Exergy assessment of building energy use in China's hot summer and cold winter climate zone

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ABSTRACT: BEU accounting and assessment is a fundamental task for development of energy efficiency in buildings. The traditional methodology is based on caloric value of energy carriers, which is only relates to energy quantity. To address a comprehensive assessment, an exergy assessment methodology is put forward in this paper. Furthermore, in existing China's statistical yearbook, there is no specific item for building energy use. This paper processes analysis for statistical yearbook and acquires relevant rough data of building energy use. With the methodology, an analysis of BEU in Hot Summer and Cold Winter Zone of China is employed in the paper. According to analysis, the BEU (only refer to use in building operation in this paper) accounts for about 20% in local energy use. And the exergy efficiency is only around 0.3 in building energy supply, which is quite different with that by traditional methodology. From Burden Index of BEU, it can be found that BEU takes large share in local exergy production and more developed takes more. Especially in Shanghai, the Burden Index of BEU is at 7.0, which is very over-burdened. The building sector consumes the resources reserved in last thousands of years.

KEYWORD: building energy use, exergy assessment, cumulative embodied exergy consumption, exergy efficiency, burden index

1. INTRODUCTION

Buildings are energy gluttons and have a large impact on the global climate change and other energy-related environmental issues. Buildings consume between 40% and 60% of all energy use in most developed economies throughout the world, and an increasing proportion in many developing and emerging economies. Correspondingly, they are responsible for a similar proportion of humankind's carbon dioxide emissions with a consequential impact on global warming. A worldwide cooperation has been establishing to stimulate and coordinate the research on the impact that buildings have on climate change as well as the impact that climate change will have on buildings in the future.

The traditional approach to energy use accounting and assessment is caloric value of energy carriers. And it is adopted to normalize different energy carriers into uniform unit for energy analysis. However, this approach can only value energy use based on quantity, which can be called quantity assessment. Some useful information can be obtained by the approach but not enough and comprehensive. Especially when comes to energy utilization efficiency, it maybe misleading. For an instance, more than 90% of energy utilization efficiency is for electric heating by caloric analysis. However, it is actually a very less efficient means for heating when energy grade is considered. As far as energy quantity and energy quality are both concerned, exergy is a robust indicator for a comprehensive assessment in energy sector. An exergy assessment methodology is put forward in this paper to give a comprehensive assessment for building energy use (BEU). Here, BEU refers to energy use in building operation stage only. Based on the exergy assessment methodology, assessment and analysis of BEU in Hot Summer and Cold Winter Zone (HSCW) of China's climate zone are employed to illustrate the methodology working in this paper.

2. METHODOLOGY

2.1 BEU accounting in China

As premise of exergy assessment for BEU, BEU accounting is fundamental work for assessment. Whilst In exiting China's energy statistics, there is no exclusive sector for BEU. BEU is separated into different energy statistical items, like 'transport, storage and post', 'wholesale, retail trade, hotels and catering services', 'residential consumption' and 'others', and also mixed with industrial energy use. To acquire appropriate data of BEU, statistical items of energy use in national or provincial statistical yearbook should be analysed firstly. [BEE research centre of Tsinghua University, 2007.]

2.2 Exergy assessment

Exergy is 'The maximal amount of work that can be extracted from the system in the process of reaching equilibrium with its local environment.'.[ZHAO,G and QIAN, L, 1984] Unlike energy, exergy is always destroyed because of the irreversible nature of the process. Exergy is an extensive property whose value is fixed by the state of the system once the environment has been specified. Therefore, the evaluation of exergy depends on both the state of a system under study and the conditions of the reference environment.

As regards BEU assessment, the reference environment is the physical environment. Although it is changing endless, however, it is relatively stable and constant compared with the change of building life cycle and energy use process, mostly combusting. Thus, exergy of energy carriers is regarded as constant.

- Exergy of energy carriers

Fossil energy The exergy of fossil energy is its chemical exergy, or called fuel exergy. And it is normally approximate to fuel's gross caloric value.[WANG,W, ZMEUREANU,R and RIVRD,H, 2005] Furthermore, the process of fossil energy extraction, transport and/or refining consumes some energy as well and should be considered as embodied exergy. The following equation shows the relationship between caloric value and embodied exergy of energy carriers.

$$Ex_{em} = \alpha \cdot E_f = \alpha \cdot Q_h \cdot \xi$$

In which, α refers to embodied factor which includes energy use that occurs during the energy carrier extraction, transportation and refining.

