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RESEARCH ARTICLE

Embodied exergy-based assessment of energy and resource consumption of buildings

Jing MENG[1,2], Zhi LI (✉)[2], Jiashuo LI[2], Ling SHAO[2], Mengyao HAN[2], Shan GUO[2]

1 College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
2 State Key Laboratory for Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, China

Abstract As an effective approach to achieve a more unified and scientific assessment, embodied exergy-based analysis is devised to assess the energy and resource consumption of buildings. A systematic accounting of the landmark buildings in E-town, Beijing is performed, on the basis of raw project data in the Bill of Quantities (BOQ) and the most recent embodied exergy intensities for the Chinese economy in 2007 with 135 industrial sectors. The embodied exergy of the engineering structure of the case buildings is quantified as 4.95E + 14 J, corresponding to an intensity of 8.25E + 09 J/m^2 floor area. Total exergy of 51.9% and 28.8% are embodied in the steel and concrete inputs, respectively, due to the fact that the case buildings are structured of reinforced-concrete. The fossil fuel source (coal, crude oil, and natural gas) is predominant among four categories of natural resources (fossil fuel, biological, mineral, and environmental), accounting for 89.9% of the embodied exergy, with coal as the dominant energy resource (75.5%). The material accounts for 89.5% of the embodied exergy, in contrast to 9.0%, 1.4%, and 0.1% for manpower, energy, and equipment respectively. This result indicates that great attention should be given to the use of various materials vs. their value of their contribution.

Keywords energy, resources, exergy analysis, green building, ecological assessment

1 Introduction

In 2007, buildings consumed about 47% of the total energy consumption of China (Wang, 2005). Since that time, building related energy consumption has escalated due to rapid urbanization and increasing large-scale infrastructure construction. During the last two decades, the annual growth rate of building energy consumption in China has exceeded 10% (Chang et al., 2011). To reduce the lifecycle of the energy cost of buildings, energy accounting and conservation of building construction has become an important consideration.

In light of the sustainable development perspective, the concept of green building has been proposed by the Ministry of National Construction of China (MNCC, 2006), which refers to maximizing conservation of resources (energy, land, water, and materials) during the life cycle of the buildings to minimize the impact on the environment not only in the present, but in the infinite future. In this context, thermodynamic metrics, e.g., embodied energy (Lenzen and Treloar, 2002; Yeo and Gabbai, 2011; Dixit et al., 2012), emergy (Meillaud et al., 2005; Pulselli et al., 2007; Li et al., 2011), and exergy (Liu et al., 2010), are applied to evaluate the resources used by buildings.

Embodied energy is the sum of all the energy required to produce goods or services. Much research has been conducted on embodied energy of building construction in recent years. The embodied energy of construction projects in China accounted for nearly one-sixth of the total economy's energy consumption in 2007 (Chang et al., 2010). In a study on building structure, a building with wood and concrete designs in Wälludde was evaluated (Lenzen and Treloar, 2002). A comparative analyses between the two alternative structural designs-glue-laminated timber panels and steel frame filled with concrete blocks was performed (Vukotic et al., 2010). Their results indicate that the structure of the building greatly affected the embodied energy. Embodied energy can assess the overall energy consumed by the construction of buildings; however, current interpretation of embodied energy was unclear and varied greatly (Dixit et al., 2012).

Emergy is the available energy of one kind that is used

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E-mail: lizhi_pku@163.com

up in transformations directly and indirectly to make a product or service (Odum, 1996). As one of the ecological economic methods, emergy analysis can evaluate the complex relationship between an economic system and its environment. The advantage of emergy analysis in evaluating the services or information is revealed by Meillaud et al. (2005), who conducted an evaluation on the annual emergy consumption/production of a laboratory building. However, the concept of emergy has been controversial among different academic communities, including ecology, thermodynamics, and economics (Hau and Bakshi, 2004). For a clearer and more comprehensive vision of natural resource management, an integrated environmental accounting method is required.

Due to the limitations of emergy analysis, Odum (1983) realized that available energy, i.e., exergy should be of greatest importance to the system. Therefore, between all the thermodynamic metrics shown above, exergy, defined as the maximum potential work due to the contrasts between a system and its environment, offers a unified measure and a better description of the resource use as well as environmental impact, with essential implications to sustainability (Wall and Gong, 2001; Rosen et al., 2008).

Much effort has been devoted to the investigation of energy consumption and environmental impact of buildings based on exergy analysis (Torío et al., 2009; Martinaitis et al., 2010; Schweiker and Shukuya, 2010). A generic model of exergy assessment was proposed by Liu et al. (2010), who evaluated building energy utilization and building material use through its exergy footprint and environmental impacts of the building life cycle. Gonçalves et al. (2012) assessed the energy performance of a hotel building in Coimbra and proposed a new indicator based on exergy, i.e., energy performance of building directive (EPBD), to give better insights into building energy use. In addition, exergy analysis has been conducted to study building energy systems (Tolga Balta et al., 2008; Sakulpipatsin et al., 2010; Yucer and Hepbasli, 2011).

The aforementioned studies have contributed significantly to the development of exergy analysis for buildings and indicate that they provide a unified way to measure consumption of various resources. However, several limitations have also been observed for this process-based research. Firstly, most of the research was carried out with process analysis, which only traces the main inputs, i.e., material, with inconsistent system boundaries and limited accuracy. Secondly, compared with research that adopts exergy analysis on the building operation phase and its energy systems, exploration of embodied exergy of building construction is relatively rare and scattered (Rosen et al., 2008; Yucer and Hepbasli, 2011).

