536: Feasibility Studies on the Development of Zero CO_2 Emission Residential Communities in China

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Abstract

Zero CO_2 emission urban residential community in China is studied based on quantitative methods in this paper. Algorithms and methods are firstly introduced to quantitatively calculate the lifecycle CO_2 emission of a residential community focused on two aspects: 1) CO_2 emissions of buildings in the community, and 2) CO_2 sequestration of the greenspace in the community. Then a case study is carried out using the algorithms developed and it is found that, in a typical high density residential community, the CO_2 sequestration by greenspace only balances around 3% of the lifecycle CO_2 emission of buildings, and thus CO_2 neutral community may not be realistic under current regulations and standards in Beijing. Further discussion is focused on energy efficiency strategies and incorporation of renewable energy, which may contribute to 50% of CO_2 emission reduction. The other 50% CO_2 emission will have to be neutralised by suburban forest CO_2 sequestration in urban scale based on the algorithms.

Keywords: urban residential community in China, CO_2 emission, CO_2 sequestration, Zero emission

1. Introduction

It is of realistic significance to decrease the emission of the CO_2 and slow down the pace of global warming. In China, building industry uses up to one third of the overall fossil-fuel energy. Especially residential communities, due to their large number, occupy a large quota of buildings and therefore the CO_2 emission related is considerably large. The reduction of the CO_2 emission of residential communities therefore is a key issue of the alleged 'energy saving and emission reduction' scheme in China. However, until now, there has been no method that can be used for the lifecycle estimation of the CO_2 emission of a residential community and hence the feasibility of a carbon neutral community has not been made clear. Focused on this issue, the mathematical models and computing formula are introduced in this paper, and based on the quantitative estimation, the feasibility of zero emission will be analyzed and the mitigation measures will then be discussed. This may further lead to operational assessment of the current standards, design methods and strategies towards zero emission community in China.

2. Development of the algorithm

2.1 Lifecycle net CO_2 emission

The net CO_2 emission of a residential community is determined by the CO_2 emitted due to the energy consumption of buildings and the CO_2 sequestration by the greenspace in the community. Thus, the lifecycle net CO_2 emission of a residential community can be calculated using the formula:

$$P_n = P - S_q \tag{1}$$

where P_n is the lifecycle net CO_2 emission of a residential community, P is the lifecycle CO_2 emission attributable to the buildings, S_q is the CO_2 sequestration of the greenspace.

2.2 CO_2 emission of Buildings

2.2.1 General

Generally, the lifecycle of a building in China consists of 4 stages (as shown in Fig 1): 1) procurement (manufacture and transportation), 2) construction, 3) operation and maintenance, 4) demolition. The CO_2 emission of each stage needs to be calculated in different ways. The total lifecycle CO_2 emission is obtained as:

$$P = P_1 + P_2 + P_3 + P_4 \tag{2}$$

where P_1, P_2, P_3, P_4 are the CO_2 emission of procurement, construction, operation and maintenance, demolition respectively.

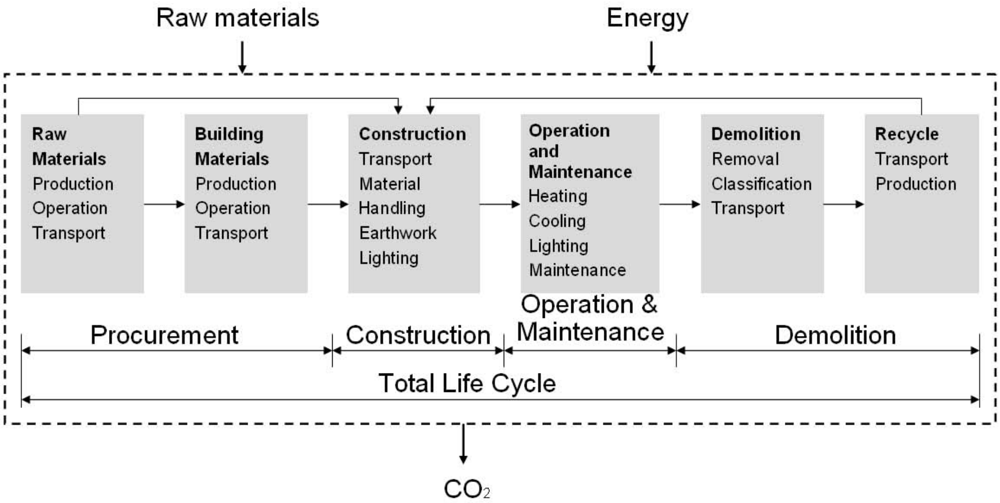

Fig 1. Building's Life Cycle [3]

