RESEARCH

QUANTIFYING LIFE CYCLE ENERGY AND CARBON FOOTPRINTS OF CHINA'S RESIDENTIAL SMALL DISTRICT

Wu Deng,[a] Deo Prasad,[a] Paul Osmond,[a] Feng Ting Li[b]

ABSTRACT

Whereas current building related life cycle energy and carbon assessment in China has typically focused on either the national building stock or the single building level, this paper attempts to evaluate life cycle energy consumption and carbon emissions at the level of Chinese residential small district (RSD). This paper discusses a case study of RSD in order to illustrate the way of measuring material, energy and water flows at this spatial level with transparent assessment boundary. Results indicate that evaluating the RSD as a whole, rather than building by building, can provide extra decision-making information for various stakeholders such as housing buyers and RSD designers.

KEYWORDS

life cycle, energy footprint, carbon footprint, quantification, China's residential small district

1. INTRODUCTION

China is the largest populated country, and has had a tremendous and ever growing construction market. China's volume of existing building stock is unsurpassed. The International Energy Agency (IEA 2007:307) projects that 800 million m^2 of new urban residential floor space will be built in China annually through to 2030. This is largely attributable to the steady urbanization, growth of household income, growth of the service sector (Taylor et al 2001) and decreasing average household size (IEA 2007:306). Residential housing consumes more material than other building types. A residential building may consume approximately 7.7 times and 1.6 times the volume of materials used respectively in an industrial building and a commercial building of comparable floor area (Fernandez 2007). Since most of new construction in China is housing (synthesis from China Statistic Yearbooks, e.g. housing constitutes 72%, 73% and 84% of the total national construction area in 2007, 2006 and 2005 respectively), it is clear that the recent construction boom in China not only has progressed at an unprecedented pace but has been focused on the building types of greatest material density (Fernandez 2007).

[a]Faculty of Built Environment, University of New South Wales Australia, dengwu2000@hotmail.com.
[b]UNEP TONGJI Institute of Environment for Sustainable Development, State Key Laboratory of Pollution Control and Resource Reuse Study, Tongji University China.

Beside the enormous consumption of construction materials, there is also immense energy used in the building sector. The estimations of China's building energy use are diverse in different studies. There are no universally accepted data on energy consumption in building operation, let alone the indirect energy use for manufacturing construction materials. As synthesized by Yang and Kohler (2008), the ratio of building operational energy to the national total energy consumption varies between 17.7% and 27.0%. If the embodied energy in building material is taken into account, the percentage will be over 45% (Li and Jiang 2006, cited in Yang and Kohler 2008).

The idea of the carbon footprint (CF) is an indicator of the environmental effects of energy use, which recently has become a widely used term and concept in the public debate on appropriate responses to mitigate the threat of global climate change (Wiedmann and Minx 2008). Currently, there is no consensus on how to measure or quantify a carbon footprint (Wiedmann and Minx 2008, Matthews et al. 2008). Wiedmann and Minx (2008) found that there are a large variety of definitions that differ in which gases are accounted for, where boundaries of analysis are drawn, and several other criteria. The spectrum of definitions ranges from direct CO_2 emissions to full life cycle greenhouse gas emissions, and even the units of measurement are not clear. For example, the Stockholm Environment Institute (SEI) uses the total amount of CO_2 emissions per capita to measure the carbon footprint for the city of York (Haq and Owen 2009). Some definitions involve the total amount of CO_2 equivalent emissions by incorporating other greenhouse gases substances. Others argue that CF is a part of the Ecological Footprint and it is measured in terms of "CO_2 land" that is the amount of "unharvested forests, needed to absorb that fraction of fossil CO_2 that is not absorbed by the ocean" (Wiedmann and Minx 2008).

Literature review has revealed that little research has been undertaken in this area in China, particularly in terms of modeling life cycle material & energy flows and the related carbon emissions for a large spatial scale of merged building sites such as a residential neighbourhood. Studies have typically assessed either the national total building stock (e.g. Fernandez 2007, Yang and Kohler 2008) or the single building (e.g. Zhang et al 2006, Gu et al. 2006). These studies have typically focused on building performance without consideration of the users' activities such as traffic between home and work. Some concerns such as interior housing decoration[1] and recurring energy for building maintenance are also neglected.

This paper aims to establish a method for assessing and evaluating life cycle material & energy flows and the related carbon footprint for the Chinese residential small district (RSD). It acknowledges the definition proposed by Wiedmann and Minx (2008) that "the carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product." This definition includes only CO_2 in the analysis and adopts life cycle thinking. It provides a simple, straightforward and practical way to facilitate generation of clear solutions.

2. CHINA'S RESIDENTIAL SMALL DISTRICT

A key feature of China's urban transformation in recent years has been the appearance of huge numbers of new residential housing estates, designed by professional planners and architects. They are known as "residential small districts", or *xiaoqu* (Bray 2006). It has dramatically changed and redefined Chinese new urban space. As estimated by Sun (2004:6), between

1991 and 2000, 83% of housing development in Shanghai is in this form and 80% of the Guangdong population is living in RSDs.

The concept of the RSD, sanctioned by national planning codes, has become the basic unit in planning and developing residential construction in China (Miao 2003:47). It is a planned neighbourhood where housing is integrated with communal facilities like kindergartens, clinics, restaurants, convenience shops and communication infrastructure (Sun 2004:15, Bray 2005:176-177) all under the control of a professional property management company. RSD has similar residential building types, primarily high- (10 or more stories) and mid-rise (6-storey walk-ups) (Miao 2003:48). The public space between different RSDs varies greatly. Depending on the price range of the apartments, it ranges from a mere concentrated green space as the minimum to a variety of extras such as playgrounds, a clubhouse, and swimming pools (Miao 2003:47).