In this paper, to completely and comprehensively understand the energy and resource consumption of building construction, an exergetic systematic accounting procedure and its application to case buildings in Beijing is presented, in support of the raw project data in the Bill of Quantities (BOQ) provided by the Beijing Development Area Co, Ltd (2009). To our knowledge, this is the first application of embodied exergy used in the engineering of the building constructions. It provides concrete accounting procedures to evaluate embodied exergy of various material, equipment, energy, and manpower inputs, and reveals the components of embodied exergy of typical office buildings. The results could be used as a reference to reduce energy consumption of building construction.

2 Methodology

2.1 Embodied exergy

Human activities are supported by the utilization of natural resources which differ in their composition and/or thermal parameters from the common levels appearing in the environment (Szargut et al., 1988). Unlike energy, exergy is not conserved, which is the fundamental resource to sustain a system and is lost in driving the irreversible process associated with the system, as required by the second law of thermodynamics (Chen, 2006). The exergy method was initially employed in thermal and thermochemical systems (Szargut et al., 1988). Subsequently, Wall (1977) pioneered the resources exergy accounting framework for countries and evaluated the exergetic consumption as ecological cost for systems and processes. Moreover, cumulative exergy (Szargut and Morris, 1985), extended exergy (Sciubba, 2001; Liu et al., 2011; Dai et al., 2012), and cosmic exergy (Chen, 2005, 2006) have also been proposed as extensions of exergy.

The concept of embodied exergy first emerged in Odum’s book without a definition (Odum, 1983). After 23 years, Chen (2006) defined it as the total exergy directly or indirectly consumed in making or sustaining the commodity, based on the revealed scarcity of cosmic exergy availability in the material earth. Generally, embodied exergy of a specific object is defined as the sum of the direct and indirect exergy consumed by all intermediate inputs from the economy in its production process. In this paper, embodied exergy refers to the exergy hidden in all the inputs of the construction of the building.

2.2 Procedures of systematic accounting for buildings

Suffering from subjective system boundaries and the truncation error, process analysis can only trace the embodied exergy of some key inputs. Tracing all related processes of a building is a time and cost intensive task and might even fall into an endless loop (Bullard et al., 1978). Input-output analysis only gives the average intensity of a sector’s output and has limited accuracy. It provides researchers with a functional assessment tool for macro-level studies and is not appropriate for the analysis of an individual building (Leontief, 1970).

Upon consideration of the integrity of the input-output analyses that cover the connection of all objects, and the pertinence of process analyses which can calculate embodied exergy of the target product, Bullard et al. (1978) suggested the use of a hybrid method, as a combination of process and input-output analysis, to determine energy required by a target product. The definition of the accounting boundary for the terminal accounting and process analysis directly affects the results because it determines the truncation error. The embodied exergy of all the inputs (materials, equipment, energy and manpower) is included in the hybrid method. A change in the accounting boundary only converts some of the direct/indirect exergy consumption into indirect/direct exergy consumption and thus, in principle, the hybrid method does not influence the accounting result since no truncation has been made.

The hybrid method has been developed to calculate the embodied ecological elements of a variety of goods and services, e.g., carbon emissions of an individual building (Chen et al., 2010; Chen et al., 2011a), the nonrenewable energy cost and greenhouse gas emissions of a solar power tower plant (Chen et al., 2011d) or a wind power plant (Chen et al., 2011c), ecological systems (Chen et al., 2011b; Li et al., 2012), and even greenhouse gas emissions by Macao (Li and Chen, 2013; Li et al., 2013). In analogous fashion, the hybrid method is appropriate to calculate the embodied exergy of a target product. Moreover, to our knowledge, this is the first systematic accounting of embodied exergy used for the engineering of the building constructions.

Embodied exergy of a specific product or service is obtained by multiplying the quantity of raw material by its embodied intensities. Many contributions have been made from recent studies on embodied exergy intensity. At the national scale, Zhou presented two embodied exergy databases for China: one covering 151 goods in 1992 based on Material Products System and the other covering 42 industrial sectors in 2002 based on the economic input-output table (Zhou, 2008). Chen and Chen (2010) provided a database covering 135 industrial sectors for the 2007 Chinese economy, accounting for 37 sources of four natural resource groups evaluated by exergy. At the regional scale, Zhou et al. (2010) provided a database for Beijing in 2002, accounting for 27 sources in three natural resource groups evaluated by exergy.

The database presented by Chen and Chen (2010) is adopted in this study due to the following reasons: 1) case buildings were constructed around 2007, almost all inputs were produced in China, and the time scale and space scale match perfectly; and 2) the database providing embodied water intensities of 135 industrial sectors has the most detailed classification. The accounted natural resources evaluated by exergy encompass 37 sources of four groups, i.e., fossil fuel (coal, natural gas, and crude oil), mineral (iron ore, copper ore, zinc ore, gypsum, bauxite, pyrite, lead ore, cement, phosphorite, and nuclear fuel), biological (grain, beans, tubers, sesame, silkworm feed, cotton, peanuts, tea, bamboo, rapeseed, pulp, sugarcane, jute, sugar beet, tobacco, wool, vegetables, wood, milk, meat, fruits, egg, and aquatic products), and environmental (hydropower). Data are collected from CESY (2008), CEY (2008), and CSY (2008) or calculated by the authors according to AEM (1983), Fang et al. (1998), Liu (1999), and Zhou (2008). The direct external exergy resources for the 2007 Chinese economy are based on exergy intensities taken from Chen and Qi (2007), Kotas (1985), and Szargut (2005).