2.2.2 CO_2 emission of the procurement

The CO_2 emission of this stage consists of two parts and thus is calculated as:

$$P_1 = P_m + P_t \quad (3)$$

where P_m is the CO_2 emission of the manufacture of the building systems, P_t is the CO_2 emission of the transport of the building systems.

(1) The CO_2 emission of manufacture is calculated as:

$$P_m = \sum_i B_i X_i (1 - \alpha_i) \quad (4)$$

where *B* is the weight of the material including the amount for repairing and replacing, *X* is the CO_2 emission factor of the material (Table 1), *α* is the recovery coefficient of the material (Table 2), *i* is building material used.

Table1: CO_2 emission factor of the building material [1]

Building material	CO_2 emission factor(t/t)
Cement	0.8
Steel	2.0
Aluminium	9.5
Glass	1.4
Timberwork	0.2
Construction ceramics	1.4
Clay brick	0.2
Concrete block	0.12

Table2: Recovery coefficient [1]

Section steel	Steel bar	Aluminium
0.90	0.50	0.95

(2) The CO_2 emission of the transportation is calculated as:

$$P_t = \sum_{i,j} B_i L_{ij} Y_j \quad (5)$$

where *B* is the weight of the material, *L* is the transportation distance, *Y* is the CO_2 emission per Ton-Kilometre (Table 3), *i* is building material used, *j* is transportation mode .

Table3: CO_2 emission per Ton-Kilometre

Transportation mode	CO_2 emission(t/t·km)
Road	1.69×10^{-4} [4,5]
Rail	9.1×10^{-6} [9]

2.2.3 CO_2 emission of construction

The construction CO_2 emission is calculated according to different processes:

$$P_2 = \sum_i q_i \times Vb_i \quad (6)$$

where *q* is the CO_2 emission factor of construction process (Table 4), *Vb* is the quantity of construction process, *i* is the construction process.

Table 4: CO_2 emission factor of construction process [6]

Construction process	CO_2 emission
Present mixed concrete	41.8kg/t
Ready mixed concrete	23.8kg/t
Earth excavation, Earth-fill	30.4kg/m^3
Site clearing	1.9kg/m^2
Materiel handling	2.85kg/t
Lighting for construction sites	24.7kg/m^2

2.2.4 CO_2 emission of operation and maintenance

The CO_2 emission due to lighting, heating, ventilation and air conditioning is the main part of this stage, while cooking, electrical appliances etc are ignored. Then, the emission of operation is obtained as:

$$P_3 = (P_{ch} + P_e) \times \theta \times n \quad (7)$$

where P_{ch} is the annual CO_2 emission due to the energy consumption for heating and cooling, P_e is the annual CO_2 emission due to lighting, θ is the correction coefficient related to the emission reduction, *n* is the lifetime of a building.

(1) Annual CO_2 emission of heating and cooling:

Energy consumption for heating and cooling is determined by the climate factors, building envelope, equipment efficiency, etc. In China, a variety of energy conservation standards have been enforced focused on factors list above for different climate and building types, with relevant design regulations and methods implemented respectively. The CO_2 emission is calculated using the following procedures.

Firstly, the annual energy consumed for heating E_{HY} and cooling E_{CY} is calculated according to the method introduced by the standards mentioned above.

Secondly, the annual CO_2 emission due to heating and cooling P_{ch} is calculated:

$$P_{ch} = E_{CY} \times \omega_C / \eta_C + E_{HY} \times \omega_H / \eta_H \quad (8)$$

where ω_C, ω_H are CO_2 emission factors (Table 5). η_C is the efficiency of cooling system, η_H is the efficiency of heating system.