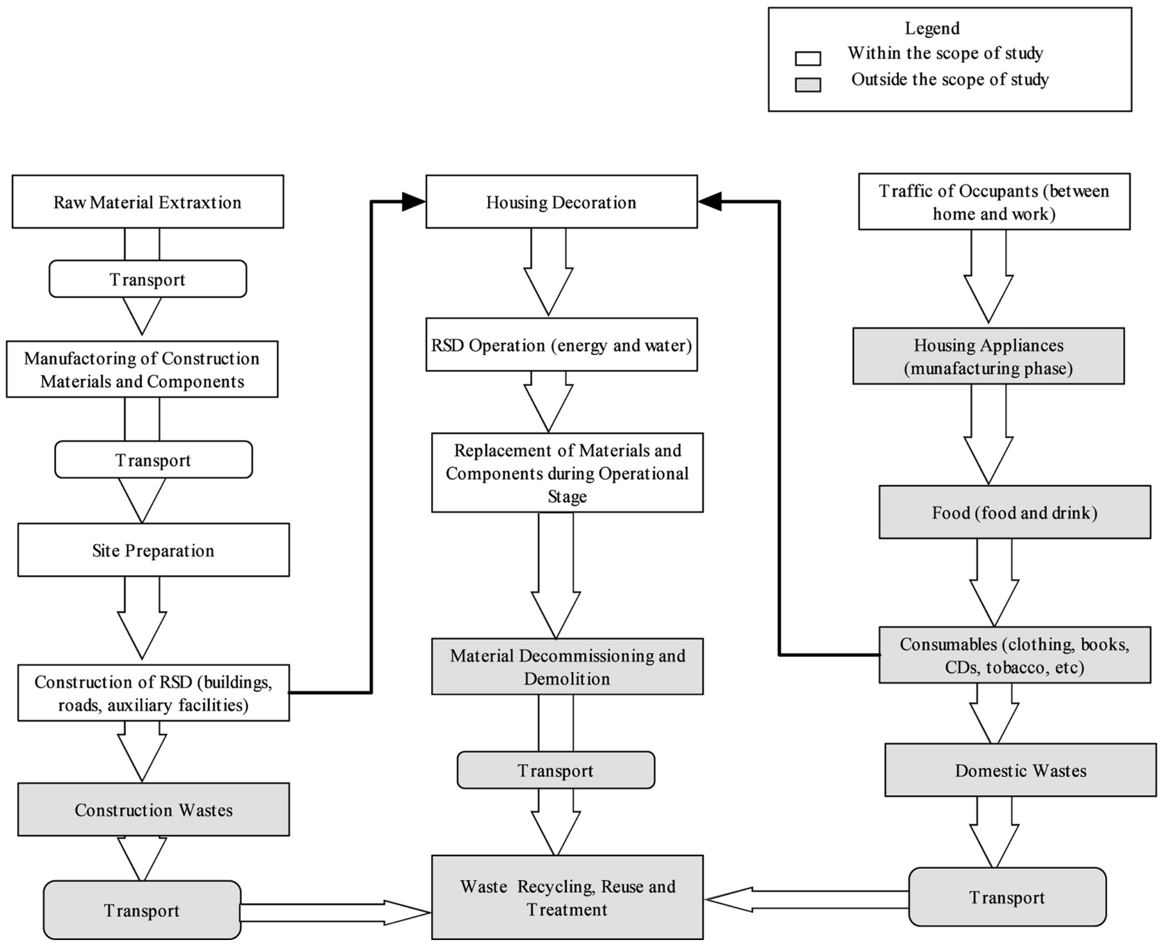
Most RSDs have some kind of barrier-walls or fence, and may have security guards monitoring the entire site (Sun 2004:15), as well as which gates are staffed (Bray 2006) to prevent unauthorized entry. Thus it is a type of "gated neighbourhood". Clause 73 of China's Real Right Law stipulates that, the roads, green lands, common facilities and houses, and other public place are commonly owned by all the property owners of a particular RSD. This means that residents not only own their apartments, but also share ownership of the public area, which further implies residents also 'own or share' the environmental impacts resulting from the construction and operation of an RSD.

3. ASSESSMENT BOUNDARIES

In its broadest context the 'carbon footprint' calculates not just the carbon produced as a result of the energy used for the construction, operation and maintenance of an RSD. There are broader issues that relate to carbon emissions produced as a result of the users interacting with their environmental, social and economic contexts. This is particularly important with regard to the location of an RSD, the urban configuration and local transport network. Such factors are highlighted in neighbourhood rating systems such as LEED-Neighbourhood Development and BREEAM-Communities. The traffic between homes and other built entities such as workplaces, amenities and urban services greatly increases the overall carbon footprint of the RSD. In addition, carbon generation is associated with people's everyday lives such as objects of life sustaining necessities (e.g. food, clothing), life quality commodities (e.g. TVs, fridges) and entertainments (e.g. books, CDs). Therefore, it is argued by Treloar et al. (2000) there is a need to consider not only the life cycle energy of a building but also the life cycle energy attributable to activities being undertaken by the actual users of the building.

The biggest obstacle of material and energy accounting is data availability. Fridley et al. (2007) observe that data almost completely lacking in China are the "upstream" components of building energy use in the production and construction phase. Data are also lacking with regard to consumer goods such as food and clothes, as well as household appliances. These data are collected not at the RSD level but at the municipality level. Given the data availability in the Chinese context, this study is only concerned with energy based CO_2 emission as defined below. It is not the full carbon footprint of the RSD. Further research would be required to understand this full carbon footprint and the links between users' behaviors and their socio-economic contexts.

FIGURE 1. System boundary for the carbon footprint calculations used in this study.



Given there is no consensus on the scope and boundaries for life cycle energy and carbon footprint analysis, it is vital to define them clearly at the outset. For this study, the scope of the analysis covers CO_2 emission related to manufacturing, conveyance, construction, interior decoration, maintenance, direct energy for operation, and energy used for transport between home and work. Emissions associated with people's life-styles such as consumption of food and consumer goods, embodied energy used for manufacturing household appliances and the treatment of various wastes are excluded from this analysis due to data availability. Figure 1 shows the boundaries that have been defined for this study.

4. ANALYSIS MODEL

4.1 Overall Assumption

It is important to define the service life of an RSD to assess its life cycle impact. The service life of an RSD will affect the total recurring embodied energy as well as the life cycle operational energy and the related emissions. In this study, the service lives of buildings and public open space (e.g. roads, walls, parking lots and landscaping works) of an RSD are assumed to be 50 years and 15 years[2] respectively.

The construction process may involve dozens to hundreds of materials. It is extremely difficult to account for all of them. As demonstrated in Chen et al. (2001), the use of steel, aluminum, concrete, timber, PVC, and tiles constitutes 97% of the total embodied energy in the residential buildings of Hong Kong. In order to reduce analytical complexity, this research only examines these six main materials[3] in assessment of the case study RSD.