Thanks to the embodied exergy intensity database, which is based on ecological input-output analysis, a detailed and scientific analysis on building construction's embodied exergy could be conducted for the first time. However, several limitations could be found in the current research. For instance, the intensities in the database are derived from the 2007 input-output table, but not all buildings were constructed in 2007. In addition, the intensities are the averages for each sector for all of China, not the exact intensities of the inputs in Beijing. As a result, uncertainties cannot be avoided by the current study.

By employing the hybrid method, and in reference to the frame work provided by Chen et al. (2010) to account for energy carbon emissions of the buildings, a concrete exergy accounting procedure for building construction is elaborated. The main steps are shown below.

1) Form an inventory including all the materials, equipment, energy sources, and manpower inputs during the construction stage of the building. The productive sectors of materials and energy sources can be promptly determined with an extensive understanding of the input-output table. The embodied exergy of the equipment input can be calculated by: total exergy consumption of the equipment multiplied by work time for the target building, divided by total life time. As one essential factor of production, manpower input is important and cannot be ignored. In the process of compiling the economic input-output table, manpower input, such as remuneration, has been incorporated into each sector as economic input. The embodied exergy intensity of a specific sector's manpower can be considered identical with the main products of the embodied exergy consumption intensity of the sector's main products. Thus, the intensity for the manpower used in the engineering of the building is taken as the mean intensity for the construction industry;

2) Identify the corresponding industrial sector for each item and obtain the corresponding embodied exergy intensities from the appropriate database;

3) Multiply the quantity of raw material by its corresponding intensity to obtain the embodied exergy of each input;

4) Add the exergy of all inputs to result in the embodied exergy of the building construction.

3 Case study

The proposed scheme is applied to a typical group of buildings, i.e., the landmark arrow of six office buildings in the International Enterprise Avenue Industry Park (IEAIP) (Phase 2) of BDA with a total floor area of 60,000 m^2, as shown in Fig 1. The Beijing Economic-Technological Development Area (BDA) located in E-town (Yizhuang region) of the capital of China, the raw project data, and the BOQ of the six case buildings, are provided and authorized by Beijing Development Area Co Ltd (2009)[1)].

Fig. 1 The layout for the six case buildings.

3.1 Case buildings description

Established in 1992 with a designed area of 46.8 km^2, BDA is the only state-level economic and technological development zone in Beijing ratified by the State Council, and enjoys the preferential policies of both a national hi-tech industrial park and an economic and technological development zone. As a major platform of Beijing, enlarging and strengthening the real economy, BDA has always insisted on the development goal of "Three-High and Two-Low" (high end, high efficiency, high radiation and low energy consumption, low emission), developing clean energy and strengthening environmental management. Thus, BDA has been walking in the forefront of all national development zones. After years of intensive development, cluster development, innovation development, and sustainable development, BDA has gathered more than 4,800 enterprises from over 30 countries and regions, including almost 100 projects invested by 77 Fortune 500 enterprises, as well as numerous high quality domestic projects. As a result of the BDA development strategy, electronic information, biological medicine, equipment and automobile manufacturing form four leading industries, the output values of which account for 50%, 48%, 22%, and 17% of the total output value of industry in Beijing, respectively.

3.2 Embodied exergy accounting and analysis for the case buildings

Supported by the BOQ provided by the Beijing Development Area Co Ltd (2009) for the engineering structure of the case buildings, the inputs inventory associated with the production sector of the engineering structure of the case buildings is shown in Table 1.

The corresponding embodied exergy intensities of these inputs can be obtained from the embodied exergy intensity database provided by Chen and Chen (2010), in which the accounted natural resource exergy encompasses four groups, namely, fossil fuel, biological, mineral, and environmental sources. Since many different items from the same production sector have the same intensity, we aggregate the items from the same sector in the following calculation. In Table 3, only the intensities of the related production sectors instead of the intensities of all items are presented. Meanwhile, for a more clear and convenient expression of the results, the full sector names are abbreviated, as listed in Table 2.

Accordingly, the embodied exergy of the engineering structure is calculated. Table 3 shows the embodied exergy from the 37 kinds of natural resources; an aggregation and embodied exergy from the four categories are shown in Table 4.

4 Results and discussion

The embodied exergy of the case buildings' engineering structure is evaluated as 4.95E + 14 J, with an intensity of 8.25E + 09 J/m^2 floor area. The components of the embodied exergy are shown in Fig. 2.

The fact that all the case buildings are structured with reinforced-concrete, steel, plays a significant role in determining the exergy inputs of the case buildings; 51.9% and 28.8% of the total exergy inputs are embodied the inputs of steel and cement, respectively. As further explanation of the input-output table, the used concrete is identified as a processed cement product (from the Manufacture of products of Cement and Plaster sector) instead of purely cement (from the Manufacture of Cement, Lime and Plaster sector), thus the embodied exergy attributed to the inputs from the Manufacture of Cement, Lime and Plaster sector share less than 1.0% of

1) Beijing Development Area Co Ltd (2009). The Bill of Quantities of Group A and Group B in Beijing Development Area. Beijing (in Chinese)

Table 1 Social inputs inventory associated with input-output sectors of the engineering structure