Ex_{em}: embodied exergy of energy carrier, kJ/kg or kJ/m3 or kJ/kWh

E_f: fuel exergy of energy carrier, kJ/kg or kJ/m3 or kJ/kWh

Q_h: gross caloric value of energy carrier, kJ/kg or kJ/m3 or kJ/kWh

ξ: 0.95 for gas fuel, 0.975 for liquid fuel and 1.00 for solid fuel[WANG,W, ZMEUREANU,R and RIVRD,H, 2005]

Embodied factor of some selected fossil energy carriers are listed in table 1.

Table 1: embodied factor for selected energy carriers[WANG,W, ZMEUREANU,R and RIVRD,H, 2005]

Energy carrier	Embodied factor (α)/J/J	Energy carrier	Embodied factor (α)/J/J
Raw coal	1.07	Kerosene	1.21
Coal gas	1.10	Diesel oil	1.22
Crude oil	1.18	LPG	1.22
Fuel oil	1.22	Natural gas	1.19
Gasoline	1.21	Power (2004)	1.06

Electricity As far as electricity is concerned, exergy equates to its caloric value and electricity delivery efficiency (EDE) should be considered as well, which includes electricity generation efficiency (EGE) and electricity transmission efficiency (ETE). From China's statistical yearbook, power is basically from four main kinds of energy carriers, which are raw coal, petroleum products, hydro-energy and nuclear energy. Nuclear energy is a type of alternated and transitional energy resources for fossil energy and it is temporarily clean or renewable compared with fossil energy. Thus, embodied exergy factor is designated as 1.0 for nuclear power. Moreover, hydro-energy is regarded as clean and renewable, however, large-scale hydropower station imposes many negative unknown or under assessing impacts on the environment. Considering the condition, 1.0 is also appointed for hydropower. As for thermal power, the EDE for thermal power is about 39.45%[China Statistical Bureau, 2006] and, combining with fossil energy embodied factor, the overall embodied factor is also shown in table 2.

Renewable energy The exergy of renewable energy is equivalent to its caloric value, omitting its production and transportation loss.

- Exergy efficiency

Combustion is the common means for fossil energy utilization. According to the second law of thermodynamics, exergy equation is[BEE research centre of Tsinghua University, 2007, Ivar S. Ertesvag, 2005]:

$$W = E_{x,Q} = \int (1 - \frac{T_0}{T}) \delta Q$$

For gas, coal and oil, the maximum efficiency of embodied exergy supply is as follows

$$\beta_{em,\max} = \frac{W \cdot \eta}{Ex_{em}} = (1 - \frac{T_0}{T - T_0} \ln \frac{T}{T_0}) \cdot \xi^{-1} \cdot \alpha^{-1} \cdot \eta$$

In which,

T : complete combustion temperature of gas, coal or oil, K

T_0 : environmental temperature, K

$\beta_{em,\max}$: the maximum efficiency of embodied exergy supply

η : equipment efficiency

Renewable energy is sustainable carrier for energy use. And 100% can be granted to its exergy efficiency despite its actual transition efficiency of equipment.

- Exergy assessment

With the exergy value and exergy efficiency, two assessment indicators are brought forward to address assessment. And they are cumulative embodied exergy consumption ($CEx_{em}C$) and overall maximum efficiency of embodied exergy supply ($Ex_{em}E_{s,\max}$). When using $CEx_{em}C$ as an indicator to assess environmental impact, the exergy of renewable energy should be wiped off owing to its sustainability, which is $CEx_{em}C_{impact}$

Therefore, the equations of exergy assessment are:

$$CEx_{em}C = \sum_i Ex_{em,i} = \sum_i \alpha_i \cdot Ex_i = \sum_i \alpha_i \cdot Q_{h,i} \cdot \xi$$

$$Ex_{em}E_{s,\max} = \frac{\sum_i Ex_{benif,i}}{CEx_{em}C} = \frac{\sum_i \beta_{em,\max,i} \cdot Q_{h,i} \cdot \xi_i}{\sum_i \alpha_i \cdot Q_{h,i} \cdot \xi_i}$$

in which,

Ex_{benif} : benefit exergy, J

other parameters are described in the above.