The interior housing decoration, in its broadest way, may include a number of activities such as decorating ceiling and floor, painting walls, installing furniture and housing appliances. Due to data availability, only flooring materials including timber decking tiles, marble tiles and ceramic tiles are included in the analysis.

The energy and emissions associated with material or component replacement and periodic maintenance during the service life of a building can be up to 32% of the initial embodied energy or emissions (Crawford 2009). In this study, cement and steel used in buildings are assumed to be all for structural components. Thus there is no material recurrence of cement and steel during the building service life. For other building materials examined, the recurring material and energy consumption is determined by initial material input and the related replacement factors[4].

According to Figure 1, the whole analysis can be generally expressed by the following equations, where CF means Carbon Footprint:

$$CF = CF_{pre\text{-}occupancy} + CF_{post\text{-}occupancy}$$

$$CF_{pre\text{-}occupancy} = CF_{manufacturing} + CF_{conveyance} + CF_{construction}$$

$$CF_{post\text{-}occupancy} = CF_{decoration} + CF_{maintenance} + CF_{operation} + CF_{transport}$$

These equations split the whole RSD life cycle into two stages: pre-occupancy and post-occupancy. The pre-occupancy stage refers to energy and emissions related to manufacturing of building materials, conveyance to the development site and the construction process, which is mainly under control of developers, designers and contractors. The post-occupancy stage involves energy and emissions associated with activities such as interior decoration, operation of buildings and open space, maintenance and transport between home and work, which is mainly controlled by individual householders and RSD management companies.

4.2 Calculation Scenarios

4.2.1 Energy for Manufacturing of Building Materials

Energy will be consumed to convert raw materials into various construction materials which can be assembled into a building or a road. The calculation of embodied energy for each material can be expressed by the following equation[5]:

$$E_{manufacturing} = \sum_{i=1}^{n} \mu_i \left[\sum_{i=1}^{n} q_i e_i \right]$$

Where μ_i is the replacement factor for material i during the life span of an RSD. q_i is the quantity of material i used in the RSD that can be totalized based on the Bill of Quantity[6] (BQ). e_i is the energy intensity for material i (MJ per unit).

Literature review has revealed that there is very little information found associated with energy intensities of Chinese construction materials and the related emission factors (see also

TABLE 1. Energy intensities and the associated emission factors of materials & water.

Material	Steel* (kg)	Timber* (m3)	Cement* (kg)	Aluminum* (kg)	PVC (kg)	Ceramic tile (kg)	Marble tile (kg)	Water (m3)
Energy intensity (MJ)	38.6	3355	10.2	424	67.5	9	3.33	0.72
CO2 emission (gram)	6778	95000	1594	24978	2500	590	187	213

Source: Materials with asterisk are based on Yang (2003:86). Materials without asterisk are based on Hammond and Jones (2008).

Fridley et al. 2008). As a result, studies have to rely on international data to act as proxies for China's calculation (see examples Gu et al 2006 and Chen et al 2001). A study from Tsinghua University (cited in Yang 2003:86) suggests the cradle-to-gate energy intensity and the related emission factors of some Chinese building materials including steel, cement, aluminum, and timber. For other materials not included in this study, the data from the University of Bath's inventory of carbon and energy (ICE) database[7] (Hammond & Jones 2008) will be adopted. The ICE is one of the most comprehensive databases available. It covers not only embodied energy coefficients of building materials but also the related carbon emission factors. The current ICE contains over 1700 records on embodied energy.

It should be noted that the ICE values are likely to differ from those which reflect Chinese production processes. Given the absence of China-specific data, they only provide initial and rough approximations to present embodied energy use and the related carbon emissions of a Chinese RSD. To improve accuracy, further research including establishing a reliable database for China's building materials will be needed.

The synthesis of embodied energy coefficients and the related CO_2 emission factors of the main construction materials and water production is shown in Table 1.

4.2.2 Energy for Conveyance and Construction

Energy used for transportation of construction materials from manufacturing plants to construction sites can be expressed as:

$$E_{conveyance} = \sum q_i d_i e_{it}$$

Where q_i is the quantity of material i dealt with in conveyance; d_i is the conveyance distance for material i; e_{it} is the energy intensity for a specific transport means. The average distance of freight transport by roads in China is 61 km in 2004 (cited in Gu et al 2006). This distance is assumed to be the average distance of transferring building materials. Given assumption that all materials are road conveyed and fueled by diesel oil, it is suggested by (Yang et al. 2002:118) that the average conveyance energy consumption in China is 2.423MJ/tonne-km and the related CO_2 emission is 0.2377kg/tonne-km. Thus, the total energy for conveyance of building materials can be calculated given the amount of materials, average distance and transport energy coefficient.

Energy used for the construction process can also be obtained directly from the BQ in which contractors often record the electricity and water usage.

4.2.3 RSD Operation

The electricity, liquefied petroleum gas (LPG) and water consumed for RSD operation can be categorized as:

- Household usage: appliances, toilet flushing, cooking, etc;
- Landscaping: fountains, vegetation irrigation, etc;
- Public usage: street lamps, running of the property management office, etc;

The quantity of energy and water used for running of the public area has been obtained from the property management company. The energy and water consumption has been obtained by a household survey.

Yang et al. (2002:113) give a CO_2 emission factor of 317 grams in producing 1MJ (approximately 0.278 kWh) electricity in China. The University of Bath's ICE database estimates 213 grams CO_2 emission in producing $1m^3$ tap water (Hammond and Jones 2008) that can be used as the proxy to calculate the case study RSD. Jungbluth et al. (1997) suggest 122kg CO_2 emission in use of 1 GJ LPG. Given the above presumptions, the CO_2 emission in operation of the RSD can be calculated by linking them with the actual usages of electricity, water and LPG.

4.2.4 Transport and Travel between Home and Work

In order to calculate the petrol consumption for transport between home and work, information such as transportation means, percentages, and average commuting time is required. This type of information has been collected by a household survey. This study only involves the use of private car, motorbike, and bus. Other transportation means such as walking, cycling, and cell-powered scooter are assumed to be environmentally neutral. It is also assumed that the average speed for car, motorbike and bus is 40km/hour, 30km/hour and 20km/hour respectively. The average petrol consumption for a 100km ride is 8.06 liters, 3 liters and 31 liters[8]. Each bus ride conveys 50 passengers. Yang et al. (2002:136) suggests a CO_2 emission coefficient of 3172 grams in use of 1 kg petrol in China. Thus, the total carbon emissions attributable to transport can be quantified. It should be noted that the analysis involves only petrol consumption without consideration on the embodied energy for manufacturing vehicles and petrol.