Table 5: CO_2 emission factor [1]

Energy	CO_2 emission factor[10^{-3}t/(kW·h)]
Electricity	0.95
Natural gas	0.1984
Fuel	0.31
Coal	0.39

(2) Annual CO_2 emission of lighting

The calculation will be carried out by two steps:

Firstly, the annual energy consumed for lighting E_Y [1]:

$$E_Y = \sum W_T \times A \times T \times F \quad (9)$$

where W_T is the lighting power density of each room, also the lighting power per unit area, including the power of luminance, ballast and transformer, A is the floor area of each room, T is the lighting duration of each room, F is the correction coefficient.

Secondly, the annual CO_2 emission due to lighting P_e:

$$P_e = E_Y \times \omega \quad (10)$$

where ω is CO_2 emission factor.

2.2.5 CO_2 emission of demolition

The CO_2 emission due to demolition, P_4 is:

$$P_4 = P_d + P_s \quad (11)$$

where P_d is the CO_2 emission due to removal of buildings, P_s is the CO_2 emission due to disposal of demolition materials.

(1) The CO_2 emission of removal is calculated corresponding to destruction processes:

$$P_d = \sum_i q_i \times V_i \quad (12)$$

where q is the CO_2 emission factor of removal process (Table 6),V is the engineering quantity of the destruction process, i is the destruction process.

Table 6: CO_2 emission factor of destruction process [6]

Removal process	CO_2 emission(t/unit)
Destruction	7.78kg/m^2
Excavation, Fill	30.4kg/m^3
Site clearing	1.9kg/m^2
Material handling	2.85kg/t

(2) The CO_2 emission due to disposal of demolition materials is calculated:

$$P_s = \sum_i Be_i Xe_i \quad (13)$$

where Be is the weight of the demolition materials, Xe is the CO_2 emission factor of demolition materials, i is demolition material used.

In China today, most of the construction waste is placed in open air or buried underground at the final disposal site. So the emission is mainly attributed to transportation. However, for the materials that can be recycled or reused, the CO_2 emission associated with the energy consumption of reproduction should also be calculated (Table 7).

Table 7: CO_2 emission factor of the recyclable material [1]

Material	Steel	Aluminium
CO_2 emission (t/t)	0.80	0.57

2.3 CO_2 sequestration

CO_2 fluxes between the atmosphere and greenspace ecosystems are primarily controlled by uptake through plant photosynthesis and releases via respiration, decomposition and combustion of organic matter [16]. Then, the carbon is mainly stored in three components of the ecosystems: 1) biomass, 2) dead organic matter, 3) soils. Besides, urban greenspace also contributes to CO_2 emission through the consumption of energy for landscape management activities, such as mowing, pruning, irrigation, and fertilization [18].

Urban greenspace can reduce atmospheric carbon in two ways: (1) directly, through sequestration and (2) indirectly, through savings in the heating and cooling energy of buildings [18]. However, indirect carbon reduction is not considered in this study.

Then, during building lifecycle, CO_2 sequestration by the greenspace of the community is calculated by:

$$S_q = A_g \times Z \quad (14)$$

where: A_g is the area of the greenspace in the community. Z is the CO_2 sequestration during the building lifetime per unit area of the greenspace.

The estimate of greenspace sequestration, Z will be based on the three aggregate carbon pools (biomass, DOM and soils), while CO_2 emission due to landscape management will be neglected in this paper because of the low frequency and mechanization level of the management activity in China.

3. Case Study

3.1 Case description

The residential block for case study is a typical unit of a community with arrays of residential buildings in Beijing, China (Fig.2). The size of the block is 72m×50m (0.36ha); the greenspace area is 1200m^2, and the green ratio is 33%. The selected residential building (Fig. 3) is 64m long and 14m wide. Its total building area is 5376m^2, and the FAR (floor area ratio) is 1.5. This is a standard building introduced in *Design Standard for Energy Efficiency of Residential Buildings* [7]. It is a composite structure building with 6 floors, 2.7m storey height, no basement, 8 apartments for each floor and 112m^2 for each apartment. The lifetime of this building, according to the common requirement of residential building regulations in China, is 70 years. The U-Value of this building envelope will accord with requirement of design standard [7] (Table 8). In [7] the government established standard and target that the annual heating energy consumption should be 65% below 1980 levels.