Item	Sector code	Sector contents
Manpower		
Manpower	95	Construction
Material		
Grit Cobble stone Peastone	9	Mining of non-ferrous metal ores
Hemp cut Flax silk	27	Spinning and weaving of hemp and tiffany
Timber Wood pattern plate Wood stay brace	32	Processing of timbers, manufacture of wood, bamboo, rattan, palm and straw products
Petroleum asphalt Paint solvent	37	Processing of petroleum and nuclear fuel
Polyurethane waterproofing coating SBS elastic bitumen JS-compound waterproof coating Rubber watertight strip Water swelling water stop P-type rubber strip Antirust coating Boiled oil Acetone Preservative Ethylene diamine Acid resistant paint Acid resistant paint thinner Fireproof coating Thin steel structure fireproof coating	42	Manufacture of paints, printing inks, pigments and similar products
Polyurethane	43	Manufacture of synthetic materials
SBS modified asphalt felt coiled material E44 epoxy resin Ethyl acetate 401 glue All-purpose adhesive Sealant Primer Toluene Waterproof powder Binder Adhensive agent Cobalt dryer	44	Manufacture of special chemical products
Glass fiber sheet Polyester cloth Glass fibre cloth Wood shell nosing line	47	Manufacture of chemical fiber
Ethylene propylene rubber Rubber slab	48	Manufacture of rubber
Polyurethane foam plastic Extruded polystyrene board Foam plastic Plastic sheath Compound polyethylene foaming composites Plastic fall pipe Plastic rainwater funnel	49	Manufacture of plastic
Lime Cement	50	Manufacture of cement, lime and plaster

(*Continued*)

Item	Sector code	Sector contents
Civil air defense concrete airtight door	51	Manufacture of products of cement and plaster
Civil air defense concrete hanged-plate door		
Pre-mixed percolation resistance concrete		
Trench cover		
Pre-mixed concrete		
Pre-mixed peastone concrete		
Mortar		
Caulking paste		
Gas concrete		
Haydite concrete hollow block		
Elastic caulking paste		
Building block	52	Manufacture of brick, stone and other building materials
Low-E glass	53	Manufacture of glass and its products
Frame glass door		
Tempering laminated rubber glass		
Rockwool	55	Manufacture of fire-resistant materials
Reinforced bar	59	rolling of steel
Steel plate		
Hot-dip galvanized angel steel		
Steel civil air defense airtight door	63	Manufacture of metal products
Steel beam		
Aluminum alloy glass door		
Aluminum heat insulation break bridge profile		
Aluminum alloy shutter		
Solid aluminum panel		
Aluminum alloy barrier shutter		
Bird-preventing net		
Revolving door		
Steel roof truss		
Window frame		
Cast iron water elbow		
Floor spring		
Door pull		
Galvanizing fixing part		
Back-bolt		
U-shape		
Stainless handing tool		
Stainless bolt		
Embedded member		
Hot-dip galvanized steel keel		
Hot-dip galvanized steel structure keel		
Stainless drain tank		
Solid aluminum panel		
Steel keel		
Bolt		
Screw		
Fluorocarbon painted aluminum profile keel		
Expansion bolt		
Pad block		
Taper thread sleeve		
Galvanized iron wire		
Steel net		
Iron and steel article		
Embedded iron member		
Electrode		
Galvanizing mild steel wire mesh		
Wire gauze		
Aluminum profile keel		
Core pulling rivet		
Spring		
Galvanized-iron		

(*Continued*)

Item	Sector code	Sector contents
Water	94	Production and distribution of water
Reinforced bar transport	97	Transport via road
Energy		
Electricity	92	Production and supply of electric power and heat power
Equipment		
Machinery Trencher Vibration machine Truck	69	Manufacture of special purpose machinery for mining, metallurgy and construction

Table 2 The full and abbreviated names of related input-output sectors

Sector code	Full name	Abbreviation name
9	Mining of non-ferrous metal ores	Non-ferrous metal
27	Spinning and weaving of hemp and tiffany	Weaving products
32	Processing of timbers, manufacture of wood, bamboo, rattan, palm and straw products	Wood products
37	Processing of petroleum and nuclear fuel	Petroleum
42	Manufacture of paints, printing inks, pigments and similar products	Paints
43	Manufacture of synthetic materials	Synthetic materials
44	Manufacture of special chemical products	Chemical
47	Manufacture of chemical fiber	Chemical fiber
48	Manufacture of rubber	Rubber
49	Manufacture of plastic	Plastic
50	Manufacture of cement, lime and plaster	Cement
51	Manufacture of products of cement and plaster	Cement products
52	Manufacture of brick, stone and other building materials	Brick
53	Manufacture of glass and its products	Glass
55	Manufacture of fire-resistant materials	Fire-resistant materials
59	Rolling of steel	Rolling of steel
63	Manufacture of metal products	Metal
69	Manufacture of special purpose machinery for mining, metallurgy and construction	Machinery
92	Production and supply of electric power and heat power	Electricity
94	Production and distribution of water	Water
95	Construction	Construction
97	Transport via road	Transport

the total energy consumption. Manpower shares 9.0% of the embodied exergy as the third largest source. This is due to the fact that construction is a labor-intensive industry. However, the production sectors aforementioned, whose inputs account for more than 1.0% of the embodied exergy, include the Manufacture of special Chemical Products sector (1.9%), Manufacture of Glass and Its Products sector (1.8%), Manufacture of Metal Products sector (1.7%), Production and Supply of Electric Power and Heat Power sector (1.4%), and the Manufacture of Synthetic Materials sector (1.2%). Only 2.4% of the embodied exergy is from the remaining 13 sectors.

