise urban developments as entire metabolic systems with complex networks of infrastructure that make-up the total carbon footprint, rather than separate individual buildings. An improved understanding is required of all the components of urban carbon footprint and the sources of CO_2-e emissions within the urban system. The impact that specific choices of infrastructure have on carbon flows, costs and trade-offs that result from such design decisions can then be made. The transition to precinct scale assessment that is now happening globally is recognition of the need for this urban systems approach; this is reflected in the power of the C^{CAP}Precinct tool to give perspective on what urban development strategies are cost effective and will reduce carbon emissions.

Further development of tools that account for the CO_2-e emissions of the entire life cycle of a development will help to guide communities on their carbon footprint as a whole urban metabolism. This improved knowledge of CO_2-e emissions will help stakeholders understand mitigation opportunities and appropriate targets based on informed decisions of carbon consequences for delivering a portfolio of strategies for carbon reduction action. Further research is needed to identify opportunities for an accreditation system with a quantitative base (carbon and costs) to encourage the market to take up sound and viable methods of reducing CO_2-e emissions.

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About the Authors

Colin Beattie
Colin Beattie is a Ph.D. candidate looking at “Decarbonising Cities” as part of the Decarbonising Cities and Regions ARC Linkage Project run by the Curtin University Sustainability Policy (CUSP) Institute in Fremantle. His undergraduate studies were in Architecture at the Robert Gordon University in Aberdeen, where he graduated with a B.Sc. (hons) and a Post Graduate Diploma. Prior to returning to academia at CUSP, he worked for 14 years as a commercial architect, and it was with a move to Perth in 2004 that an interest in sustainable design grew. The majority of his experience was with large-scale commercial, retail, mixed use and transport projects most notably with the redevelopment of Fulham Broadway Underground Station in London’s West End. Colin also ran a small business as an architectural and industrial model maker between graduate and post graduate studies, producing intricate working models and 3D computer generated models including a detailed model of Aberdeen City Centre for the Robert Gordon University.

Jessica Bunning
In 2010, Jessica received a Ph.D. scholarship at Curtin Sustainability Policy Institute in Fremantle, Australia and has been working on an Australian Research Council (ARC) Linkage project: ‘Decarbonising Cities and Regions.’ Her research focuses on distributed green infrastructure strategies (including governance) and technologies for reducing carbon emissions in a new urban development. The practical component requires developing a framework and applying it to case studies of low carbon urban development in Western Australia. Previously from 2004–2008, Jessica worked with UNESCO, World Heritage Centre and Ecological and Earth Sciences dept. in Paris as a Programme Specialist. This involved providing advisory and technical expertise to assist countries in technical cooperation projects, including climate change mitigation/adaptation strategies, and sustainable development initiatives for World Heritage Sites, Biosphere Reserves and surrounding communities. Her work also required collaborating with an international consortium of partners to provide space derived products (satellite imagery, GIS maps, radar technology) to assist countries with management of sites, including assessment of climate change impacts. Her academic background includes a Bachelor of Arts (Literature, Anthropology), Master of Arts and a Master of Science in Environmental Science.

Joanne Stewart
Joanne is a sustainability consultant and has extensive professional experience working internationally as a freelance business analyst and more recently as a principal sustainability consultant in Australia for an international consulting firm. Her experience includes sustainability strategies and management plans for organisations and urban development projects, sustainability assessment of major infrastructure projects, cost benefit analysis, and economic incentives. She is currently undertaking Ph.D. research at Murdoch University that models the connections between carbon neutral settlements and development of sustainable livelihoods in Aboriginal communities. This involves developing a carbon accounting framework, establishing the current carbon and livelihood situation in three scales of community, and reviewing existing and proposed programs to improve carbon management and the possibilities for income generation. The interdependencies and correlations between the programs

will then be mapped to produce a future scenario framework. The research is based on the holistic concept that closed-loop carbon management cycles will produce positive results in livelihood (financial, physical, environmental, human and social) assets.

Prof. Peter Newman
Peter Newman is the Professor of Sustainability at Curtin University. He is on the Board of Infrastructure Australia and is a Lead Author for Transport on the IPCC. He has three recent books: *Technologies for Climate Change Mitigation: Transport* for the UN Environment Program, *Resilient Cities: Responding to Peak Oil and Climate Change* and *Green Urbanism Down Under* for Island Press. From 2001–2003, Peter directed the production of WA's Sustainability Strategy in the Department of the Premier and Cabinet. From 2004–2005, he was a Sustainability Commissioner in Sydney, advising the government on planning and transport issues. In 2006 and 2007, he was a Fulbright Senior Scholar at the University of Virginia Charlottesville. Peter's book with Jeff Kenworthy *Sustainability and Cities: Overcoming Automobile Dependence* was launched in the White House in 1999. In late 2011, Peter was awarded the Sidney Luker medal by for his contribution to the science and practice of town planning in Australia.

Dr. Martin Anda
Martin is Academic Chair of Environmental Engineering at Murdoch University, a sustainability consultant to industry and a Chief Investigator in the Decarbonising Cities and Regions ARC Linkage Project. Martin has led teams on resource flows audits at various mine sites, developed energy efficiency education programs with remote indigenous communities across Western Australia and conducted numerous housing thermal performance studies. He is currently a board member of the Urban Development Institute of Australia assessing urban land developments for the Envirodevelopment scheme, expert advisor for French renewable energy investments into Indonesia and chair of the organising committee for the World Renewable Energy Network conference to be held in Perth in July, 2013. Martin lives in a solar home in Fremantle.

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