Table 8: U-Value: overall heat transfer coefficient of building envelope [W/(m^2·K)] [7]

Outer-wall	Outer-window	Roof
0.60	2.80	0.60

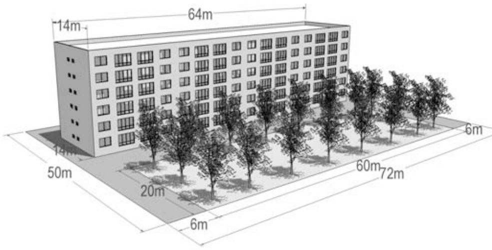

Fig 2. Perspective of the community block

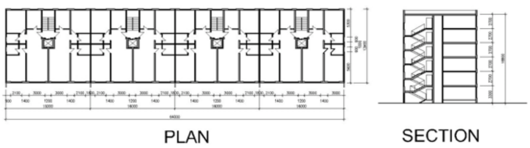

Fig 3. Plan, section of the residential building

3.2 Calculation

3.2.1 Procurement

The building materials consumption can be estimated according to *Technical and Economic Index of Construction Engineering of Beijing* [11]. To simplify the problem, only the CO_2 emission due to the main building materials, steel, cement, concrete, perforated brick, are calculated. The CO_2 emission factor of the material is from Table1 and [13]. It is assumed that all building materials are delivered by highway and the average transportation distance each is 200km. The CO_2 emission per Ton-Kilometre is listed in Table 3.

Table 9: CO_2 emission of procurement

Building material	Amount	Distance	CO_2 emission
Steel bar	722t	200km	457t
Cement	209t	200km	216t
Concrete	1403m^3	200km	481t
Perforated brick	1356t	200km	317t
Total: P_1			1471t

3.2.2 Construction

The construction CO_2 emission is calculated in Table 10.

Table 10: CO_2 emission of construction

Construction process	Quantity	Emission
Ready mixed concrete	3438t	82t
Earth excavation, fill	4268m^3	130t
Site clearing	896m^2	1.7t
Materiel handling	5725t	16.3t
Lighting	5376m^2	133t
Total : P_2		363t

3.2.3 Operation and maintenance

(1) Annual CO_2 emission due to heating and cooling

Firstly, the annual energy consumed for heating and cooling is calculated on the basis of the parameters and method introduced in [7].

The heating energy consumption is in relation to the heat loss through building envelope and air infiltration as well as the indoor heat gain. The indoor temperature is set to 16°C, while the average outdoor temperature during the heating period is set to -1.6°C [7].

The heat transfer loss of building envelope per unit area, q_{HT} (W/m^2) is:

$$q_{HT} = \frac{17.6}{A_0} \sum \varepsilon KF = 7.74 W/m^2$$

where K is heat transfer coefficient of building envelope, ε is correction factor of K, F is area of different parts of the building envelope, A_0 is total area of the building.

Calculation of $\sum \varepsilon KF$ is shown in Table 11.

Table 11: $\sum \varepsilon KF$ [7]

		ε	K (W/ m^2·K)	F (m^2)	εKF
	Roof	0.91	0.60	896	489
Outer-wall	South	0.70	0.60	687	289
	East,west	0.86		480	248
	North	0.92		824	455
Outer-window	South	0.18	2.80	439	221
	East,west	0.57		13	21
	North	0.76		302	643
	$\sum \varepsilon KF$				2366

The heat loss of air infiltration per unit area, q_{INF} is:

$$q_{INF} = \frac{2.08 V_0}{A_0} = 6.10 W/m^2$$

where V_0 is volume of the space enclosed by building envelope.

Then, the heat loss of building per unit area, q_H is:

$$q_H = q_{HT} + q_{INF} - 3.8 = 10.04 W/m^2$$

where 3.8 is the heat gain of building per square metre, including cooking, lighting, and other electrical appliances.

According to the regulations in Beijing, the annual heating energy consumption during the 125 days of heating period is:

$$E_{HY} = q_H \times T_H \times A_0 / 1000 = 161925 kW \cdot h / year$$

where T_H is heating period of the building per year.