Sustainability of BEU

From ecological carrying capacity's view, a global average ecosystem productivity is used to measure carrying capacity. The exergy yield of terrain is taken from[Wackernagle,M and Rees,W, 1996, Olgyay,V and Herdt,J, 2004], and assumed to be an average of 100 GJ/ha.a. Building Impact Footprint of BEU is used to assess the sustainability of BEU. The equation is as follows:

$$BIF_{BEC} = \frac{CEx_{em}C_{impact}}{Ex_{prod}S}$$

In which,

BIF_{BEC} : Building Impact Footprint of BEU,

Ex_{prod} : exergy yield of terrain, 100 GJ/ha.a,

S: terrain area of province or city, ha,

Other parameters are described in the above.

3. BEU ASSESSMENT IN CHINA'S HSCW CLIMATE ZONE

3.1 Typical provinces or cities

HSCW climate zone covers sixteen provinces and municipalities in China with the area of 1.8 million km2 and the population of 0.55 billion. And it accounts for nearly half of national GDP. It is the most population-dense and ecomonic-developed area in China. Thus, the BEU condition in the area is crucial to national development. Due to not complete overlapping with climate zone and national administration classification, seven provinces and municipalities are selected as typical provinces for exergy assessment of HSCW climate zone, which can guarantee data accessibility and integrality. The seven typical provinces are two municipalities (Shanghai and Chongqing) and five provinces (Zhejiang, Anhui, Jiangxi, Hubei and Hunan). The raw data in the following analysis are data in year 2004 from China's statistical yearbook (2005) and China's energy statistical yearbook unless specified.

3.2 Building development

With the rapid urbanization and economic development in China, building sector has been gaining much development. And according to World Bank prediction, there would be 1.0~2.0 billion m2 floor area of new buildings in China annually until 2020. And by then, 50% of building stock would be buildings after year 2000.

3.3 Exergy assessment of BEU

Using $CEx_{em}C_{impact}$ and $Ex_{em}E_{s,\max}$ as indicators, BEU of typical provinces in 2004 is assessed as shown in table 2, table 3 and table 4.

Table 2: $CEx_{em}C_{impact}$ per sq.m of typical provinces in year 2004

Unit: MJ/m2

Item	CQ	SH	ZJ	AH	JX	HB	HN
PB	340.6	1210.1	791.3	469.1	358.0	482.7	273.9

CPB	223.5	838.7	524.2	303.4	229.8	323.6	185.0
LPB	1341.3	5031.9	3145.3	1820.1	1378.9	1941.9	1109.9
UR	323.5	450.0	263.6	549.1	228.4	302.8	180.3
RB	118.5	293.3	99.5	89.9	70.6	91.0	51.0
UB	329.4	758.9	450.0	522.8	270.2	368.7	215.3
Total	200.5	663.9	256.7	215.6	130.6	193.7	100.7

Table 3: $CEx_{em}C_{impact}$ of typical provinces in year 2004

Unit: 10^8 GJ

Item	CQ		SH		ZJ		AH		JX		HB		HN	
PB[1]	0.378	0.227	2.916	0.590	2.429	0.488	0.652	0.208	0.430	0.266	1.163	0.338	0.701	0.308
CPB	0.222	0.133	1.842	0.372	1.445	0.291	0.376	0.120	0.245	0.152	0.703	0.204	0.428	0.188
LPB	0.156	0.094	1.074	0.217	0.984	0.198	0.277	0.088	0.185	0.114	0.460	0.133	0.273	0.120
UR	0.686	0.412	1.584	0.320	1.481	0.298	1.554	0.496	0.576	0.356	1.262	0.366	0.772	0.339
RB	0.602	0.361	0.446	0.090	1.063	0.214	0.926	0.296	0.610	0.378	1.020	0.296	0.806	0.354
UB	1.064	0.639	4.500	0.910	3.911	0.786	2.206	0.704	1.005	0.622	2.426	0.704	1.473	0.646
Total[2]	1.666/19.4%		4.946/25.4%		4.973/17.1%		3.133/19.1%		1.616/16.7%		3.446/17.2%		2.279/13.8%	
Local EC[3]	8.584		19.499		29.016		16.434		9.648		20.063		16.505	