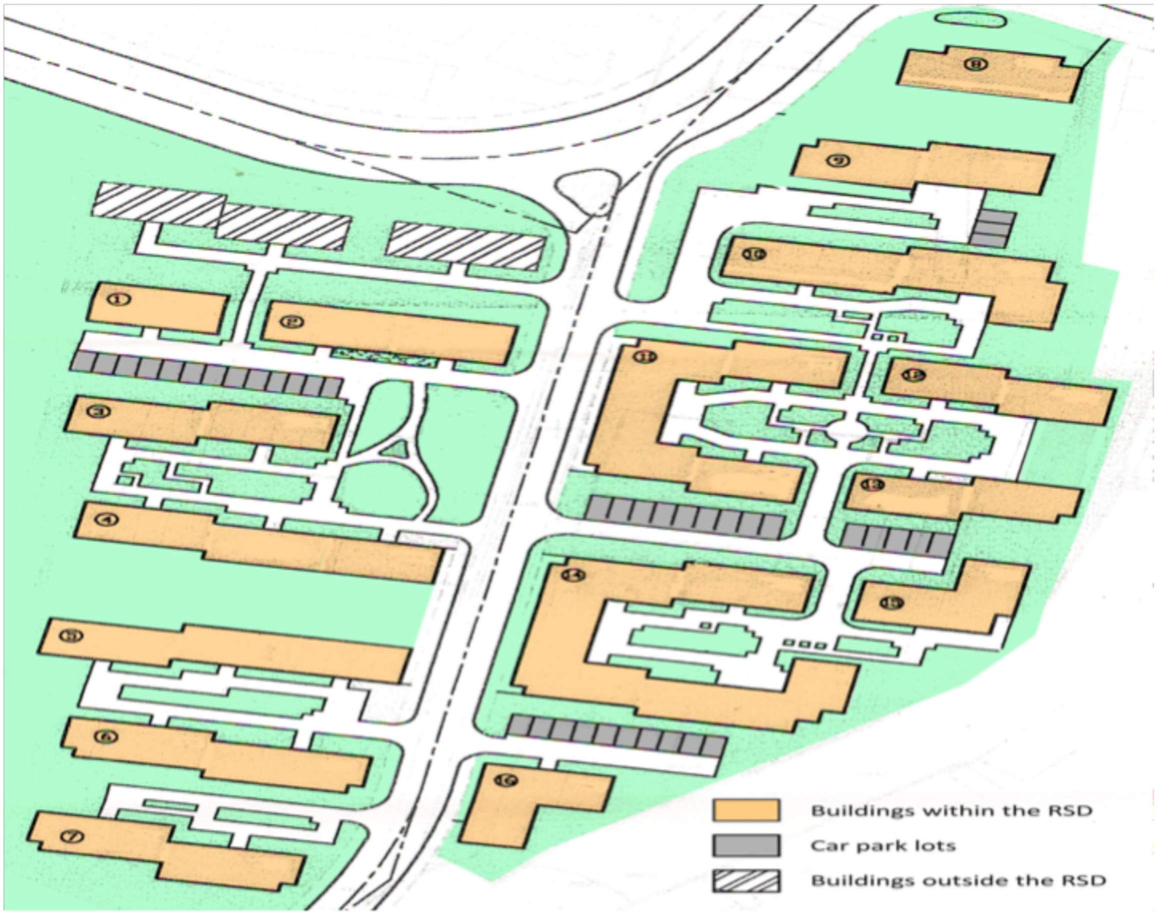
5. CASE STUDY

5.1 Description of the Case Study RSD

An RSD with 462 households was selected to demonstrate the working of the analysis model. This RSD is located in Guilin, south China, which was completed in 2007 with an average construction area of 116 m^2 per household. It has a ground area of 3.35 ha with a total residential construction area of 53592 m^2. It comprises 16 seven-storied (walk-up) residential buildings, internal walkways and roads ($1400m^2$), walls (concrete base with steel bars on the top), parking lot with permeable pavement ($812m^2$), and landscaped area (about $1000m^2$, lawns with paved alley) (Figure 2).

This RSD is under management of a property management company that maintains an onsite office with 17 staff working on cleaning, guarding, gardening and other public duties. The RSD is located on the developed area of the city with existing facilities around such as shops, hospital and schools. The walking distances from its main entrance to the nearest facilities and services are about: 100m (bus stop), 700m (food market), 1300m (park), 1500m (hospital), and 1600m (primary school).

FIGURE 2. The layout and configuration of the case study RSD. *Source:* Adapted from the master plan of the case study RSD.



5.2 Survey of Bill of Quantity

A set of BQs has been obtained for each of the buildings, and also for the roads, walkways, and parking lots. The life cycle material consumption and the electricity & water usage during the construction process is shown in Table 2. It reveals that the total consumption of various construction materials during a life cycle of 50 years is 20864 tonnes. The initial construction materials consumed in the largest quantities for this RSD are cement and steel, followed by timber (given density of 900kg/m^3), various tiles, aluminum and PVC. However, the order will be re-arranged in a view of the life cycle consumption. The life cycle materials consumed in the largest quantities are cement and various tiles, followed by timber, steel, PVC and aluminum. The reason is because materials such as timber, tiling materials and PVC are more frequently replaced during the lifespan.

5.3 Survey of households

A survey of the households was conducted with the focus on the energy and water consumption for RSD operation. It involved 46 households or 10% of the total households. The survey indicates that the average household size in the RSD is about 3.39 persons. This survey also reveals the energy and water consumption model of the RSD. On average, 257 kWh

TABLE 2. Life cycle material consumption and construction related electricity & water consumption of the case study RSD[9]

Material	Steel (kg)	Timber (m3)	Cement (kg)	Aluminum (kg)	Tiles (kg)	PVC (kg)	Water (m3)	Electricity (KWH)
Buildings (initial)	2064000	1703	10293000	52879	537180	48729	42489	244216
Open space (initial)	12000		226000				978	1748
Housing decoration		212			264542			
Recurrent materials	24000	1915	452000	52879	3206888	194916		
Sum	2088000	3830	10971000	105758	4008610	243645	43467	245964
Total: 20864 tonnes								

electricity is consumed per household per month or 76 kWh/month-person. For water consumption, 15.18 m^3 are consumed per month per household or 4.38 m^3 /month-person. Regarding gas consumption, on average each household consumes 11.74 LPG containers[10] annually. The monthly amount of electricity and water used for the public area are provided by the property management office, which include: street lamps (750kWh), office and guard kiosks (2230kWH), vegetation irrigation (500 m^3).