Then, according to [7], the annual cooling energy consumption, E_{CY}, makes up to about 15% of the total energy for heating and cooling.

$$E_{CY} = 0.15 E_{HY} / 0.85 = 28575 kW \cdot h / year$$

Secondly, the CO_2 emission due to heating and cooling is calculated by formula (8), where, $\eta_H = 0.9 \times 0.68 = 0.612$ [8], $\eta_C = 2.9$ [7, 12]:

$$P_{ch} = 112.6 t / year$$

(2) Annual CO_2 emission of lighting

The lighting power density is assumed as 7W/m^2 [10], and the average lighting duration for each room is assumed as 3 hours a day, *F* as 1. The annual CO_2 emission due to lighting is:

$$P_e = 39.1t / year$$

(3) Total CO_2 emission of operation and maintenance

The total lifecycle CO_2 emission can be obtained using the equation (7), assuming θ=1, n=70:

$$P_3 = (P_{ch} + P_e) \times \theta \times n = 10619t$$

3.2.4 Demolition

The demolition CO_2 emission is calculated in Table 12.

Table 12: CO_2 emission of demolition

Construction process		Quantity	CO_2 emission
Removal	Destruction	5376m^2	41.8t
	Site clearing	896m^2	1.7t
	Material handling	5725t	16.3t
Disposal	non-recyclable material	168600tkm	28t
	Recyclable material	105t	1t
Total P_4			89t

3.2.5 Total CO_2 emission

According to the calculation above, the total lifecycle CO_2 emission is:

$$P = P_1 + P_2 + P_3 + P_4 = 12542t$$

The CO_2 emission due to operation and maintenance accounted for 85% of total emission, followed with 11% procurement, 3% construction and 1% demolition.

3.2.6 CO_2 sequestration

According to the sequestration data of urban greenspace in [16, 18, 19], it is assumed that the CO_2 sequestration of the residential greenspace is 300kg/m^2 during the 70 years. So the total CO_2 sequestration is:

$$S_q = 360t$$

3.2.7 Lifecycle net CO_2 emission of this block is

$$P_n = P - S_q = 12182t$$

3.3 Further discussion

As demonstrated above, in a typical high density residential community, building CO_2 emission is 2.33t/m^2, CO_2 sequestration by greenspace balances only around 3% of the lifecycle CO_2 emission of buildings, and CO_2 neutral community may not be realistic under current regulations and design standard, energy structure and level of technology in Beijing.

However, according to the algorithms above, there is a great potential in CO_2 emission reduction by adopting energy efficiency strategies, and incorporating renewable energy.

3.3.1 Energy efficiency strategies

Energy efficiency strategies, such as improvement of building envelope and utilization of energy-saving home appliances, encouraged by the Chinese government, will play an important role in CO_2 emission reduction.

(1) Improvement of building envelope thermal performance

Table 13 lists the U-values of building envelopes in Beijing and other regions of similar climate. By improving thermal performance of building envelopes, for example to the level of American regions, the CO_2 emission will decrease by 2365t, 19% of the total emission.

Table 13 U-value in Beijing and other regions [7]

Region	Outer-wall	Outer-window	Roof
Beijing	0.60	2.80	0.60
Berlin, German	0.3-0.2	1.5	0.20
American regions	0.45-0.32	2.04	0.19
Hokkaido, Japan	0.42	2.33	0.23

(2) Reduction of lighting energy consumption

The efficiency of lighting system may improve by energy-saving lamps, frequency converters and intelligent control system. Then the power density may reduce from 7W/m^2 to 6W/m^2, the target value prescribed in the standard [10], the CO_2 emission will decrease by 391t, 3% of the total emission.

3.3.2 Utilization of renewable energy

Coal-fired boilers is the supplier of heating and cooling in most urban residential communities in Beijing. However, more and more communities are incorporating renewable energy in recent years.

(1) Solar energy heating system

60% of the heating energy demand will be met when the solar collectors are installed fully on the roof of the building [15]. By using compound system of solar energy and coal-fired boilers, the CO_2 emission may be reduced by 35%.

(2) Ground source heat pump

Ground source heat pump is now incorporated in heating and cooling system together with coal-fired boiler and cooling tower. By this compound system, when ground source heat pump meets 60% of the total energy demand and the system efficiency reaches 5 (COP value), the CO_2 emission will reduce by 26%.