Note: 1. left column is for amount and right column is for share in building sector

2. amount/percentage in local EC

3. EC: energy consumption

Table 4: energy supply efficiency of typical provinces in year 2004

Item	CQ		SH		ZJ		AH		JX		HB		HN	
	ExE	EE	ExE	EE	ExE	EE	ExE	EE	ExE	EE	ExE	EE	ExE	EE
PB	0.331	0.524	0.336	0.518	0.330	0.535	0.332	0.535	0.341	0.490	0.339	0.521	0.352	0.442
UR	0.369	0.519	0.355	0.532	0.358	0.513	0.323	0.649	0.349	0.550	0.341	0.547	0.348	0.485
RB	0.316	0.641	0.321	0.639	0.357	0.487	0.321	0.619	0.321	0.627	0.324	0.634	0.323	0.612
UB	0.355	0.521	0.343	0.523	0.341	0.527	0.326	0.615	0.345	0.524	0.340	0.534	0.350	0.464
Total	0.341	0.565	0.341	0.533	0.344	0.518	0.324	0.616	0.336	0.564	0.335	0.564	0.340	0.517
Local EC	0.327	0.589	0.319	0.555	0.328	0.552	0.320	0.605	0.339	0.581	0.322	0.587	0.325	0.574

Note: ExE, the maximum efficiency of embodied exergy supply; EE, energy supply efficiency based on caloric value

The sustainability of BEU in typical provinces is illustrated in fig.1

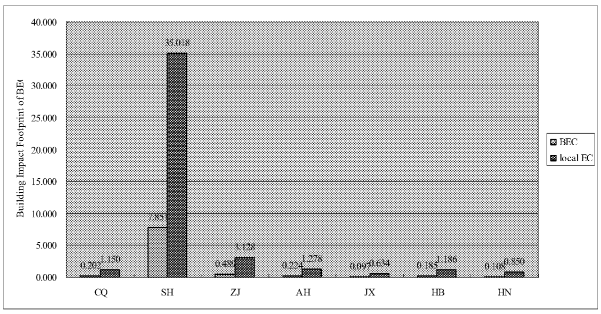

Fig.1 Building Impact Footprint of BEU and local EC in typical provinces

4. DISCUSSION

4.1 BEU in China's HSCW climate zone

- From analysis above, BEU contributes around 1/5 to local EC, especially 25.4% in Shanghai, due to its higher demand on energy and higher developed level.
- Because of higher urbanization development in developed provinces, UB, especially PB, takes more share in BEU with about a half in Shanghai and Zhejiang. This also comes from developed economic condition in the provinces.

- As far as BEU in UR is concerned, there is no obvious relationship between BEU and economic development like that for BEU in PB. While the BEU is more related to local climate condition.

4.2 Energy supply efficiency in China's HSCW climate zone

- When comes to energy supply efficiency, $Ex_{em}E_{s,\max}$ is only around 0.3 to 0.4 while EE is nearly 0.6, which shows that the total efficiency on quantity and quality is much less efficient.
- Taking UB as an example, the efficient order on exergy is CQ>HN>JX>SH>ZJ>HB>AH, and the order on caloric value is AH>HB>ZJ>JX>SH>CQ>HN. The efficiency on quantity only is quite different with that on quality and quantity both. If quantity is considered only, the analysis result would mislead the energy efficient development. The most effcient part by EE may be the least efficient part by $Ex_{em}E_{s,\max}$.
- Within building sector, except Anhui, the highest part is in UR, and following with PB and RB. In Anhui, because of central heating by coal-fired, the UR part is less efficient than that in PB.

4.3 Sustainability of BEU

From fig.1, the developed provinces is more over-burdened. For an instance, in Zhejiang, nearly half of annual terrain exergy production is consumed in building operation. If the BIF is over 1, it means that the consumption is over-burdened and the development is not sustainable. The development relies on the resources reserved during last thousands of years.

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