Figures 3 and 4 show the components of 37 kinds of accounted natural resources and aggregated four categories evaluated by exergy, respectively.

The fossil fuel source (coal, crude oil, and natural gas) accounts for 89.9% of the total exergy inputs (see Fig. 3), followed by the mineral source (ferrous metals, non-ferrous metals, non-metal minerals) and biological source (agricultural products, forestry products, stock products,

Table 3 The related input-output sectors and corresponding embodied exergy intensities for the structure engineering (unit: J/1E + 04 CNY) (source: Chen and Chen, 2010)

Sector code	Sector contents	Fossil fuels			Biological resources				Minerals			Environmental resources
		Coal	Crude oil	Natural gas	Agricultural products	Forestry products	Stock products	Fishery products	Ferrous metals	Non-ferrous metals	Non-metal mineral	Hydropower
9	Non-ferrous metal	2.95E + 10	9.92E + 09	3.31E + 09	1.92E + 09	2.75E + 08	2.33E + 07	1.74E + 07	1.38E + 08	2.65E + 09	7.67E + 08	1.57E + 09
27	Weaving products	2.06E + 10	6.10E + 09	2.03E + 09	5.33E + 10	1.70E + 08	1.59E + 08	2.06E + 07	5.15E + 07	1.78E + 07	9.43E + 08	8.07E + 08
32	Wood products	2.61E + 10	5.36E + 09	1.79E + 09	6.16E + 09	1.10E + 10	2.37E + 07	1.83E + 07	8.31E + 07	2.41E + 07	9.36E + 08	8.97E + 08
37	Petroleum	2.10E + 10	6.75E + 10	2.25E + 10	1.45E + 09	1.51E + 08	1.50E + 07	1.12E + 07	1.42E + 08	2.10E + 07	4.44E + 08	1.03E + 09
42	Paints	3.93E + 10	1.56E + 10	5.21E + 09	6.61E + 09	3.59E + 08	3.59E + 07	3.29E + 07	1.12E + 08	5.75E + 07	2.42E + 09	1.37E + 09
43	Synthetic materials	3.59E + 10	2.86E + 10	9.53E + 09	2.12E + 09	2.30E + 08	1.91E + 07	1.16E + 07	1.04E + 08	3.69E + 07	2.18E + 09	1.39E + 09
44	Chemical	5.23E + 10	1.25E + 10	4.18E + 09	5.38E + 09	1.36E + 09	4.69E + 07	2.15E + 07	1.12E + 08	7.42E + 07	3.69E + 09	1.52E + 09
47	Chemical fiber	3.42E + 10	2.45E + 10	8.16E + 09	4.68E + 09	2.53E + 08	2.35E + 07	1.20E + 07	9.42E + 07	3.23E + 07	1.60E + 09	1.37E + 09
48	Rubber	3.15E + 10	1.14E + 10	3.80E + 09	3.66E + 09	5.12E + 09	3.33E + 07	1.46E + 07	1.51E + 08	3.98E + 07	1.28E + 09	1.11E + 09
49	Plastic	3.12E + 10	1.49E + 10	4.96E + 09	2.94E + 09	3.55E + 08	2.59E + 07	1.31E + 07	9.13E + 07	3.52E + 07	1.64E + 09	1.30E + 09
50	Cement	7.63E + 10	5.87E + 09	1.96E + 09	2.33E + 09	3.20E + 08	1.99E + 07	1.27E + 07	1.39E + 08	2.75E + 07	5.92E + 09	1.75E + 09
51	Cement products	5.69E + 10	7.68E + 09	2.56E + 09	2.12E + 09	3.10E + 08	2.13E + 07	1.38E + 07	2.41E + 08	2.61E + 07	4.33E + 09	1.37E + 09
52	Brick	7.50E + 10	9.37E + 09	3.12E + 09	2.26E + 09	3.43E + 08	2.24E + 07	1.42E + 07	1.36E + 08	3.17E + 07	8.54E + 09	1.37E + 09
53	Glass	6.10E + 10	1.02E + 10	3.41E + 09	2.32E + 09	3.63E + 08	2.13E + 07	1.33E + 07	1.29E + 08	3.52E + 07	6.43E + 09	1.30E + 09
55	Fire-resistant materials	5.22E + 10	6.20E + 09	2.07E + 09	2.30E + 09	2.85E + 08	2.16E + 07	1.69E + 07	1.50E + 08	8.27E + 07	7.43E + 09	1.08E + 09
59	Rolling of steel	5.95E + 10	7.41E + 09	2.47E + 09	1.60E + 09	2.12E + 08	1.91E + 07	1.31E + 07	1.92E + 09	5.21E + 07	7.67E + 08	1.44E + 09
63	Metal	4.07E + 10	6.04E + 09	2.01E + 09	2.17E + 09	4.01E + 08	2.50E + 07	1.82E + 07	7.08E + 08	1.13E + 08	1.02E + 09	1.43E + 09
69	Machinery	3.33E + 10	5.57E + 09	1.86E + 09	1.90E + 09	2.85E + 08	2.28E + 07	1.51E + 07	6.29E + 08	6.32E + 07	6.57E + 08	1.17E + 09
92	Electricity	1.17E + 11	8.54E + 09	2.84E + 09	1.44E + 09	2.03E + 08	1.57E + 07	1.10E + 07	1.10E + 08	3.08E + 07	3.58E + 08	1.01E + 10
94	Water	3.16E + 10	4.46E + 09	1.49E + 09	1.49E + 09	1.55E + 08	1.65E + 07	1.20E + 07	7.71E + 07	1.99E + 07	3.87E + 08	2.32E + 09
95	Construction	3.49E + 10	7.53E + 09	2.51E + 09	2.99E + 09	4.84E + 08	2.30E + 07	1.71E + 07	3.92E + 08	5.04E + 07	2.97E + 09	1.02E + 09
97	Transport	1.23E + 10	1.43E + 10	4.75E + 09	2.28E + 09	2.14E + 08	2.11E + 07	1.70E + 07	8.25E + 07	1.64E + 07	2.92E + 08	4.85E + 08