This survey has revealed that interior decoration has been conducted in all sampled households. Marble tile, ceramic tile and timber are the most frequently used materials for interior decoration. Totally, there are 68% households use ceramic tiles to decorate their living space, while 25% use timber and 7% use marble tiles. Regarding the decoration of bedrooms, 86% use timber and 14% use ceramic tiles.

The survey shows that the percentages of commuters using motorbike, bus and private car are 24%, 21%, and 16% respectively, and the average time of the three transport means for travel between home and work (two-way) is 40.8 minutes, 54.8 minutes and 57.3 minutes respectively.

6. RESULTS AND ANALYSIS

Following the previously discussed analysis methodology and the survey results, the life cycle energy consumption and the related CO_2 emission can be quantified.

6.1 Overall Energy and Carbon Profile

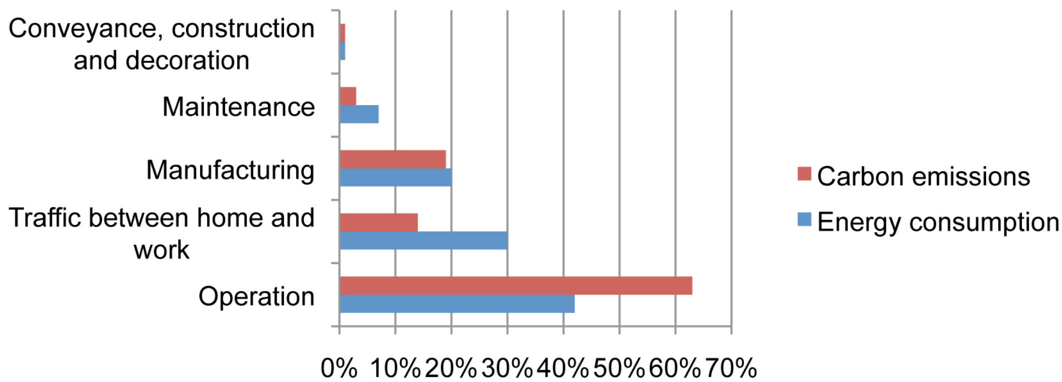
The energy use and CO_2 emission in different life stages of the case study RSD are shown in Table 3. Given service life of 50 years, the total life cycle energy use is 1100108GJ with CO_2 emission of 169855 tonnes. The annualized energy use and carbon emissions are 22002GJ and 3397 tonnes respectively. Assuming unchanged household number and size, the annualized per capita energy consumption and carbon footprint are 14.1GJs and 2.17 tonnes respectively.

The energy use and carbon emissions in different life stages are shown in Figure 3. Operational energy including electricity, water and LPG takes up 42% of the total energy consumption and 64% of the total CO_2 emission, followed by energy use for transport between home

TABLE 3. Life cycle energy consumption and the related CO_2 emissions.

	Pre-occupancy			Post-occupancy			
Life Stages	**manufacturing**	**conveyance**	**construction**	**decoration**	**maintenance**	**operation**	**transport**
Energy(GJ)	223684	3083	1067	2955	77981	458838	332500
CO_2(tonne)	32763	303	289	168	4784	107673	23875
Total	Life cycle energy use: 1100108GJ; Life cycle CO_2 emission: 169855 tonnes						

FIGURE 3. Energy and carbon emissions distributed in different life stages.



and work with 30% and 14% respectively. The embodied energy used for manufacturing of initial construction materials constitutes 20% and 19%. Gu et al. (2006) also give a similar percentage that the embodied energy consumption constitutes 20% of the life span consumption in a study of a single residential building in Beijing. The energy and emissions from RSD maintenance is relatively smaller with 7% and 3% respectively. The combination of conveyance of materials, energy consumed in the construction process and housing decoration only constitutes 1% of the total energy use and CO_2 emissions. Overall, the energy and emissions in pre-occupancy phase constitutes 20.7% and 19.6% respectively, while the post-occupancy phase constitutes 79.3% and 80.4%.

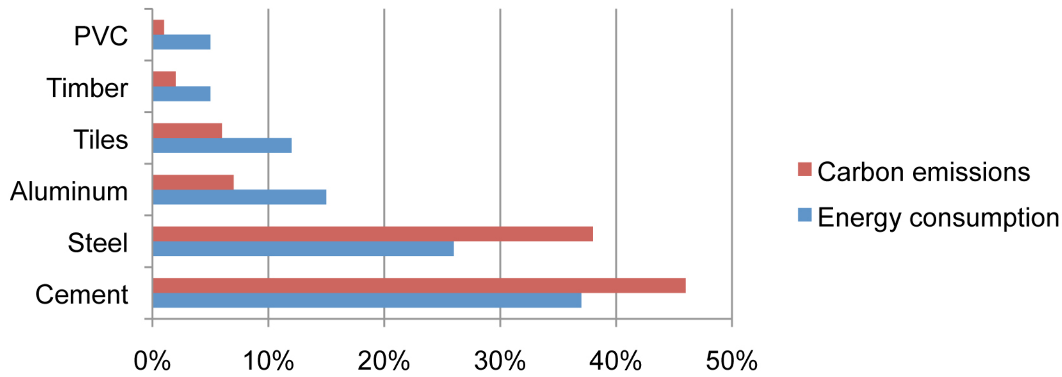
Specifically, the pre-occupancy energy consumption and carbon emissions can be measured by per m^2 residential construction area, which are 4.25 GJs and 0.62 tonnes CO_2 respectively. These factors link the embodied energy and emissions of the whole RSD to the residential area because residential buildings are the core component of an RSD and the existence of other components is to support such residential function. They may be greatly differing between different RSDs since the size and variety of the public area are diverse.

Notably, the analysis indicates that the transport between home and work alone constitutes about 30% of the total energy consumption and 14% of the total carbon emissions. If considering other city travel such as shopping and excursion, and long distance travel by train and plane, the energy consumption and carbon emissions for transport would be more significant.