3.3.3 Suburban forest sequestration

Increasing greenspace ratio of the community will increase CO_2 sequestration in urban area. However, increment is limited in this way. The rest of the CO_2 emission of the community should be considered to be balanced by the suburban forest in urban scale. On the premise that half of the building CO_2 emission reduced by measures discussed above, 1.4-1.5ha of suburban forest still be required to neutralise the CO_2 emission, that is, 1ha of case community will be neutralised by 4 ha of suburban forest.

4. Conclusions

The results of this initial study and calculation have indicated that the CO_2 sequestration of greenspace in urban high density community is limited. The idea of zero CO_2 emission residential community in China may be realistic in urban scale rather than in community scale because suburban forest sequestration, nevertheless, is essential to neutralise the lifecycle CO_2 emission of the urban community under current regulations and design standard, energy structure and level of technology. However, based on the algorithms in this paper, low CO_2 emission strategies, such as improvement of building envelope, reduction of lighting energy consumption, especially utilization of renewable energy, may contribute to 50% of CO_2 emission reduction.

This method can also be used at the initial planning and designing stage to roughly estimate the CO_2 net emission of a residential community and study relevant ideas. More detailed information regarding to the topic, such as the CO_2 sequestration of different types of plants design and the incorporation of renewable energy in HVAC systems will be further studied and integrated into the framework specified in this paper.

5. References

1. Studying team for Green Building of Beijing Olympic, Assessment System for Green Building of Beijing Olympic. China Architecture & Building Press, Beijing, 2003.

2. Studying team for Green Building of Beijing Olympic, Implementation Manual of Green Building of Beijing Olympic. China Architecture & Building Press, Beijing, 2004.

3. Hong Ziping, Wang Guigong. Introduction to Eco-materials. Chemical Industry Press, Beijing, 2001.5

4. National Bureau of Statistics of China. China Statistical Yearbook2007. China Statistical Press, Beijing, 2007

5. Gu Daojin. Studies on Life Cycle Environment Impacts of Buildings,. [Doctor's Dissertation]. Tsinghua University, Beijing, 2006

6. Zhong Ping. Study of Building Life Cycle Energy Use and Relevant Environmental Impacts. [Master's Dissertation].Si Chuan University, Si Chuan, 2005

7. Local Standard of Beijing, DBJ 11-602-2006. Design Standard for Energy Efficiency of Residential Buildings. Standardization Office of Architectural Design of Beijing, Beijing, 2006

8. Industry Standard. JGJ 26-95. Energy Conservation Design Standard for New Heating Residential Buildings, China Architecture & Building Press, Beijing, 1996

9. National Development and Reform Commission. China Medium and Long Term Energy Conservation Plan, Beijing, 2004

10. National Standard. GB 50034-2004. Standard for Lighting Design of Buildings, China Architecture & Building Press, Beijing, 2004

11. Management Office of Engineering Cost of Beijing. Technical and Economic Index of Construction Engineering of Beijing, Beijing Engineering Cost Association, Beijing, 2005

12. National Standard. GB 12021.3-2004. The Minimum Allowable Values of the Energy Efficiency and Energy Efficiency Grads for Room Air Conditioners. Standard Press of China, Beijing, 2004

13. Shui Zhonghe, Wan Huiwen. Resource Utilization of Waste Concrete, Development Guide to Building Materials, 2004, 4: pp.75-79

14. Chen Zixin, Su Xuehen, Liu Shaozong, Zhang Zongxian. Studies in Urban geenbelt ecological benefits of Beijing, (3). Journal of Chinese Landscape Architecture, 1998, 3: pp.53-56

15. Ren Shengfeng, Lu Jian, Yin Hongliang, Analysis of Solar Energy Resource in Tianjin and its Application in Heating, Solar Energy Buildings, 2007,2: pp.34-38

16. Simon Eggleston, Leandro Buendia, Kyoko Miwa, Todd Ngara, Kiyoto Tenabe. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan, 2006

17. BRE, The Government's Standard Assessment Procedure for Energy Rating of Dwellings,

18. Hyun-Kil Jo, E.Gregory McPherson, Carbon Storage and Flux in Urban Residential Greenspace, Journal of Environmental Management(1995) 45, 109-133

19. Xu Yongrong, Wang Doutian, Feng Zongwei, Liu Shaokun, Wang Guobing, Effect of Carbon Storage in Several Artificial Vegetations on Sea-beach Salinity Soil in Tianjin China, Journal of Huazhong Agricultural