Table 4 The embodied exergy of the structure engineering (unit: J)

Sector code	Sector contents	Fossil fuels			Biological resources				Minerals			Environmental resources
		Coal	Crude oil	Natural gas	Agricultural products	Forestry products	Stock products	Fishery products	Ferrous metals	Non-ferrous metals	Non-metal mineral	Hydropower
9	Non-ferrous metal	1.15E + 11	3.86E + 10	1.29E + 10	1.92E + 09	2.75E + 08	2.33E + 07	1.74E + 07	1.38E + 08	2.65E + 09	7.67E + 08	17E + 09
27	Weaving products	3.09E + 08	9.15E + 07	3.05E + 07	5.33E + 10	1.70E + 08	1.59E + 08	2.06E + 07	5.15E + 07	1.78E + 07	9.43E + 08	8.07E + 08
32	Wood products	1.75E + 12	3.60E + 11	1.20E + 11	6.16E + 09	1.10E + 10	2.37E + 07	1.83E + 07	8.31E + 07	2.41E + 07	9.36E + 08	8.97E + 08
37	Petroleum	2.66E + 08	8.53E + 08	2.84E + 08	1.45E + 09	1.51E + 08	1.50E + 07	1.12E + 07	1.42E + 08	2.10E + 07	4.44E + 08	1.03E + 09
42	Paints	4.40E + 11	1.75E + 11	5.83E + 10	6.61E + 09	3.59E + 08	3.59E + 07	3.29E + 07	1.12E + 08	5.75E + 07	2.42E + 09	1.37E + 09
43	Synthetic materials	2.74E + 12	2.18E + 12	7.28E + 11	2.12E + 09	2.30E + 08	1.91E + 07	1.16E + 07	1.04E + 08	3.69E + 07	2.18E + 09	1.39E + 09
44	Chemical	5.91E + 12	1.41E + 12	4.73E + 11	5.38E + 09	1.36E + 09	4.69E + 07	2.15E + 07	1.12E + 08	7.42E + 07	3.69E + 09	1.52E + 09
47	Chemical fiber	6.08E + 09	4.36E + 09	1.45E + 09	4.68E + 09	2.53E + 08	2.35E + 07	1.20E + 07	9.42E + 07	3.23E + 07	1.60E + 09	1.37E + 09
48	Rubber	4.66E + 11	1.69E + 11	5.63E + 10	3.66E + 09	5.12E + 09	3.33E + 07	1.46E + 07	1.51E + 08	3.98E + 07	1.28E + 09	1.11E + 09
49	Plastic	8.04E + 11	3.84E + 11	1.28E + 11	2.94E + 09	3.55E + 08	2.59E + 07	1.31E + 07	9.13E + 07	3.52E + 07	1.64E + 09	1.30E + 09
50	Cement	2.58E + 12	1.98E + 11	6.62E + 10	2.33E + 09	3.20E + 08	1.99E + 07	1.27E + 07	1.39E + 08	2.75E + 07	5.92E + 09	1.75E + 09
51	Cement products	1.07E + 14	1.45E + 13	4.83E + 12	2.12E + 09	3.10E + 08	2.13E + 07	1.38E + 07	2.41E + 08	2.61E + 07	4.33E + 09	1.37E + 09
52	Brick	1.30E + 10	1.62E + 09	5.40E + 08	2.26E + 09	3.43E + 08	2.24E + 07	1.42E + 07	1.36E + 08	3.17E + 07	8.54E + 09	1.37E + 09
53	Glass	6.25E + 12	1.05E + 12	3.49E + 11	2.32E + 09	3.63E + 08	2.13E + 07	1.33E + 07	1.29E + 08	3.52E + 07	6.43E + 09	1.30E + 09
55	Fire-resistant materials	9.92E + 07	1.18E + 07	3.93E + 06	2.30E + 09	2.85E + 08	2.16E + 07	1.69E + 07	1.50E + 08	8.27E + 07	7.43E + 09	1.08E + 09
59	Rolling of steel	2.03E + 14	2.52E + 13	8.42E + 12	1.60E + 09	2.12E + 08	1.91E + 07	1.31E + 07	1.92E + 09	5.21E + 07	7.67E + 08	1.44E + 09
63	Metal	6.20E + 12	9.21E + 11	3.06E + 11	2.17E + 09	4.01E + 08	2.50E + 07	1.82E + 07	7.08E + 08	1.13E + 08	1.02E + 09	1.43E + 09
69	Machinery	4.41E + 11	7.38E + 10	2.47E + 10	1.90E + 09	2.85E + 08	2.28E + 07	1.51E + 07	6.29E + 08	6.32E + 07	6.57E + 08	1.17E + 09
92	Electricity	5.87E + 12	4.29E + 11	1.43E + 11	1.44E + 09	2.03E + 08	1.57E + 07	1.10E + 07	1.10E + 08	3.08E + 07	3.58E + 08	1.01E + 10
94	Water	8.81E + 11	1.24E + 11	4.15E + 10	1.49E + 09	1.55E + 08	1.65E + 07	1.20E + 07	7.71E + 07	1.99E + 07	3.87E + 08	2.32E + 09
95	Construction	2.93E + 13	6.32E + 12	2.11E + 12	2.99E + 09	4.84E + 08	2.30E + 07	1.71E + 07	3.92E + 08	5.04E + 07	2.97E + 09	1.02E + 09
97	Transport	5.42E + 10	6.30E + 10	2.09E + 10	2.28E + 09	2.14E + 08	2.11E + 07	1.70E + 07	8.25E + 07	1.64E + 07	2.92E + 08	4.85E + 08
	Total	3.74E + 14	5.36E + 13	1.79E + 13	1.42E + 13	2.84E + 12	1.43E + 11	9.63E + 10	7.50E + 12	3.19E + 11	1.51E + 13	9.75E + 12