6.3 Energy Use and CO_2 Emission of Various Construction Materials

The breakdown of initial embodied energy and the associated CO_2 emission by different construction materials are shown in Figure 4. Cement constitutes 37% of the total embodied energy and 48% of the total embodied emission, followed by steel with 26% and 38% respectively. It should be noted that aluminum represents 15% of the total embodied energy and

FIGURE 4. Initial embodied energy and carbon emissions by different construction materials.

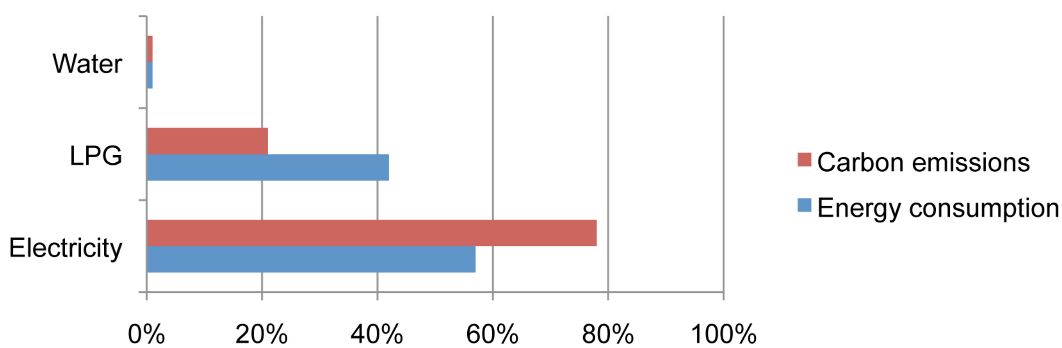


7% of the total embodied emissions given only 0.5% of the total quantity of material consumption. Various tiles constitute 12% of the total embodied energy and 6% of the total emissions. The impact of timber and PVC are smaller, together representing 10% of the total embodied energy and 3% of the total emission respectively.

6.4 Operational Energy Use and Emission

Operational energy use involves the consumption of electricity, water and LPG in homes and public area. Given the service life of 50 years, the use of electricity has the greatest impact. It constitutes 57% of the total operational energy and 78% of the total carbon emissions, followed by the use of LPG, representing 42% and 21% respectively (see Figure 5). The energy used for producing water is much less, only representing 1% of the total operational energy and the total operational CO_2 emission. This reflects a fact that the significance of water cannot be sufficiently addressed in an energy-based analysis. A parallel water footprint analysis should be undertaken to delineate the holistic picture of resource and energy consumption.

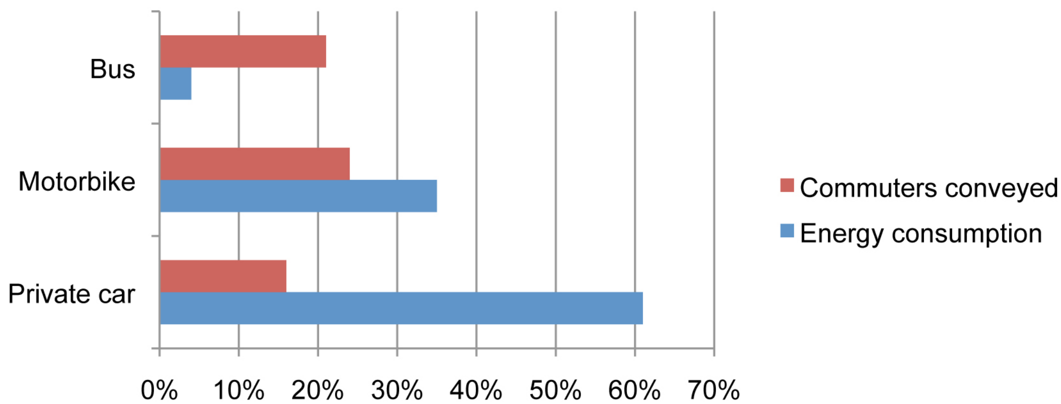
FIGURE 5. Operational energy and carbon emissions by different energy types.



6.5 Transport between Home and Work

Figure 6 reveals that the use of private car consumes 61% of the total transport energy but only conveys 16% of the RSD residents. However public bus transport, consuming only 4% of the total transport energy, conveys 21% of the total commuters. The users of motorbikes constitute 24% of the commuters and consume 35% of the total energy. Unsurprisingly, the use of public transport has the greatest environmental benefit.

FIGURE 6. Energy consumption and the related percentages of commuters of different transport means.



7. DISCUSSION AND CONCLUSION

Compared to other energy and carbon studies in China, this paper shifts the assessment focus from single building assessment to precinct based, to address the RSD as a whole. The analysis reveals that the annualized per capita energy use and carbon footprint of the RSD reviewed are 14.1GJ and 2.17 tonnes respectively. The results indicate that CO_2 emitted from the operation of the RSD constitutes the largest proportion of the total emission; followed by initial embodied energy, travel between home and work, and recurrent energy for maintenance. The pre-occupancy phase accounts for 19.6% of the total annualized emissions, while the post-occupation phase represents 80.4%. The analysis unsurprisingly shows that residential buildings consume much more construction materials and embodied energy than other component parts of the RSD. However, it should be aware this may vary in assessment of different RSDs because larger landscaped areas and more community amenities would be built in many affluent RSDs. This study indicates that cement and steel are the most energy intensive materials in construction of an RSD. It also shows that the life cycle energy and carbon impact of daily travel is significant and the urgent need to promote the use of public transport.

Troy et al. (2003) conducted a suburb scale study of Adelaide, Australia, focusing on energy consumption and the related CO_2 equivalent emissions. This study has addressed both embodied energy estimates (buildings, roads, water supply network, sewerage system, and vehicle fleet) and operational energy (electricity, gas and transport). Excluding the embodied energy estimates for infrastructure and vehicles in order to be comparable with the assessment scope in this research, the estimated annual CO_2 equivalent per capita of Adelaide was between 4.7 and 6.7 tonnes. The authors also found that operational (including transport) energy accounted for 72–83% of the total annualized emissions, and embodied energy contributed 17-28%.