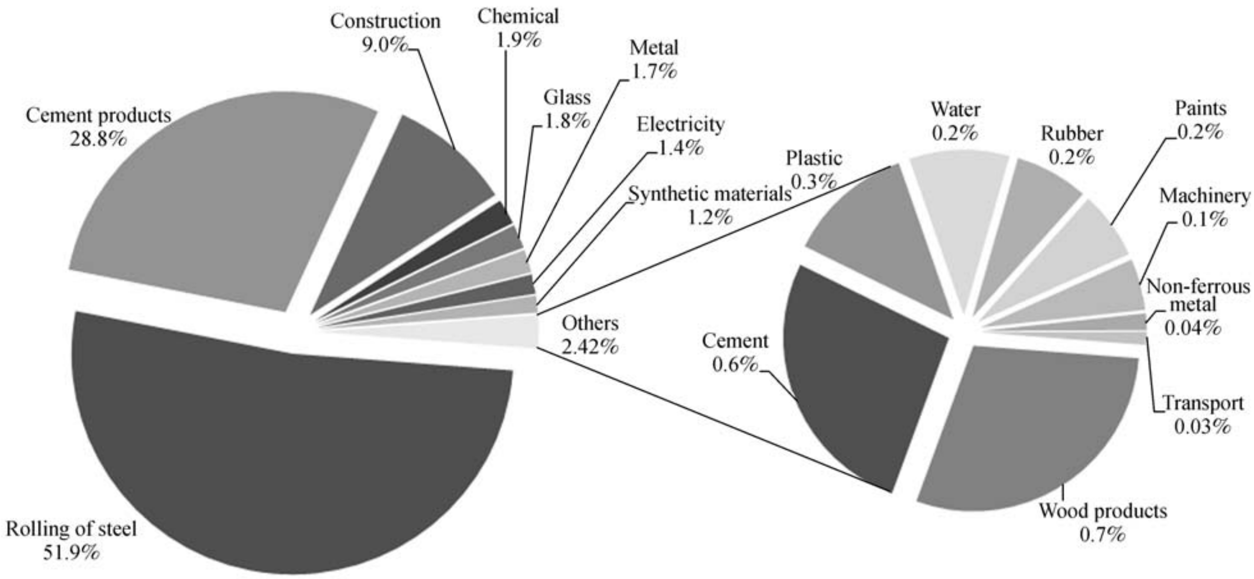

Fig. 2 The components of embodied exergy of structure engineering of buldings.

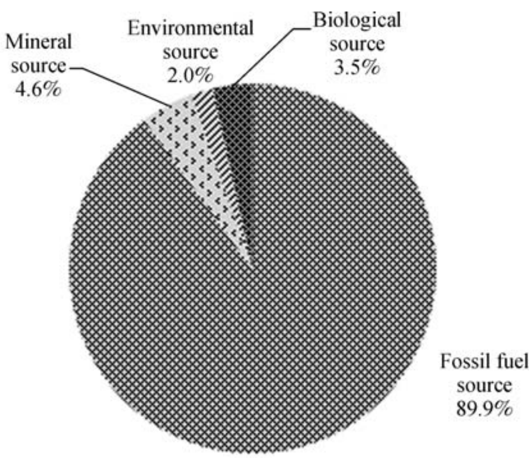

Fig. 3 The components of the four categories of accounted natural resources evaluated by exergy.

fishery products) for 4.6% and 3.5%, respectively. Meanwhile, the environmental source, (hydropower) as the smallest component, shares only 2.0% of the total exergy inputs. In Fig. 4, coal, crude oil, and natural gas as a fossil fuel energy source take up 75.5%, 10.8%, and 3.6% of total exergy inputs, respectively, due to the fact that for most sectors, the exergy intensities of coal are the top of all accounted resources. This result coincides with the fact that the fossil energy is still the predominating energy source in China, in which coal is at the leading position.

As shown in Fig. 5, the components of the four sources in terms of materials, equipment, energy, and manpower of embodied exergy in the case buildings, as classified in Table 3. Although the sector of Processing of Petroleum and Nuclear Fuel is one of the related production sectors which seems to offer energy inputs, the paint solvent and petroleum asphalt used in the project cannot be treated as energy sources. The 89.4% of the embodied exergy is from a material source; hence the use of various materials is highly significant due to their dominant contribution. Although usually neglected in traditional energy analysis, embodied exergy from manpower accounts for 9.0% of the total, owing to the fact that construction is a labor-intensive industry. On one hand, this result indicates that it is necessary to simplify and optimize the process to make it more cost-effective. On the other hand, the building construction industry can offer considerable employment opportunities. Meanwhile, less than 2% (1.4% and 0.1%) of the exergy is from the energy and equipment inputs, which indicates that the direct energy efficiency measures have little influence on the embodied exergy of the building construction.

5 Conclusions

Building related energy consumption attracts much attention all over the world due to its substantial share of total energy consumption and high annual growth rate in China. Compared with other thermodynamic metrics, exergy offers a unified measure and a better description of resource use, as well as environmental impact, with essential implications to sustainability. Exergy analysis, in combination with the hybrid method, is applied to assess the energy resource consumption of the case buildings, and the detailed procedures of the systematic accounting of various material, equipment, energy, and manpower inputs illustrated in this paper. After itemizing all these inputs of the engineering structure based on raw project data in the

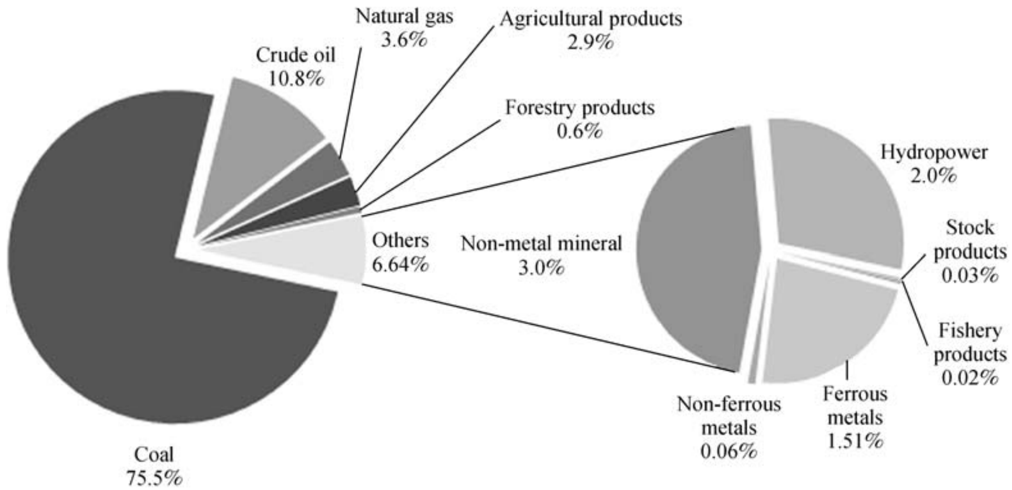

Fig. 4 The components of the 37 kinds of accounted natural resources evaluated by exergy.

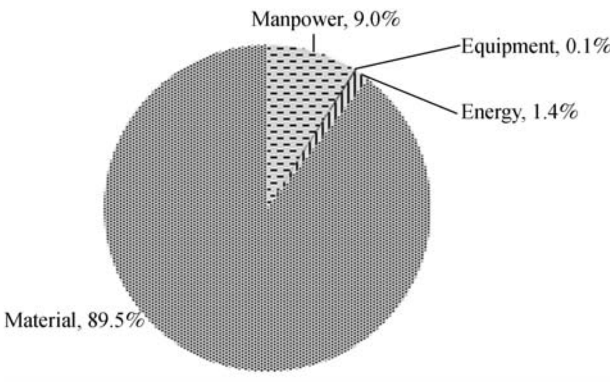

Fig. 5 The components of the four sources in terms of materials, equipment, energy, and manpower of embodied exergy.

BOQ, and on the basis of the most recent embodied exergy intensities for the Chinese economy in 2007 with 135 industrial sectors, a case study is carried out for the landmark office buildings in E-town, Beijing and the embodied exergy for the building engineering structure is quantified in full detail.

The embodied exergy of the case buildings' structure engineering structure is evaluated as 4.95E + 14 J, with an intensity of 8.25E + 09 J/m^2 floor area. The 51.9% and 28.8% of the total exergy inputs are embodied in the steel inputs from the Rolling of Steel sector and concrete inputs from the Manufacture of Products of Cement and Plaster sector. The predominant role they play is mainly due to the fact that the case buildings are structured with reinforced-concrete. It is noticeable that over 8% of the total exergy inputs are caused by manpower, as the third largest exergy source, because construction is a labor-intensive industry.

About 90% of the embodied exergy is from material, which indicates that the use of various materials should be given great attention due to their dominant contribution. Among the 37 kinds of accounted natural resources, coal, crude oil, and natural gas as fossil fuel energy sources account for 75.5%, 10.8%, and 3.6% of total exergy inputs, respectively, which coincides with the fact that coal is the leading energy source in China.

Meanwhile, the sum of energy and equipment inputs account for less than 2%,which shows that direct energy efficiency measures have little influence on the embodied exergy of building construction buildings. Due to the fact that buildings consume about one third of global energy, the building sector offers the largest and most cost-effective mitigation potential according to global and regional estimations (Metz, 2007; Ürge-Vorsatz and Novikova, 2008; Eichhammer et al., 2009). Some key strategies to capture the potential in building may alleviate, or even fully eradicate, energy poverty.

In a world with finite natural resources and large demands, increasing energy efficiency is essential. Exergy analysis is suited for furthering the goal of more efficient resource use, with the reason that it can quantify the locations, types, and magnitudes of waste and loss in a straight forward way. This paper carries out an extension of the application of exergy analysis and provides important insights into future research. More importantly, it may help to guide appropriate policies.

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