SEI (Haq and Owen 2009) conducted a more comprehensive study of York city in the UK at neighbourhood level, which include housing (construction and operational), transport, food, consumables (e.g. clothes and housing appliances), services (e.g. insurance and banking), and infrastructure (e.g. hospitals and schools). They found that housing and transport contributed 57% of the total annual CO_2 emissions, followed by the individual share of urban infrastructure that constituted 17%, while the combination of consumables and food represented 20%. Considering only housing and transport, the average York residents had carbon footprint of 7.16 tonnes annually, and the range varied between 4.68 and 8.48 tonnes in different neighbourhoods.

The above-mentioned studies have roughly similar assessment scope with the case study RSD. The case study RSD has only about 38% and 30% of the average carbon footprint of Adelaide and York residents respectively. Reasons may be mainly attributable to climate diversity, use of private vehicles, and housing conditions.

Because RSDs may have a diversity of public areas, housing sizes and life-styles, the carbon footprint between various RSDs could be significantly diverse. This is confirmed by some research, for example, Golley et al. (2008) suggest that the top 10 percentile income group in China consumes 86% more energy than the lowest 10 percentile income group. Wang and Shi (2009) suggest a greater margin than the study of Golley et al. by estimating 7.5 times difference between the top 10 percentile income households and the lowest 10 percentile income households, mainly attributable to the larger housing sizes and the use of private cars. Thus the number of CF can be used as an educational and manageable tool to reflect the contribution to climate change of the residents from a particular RSD.

Current neighbourhood environmental rating tools, such as LEED-Neighbourhood Development and BREEAM-Communities, present an overall rating score by evaluating against a checklist of "green measures". However, they cannot deliver the information about the actual environmental impact to potential property buyers. The calculation of pre-occupation energy consumption and carbon emission can be a way to provide such information. For the case study RSD, the pre-occupancy energy and emissions are 4.25 GJ and 0.62 tonnes CO_2 per m^2 residential construction area. Housing buyers can handily calculate their shares of carbon accountability by multiplying the factors with the construction area of their apartments.

Since the buildings and public open space of an RSD are already in place thus there is little opportunity to optimize the embodied materials and energy used for construction. Opportunities for improvement exist: (1) electricity consumption in homes is the greatest source of emissions, thus it should be given the priority. Measures such as using efficient LED bulbs, enhancing insulation and using passive power can be introduced; (2) transport contributes significantly to carbon emissions of the RSD, improving the effectiveness of public transport is another priority.

More generally, the carbon emissions of the day-to-day operational use of the RSD are about three times greater than embodied impact. This implies that increasing material inputs in construction stage, e.g. providing thermal mass or installing passive facilities, may considerably reduce impacts over the full life cycle (Osmond 2010) of the RSD. In addition, evaluating the RSD as a whole helps designers to expand their views beyond single buildings by incorporating public open space, thus this helps to form a holistic picture of their work. Furthermore, such a calculation can aid decision-making at an early stage of the design process. For example, providing life cycle energy and emission data helps designers to select construction materials and assess the various transport scenarios.

The conclusion from this research is that the calculation of life cycle energy and carbon for an RSD as a whole, rather than building by building, can offer extra decision-making information for various stakeholders such as housing buyers, RSD managers and designers. This can improve the quality of decisions necessary to achieve more sustainable RSDs.

8. FURTHER RESEARCH

This preliminary assessment of the estimated energy and carbon footprint of a Chinese RSD will be significantly improved by further research in areas in which China-specific data are lacking. A China-specific database for different building materials, which would need to look at regional differences as well, is required to generate more reliable results. Further research could also involve establishment of a full carbon profile for an RSD by incorporating emissions relating to daily lives such as consumption of food, clothing and waste generation. Finally, further research on the incorporation of current neighbourhood environmental rating systems and life cycle energy & carbon assessment would be interesting.

NOTES

1. In China, housing transferred to buyers usually has only low-quality flooring and painting. Buyers often conduct some interior decoration by replacing the provided finishes with high-quality materials such as timber tiles to suit their life-styles.
2. As required by the China's Design Standards for Urban Roads (CJJ 37-91), the design lifespan of hard pavement with asphalt concrete surface is 15 years. The parking area and the wall are assumed to have the same lifespan.
3. In this study, concrete is replaced by cement because cement is the major component of concrete and the quantity of cement is indicated in the Chinese BQs.
4. The replacement factors of various materials and elements can be found in Chen et al. (2001) and Chau et al. (2007). The replacement factor quantifies the number of times that material inputs are needed for construction/installation of the component within the service life of a building. In this research, Replacement factor = 50/expected service life of building materials. A particular material with the service life of 10 years means it needs to be replaced five times including the initial input.
5. This equation does not consider the *waste factors* of materials that represent the wastages and losses incurred during construction and maintenance.
6. The submission of BQ is required by the Code of Valuation with Bill of Quantity of Construction Works (GB50500-2008) issued by the Chinese Ministry of Construction. The BQs shall be prepared by the certificated engineering cost professionals. It should contain all costs of labour, materials, plant, management, risks plus profit and taxes etc.
7. The Inventory of Carbon and Energy (ICE) has been developed in the University of Bath, which not only creates an inventory of embodied energy coefficients for building materials but also the related carbon emission factors. The current ICA contains over 1700 records on embodied energy. A brief of the database can be seen from http://www2.env.uea.ac.uk/gmmc/energy/env-m558/ICE%20Version%201.6a.pdf
8. The average petrol consumption of private car in China is based on the assessment of China Vehicle Industry Association, reported on Beijing Daily 22/06/2009 http://auto.people.com.cn/GB/1049/9515071.html. The average petrol consumption of motorbike is based on the report of Financial Time 22/06/2006 http://epub.cnki.net/grid2008/detail.aspx?filename=CJSB20060612C031&dbname=CCND2006. The average petrol consumption of bus is based on Zhen and Chen (2008). Other assumptions for quantifying the energy use for transport between home and work include: (1) The yearly working days are 250; (2) The density of petrol is 0.725kg/liter and the heating value of petrol is 32MJ/liter
9. Explanations of the material calculations in Table 2:
   (1) The aggregation of the initial material consumption and the construction related electricity & water consumption is based on the BQs and there is no consideration on material recycling.
   (2) The public area includes roads, walkways, parking lots, pavement in landscaping area and walls. The calculation of roads, walkways, and parking lots is based on the BQs. The materials used for construction of walls and the pavement in landscaping area are estimated by the authors due to not being included in the BQs.
   (3) The types of materials used for interior decoration is based on the household survey; The tiles used for floor decking comprise of ceramic tiles (240180kg), marble tiles (24362kg) and timber flooring tiles (212 m^3); These tiles are assumed to be 10mm thick with densities of 2000kg/m^3, 2600 kg/m^3 and 900kg/m^3 respectively.

(4) Water and electricity usage for housing decoration and maintenance are ignored due to data availability;
(5) The recurrent materials during the life cycle is calculated based on the synthesis of Chen et al (2001) and Chau et al (2007). An expected life-span of 10 years means requiring replacement four times during the life span of 50 years. Steel and cement in building construction are assumed to be used for building structure.
(6) It is assumed that the public area (e.g. roads, walkways, parking lots, wall) needs to be totally reconstructed every 15 years. This means the reconstruction of public area need to conduct twice during 50-year life span.

10. A LPG container has 16.5kg LPG, which is assumed to have a heating value of 46.1MJ/kg

REFERENCE

Bray D. (2005). *Social Space and Governance in Urban China: The Danwei System from Origins to Reform*. Stanford: Stanford University Press.

Bray D. (2006), Garden Estates and Social Harmony: a study into the residential planning and urban governance in contemporary China, The 3rd China Planning Network Conference Proceeding. http://www.chinaplanningnetwork.org/english/2006PDF/DAVID%20BRAY.pdf.

Chau C.K., Yik F.W.H., Hui W.K., Liu H.C. and Yu. H.K. (2007), Environmental impacts of building materials and building services components for commercial buildings in Hong Kong? *Journal of Cleaner Production* 15, pp. 1840-1851.

Chen T.Y., Burnett J., and Chau C.K. (2001)., Analysis of embodied energy use in the residential building of Hong Kong, *Energy* 26, pp. 323-340.

Crawford R. H. (2009), Life cycle energy and greenhouse emissions of building construction assemblies: developing a decision-support tool for building designers, http://conference.alcas.asn.au/2009/Crawford%20Building%20Construction.pdf.

Fridley D. G., Zheng N., and Zhou N. (2008), Estimating total energy consumption and emissions of China's commercial and office buildings, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, USA.

Haq G. and Owen A. (2009), Green street: the neighbourhood carbon footprint of York, Stockholm Environment Institute.

Hammond G. P. and Jones C. I. (2008), Inventory of Carbon and Energy (ICE), Beta Version 1.6a, Sustainable Energy Research Team, University of Bath.

Fernandez J. (2007), Resource consumption of new urban construction in China, *Journal of Industrial Ecology,* Volume 11 (2), pp. 99-115.

Golley J., Meagher D. and Xin M. (2008), Chinese household consumption, energy requirements and carbon emissions, http://econrsss.anu.edu.au/~meng/Draft%20May%2012.pdf.

Gong Z.Q. and Zhang Z.H. (2004), Quantitative assessment of the embodied environmental profile of building materials, *Journal of Tsinghua University (Science and Technology)* 44(9), pp. 1209-1213. (in Chinese)

Gu, D.J., Zhu Y.X. and Gu, L.J. (2006), Life cycle assessment for China building environment impacts. *Journal of Tsinghua University (Science and Technology)* 46(12), pp. 1953-1956 (in Chinese).

Jungbluth N. et al. (1997), Life cycle inventory for cooking, *Energy Policy*, Vol. 25(5), pp. 471-480.

IEA (2007), World Energy Outlook 2007, International Energy Agency.

Li, Zh.J. and Jiang, Y. (2006) Pondering over the situation of domestic generalized building energy consumption, *Architectural Journal*, 7, pp.30-33. (in Chinese)

Matthews, Hendrickson and Weber (2008), The importance of carbon footprint estimation boundaries, *Environmental Science and. Technology*, *42,* pp. 5839-5842.

Miao P. (2003), Deserted streets in a jammed town: the gated community in Chinese cities and its solution, *Journal of Urban Design,* Vol. 8(1), pp. 45-66.

Osmond P. (2010), *Application of "streamlined" material accounting to estimate environmental impact, World Academy of Science*, *Engineering and Technology* 6(69), pp. 668-678.

Taylor R. P., Liu F., and Meyer A. S. (2001), *China: opportunities to improve energy efficiency in buildings*, Asia Alternative Energy Programme and Enery & Mining Unit, The World Bank.

Sun N. (2004), Rethinking walled residential compound in peripheral urban China: a guideline for boundary and size. Master Thesis, Massachusetts Institute of Technology, http://dspace.mit.edu/bitstream/handle/1721.1/35126/71790675.pdf?sequence=1

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

Wang Y. and Shi M.J. (2008), Energy requirement induced by urban household consumption in China, *Resource Science,* Vol. 31(12) pp.13-17, (in Chinese).

Wiedmann, T. and Minx, J. (2008), *A definition of 'carbon footprint',* In: Pertsova C.C., Ecological economics research trends: Chapter 1, pp. 1-11, Nova Science Publishers, Hauppauge NY, USA.

Yang W. and Kohler N. (2008), Simulation of the evolution of the Chinese building and infrastructure stock, *Building Research & Information*, 36(1), pp. 1-19.

Yang J.X., Xu C, and Wang R.S., (2002), *Methodology and application of life cycle assessment*. Beijing: China Meteorological Press (in Chinese).

Yang X.M. (2003), Quantitative assessment of environmental impact on construction during planning and designing phases. Master thesis, Department of Construction Management, School of Civil Engineering, Tsinghua University, (in Chinese).

Zhang, Z., Wu, X., Yang, X., and Zhu, Y. (2006), BEPAS: A life cycle building environmental performance assessment model. *Building and Environment*, *41* (5), pp. 669-675.

Zhen Y.P. and Chen Q.S. (2008), Simulation calculation of bus fuel economy under urban traffic Eenvironment, *Tractor and Farm Transport,* Vol.35(4), (in Chinese).

ABOUT THE AUTHORS

Wu Deng

Wu Deng has recently obtained a PhD from the Faculty of the Built Environment at the University of New South Wales Australia.

Deo Prasad

Professor Deo Prasad is the director of Sustainable Development Program in the Faculty of the Built Environment at the University of New South Wales Australia.

Paul Osmond

Dr. Paul Osmond is a course coordinator within the Sustainable Development Program in the Faculty of the Built Environment at the University of New South Wales Australia.

Feng Ting Li

Professor Feng Ting Li is the deputy dean of the UNEP-Tongji Institute of Environment for Sustainable Development China.