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The ecological footprint evaluation of low carbon campuses based on life cycle assessment: A case study of Tianjin, China

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ABSTRACT

Global warming is a very serious environmental problem. Universities, the most active organizations and locations for scientific research and social activities, have a responsibility to construct low carbon campuses and to play an important role in reducing CO_2 emissions. The concept and definition of a low carbon campus were proposed in this paper along with a comprehensive model. Tianjin Polytechnical University (TJPU) was used as a case study because of its innovative efforts in this aspect. The ecological footprint evaluation (EFE) and life cycle assessment (LCA) were integrated to evaluate a low carbon campus qualitatively; The ecological footprint index (EFI) was proposed for a quantitative evaluation. The EFI of TJPU was 0.61, which indicated that the low carbon campus of TJPU is classified as having strong sustainability. Last, effective recommendations were proposed based on data analysis to improve the low carbon campus; qualitative and quantitative evaluations were also discussed to enhance the progress of constructing low carbon campuses worldwide.

1. Introduction

Global warming is becoming increasingly obvious and is one of the most serious environmental problems that human beings have faced. Greenhouse gases are the main contributor to global warming, and human impacts on CO_2 emissions have been more serious than those from natural forces. As places that educate, universities should address the various needs of local societies. With increasing concerns of different environmental issues and a more recent need to respond to climate change, universities should integrate sustainability into educational and research programs and promote environmental issues to society.

University efforts towards sustainability have been initiated worldwide. More research progress were depicted in section 2. Generally, low carbon campus efforts have been undertaken in many universities, and significant progress has been made, including improved environmental performance, enhanced public awareness, and reduced campus maintenance costs. However, so far, a clear concept of low carbon campuses has not yet been proposed. Most studies are fragmented by focusing on a single target, such as promoting low carbon culture or improving waste management, instead of comprehensive studies. Such a lack of comprehensive efforts takes a serious toll on universities' commitments to further construct their campuses and may result in ineffective and inefficient implementation of their planned goals. Therefore, it is necessary to construct a comprehensive model to clarify low carbon campuses. Moreover, an evaluation method for a low carbon campus is indispensable. Various methods have been proposed to evaluate the economic, ecological and environmental characteristics of a campus over several years, however, more and more limitations were appeared in recent researches.

In general, two major problems were studied in this paper. First, the concept and definition of a low carbon campus were proposed along with a comprehensive model. Second, a new evaluation method was proposed. EFE based on LCA is used as to supplement the assessment gap of low carbon campuses, which is of great importance in this paper. Tianjin Polytechnical University (TJPU) was selected for the case study due to its innovative efforts. The whole paper is organized as follows: first, the concept and definition of a low carbon campus are proposed along with a comprehensive model; second, the research method is presented in which EFE and LCA are integrated to evaluate a low carbon campus and the ecological footprint index (EFI) based on the above method is discussed; third, the basic information of

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TJPU is presented, and innovation efforts are detailed; fourth, data analysis is conducted for interpretation; fifth, the discussion section explores how this method provides valuable information that can benefit a university by strengthening the current practices and developing links; and, finally, the research conclusions are drawn.

2. Low carbon campus

University efforts towards sustainability have been initiated worldwide. For instance, the environmental management system (EMS) has been implemented as a tool for achieving campus sustainability in several European universities (Disterheft et al., 2012). A study was conducted by Sammalisto and Brorson (2008) in the University of Gavle, in which they indicated that training is a key factor during implementation of EMS within a university campus. On a life cycle basis, Lukman et al. (2009) evaluated the environmental performance in the University of Maribor (Engineering Campus) and proposed different waste management options for plastic and paper, including recycling, incineration and landfill. Saadatian et al. (2009) studied sustainability practices in four Malaysian research universities and identified key gaps for further improvement. Lozano et al. (2013) analyzed the texts of eleven declarations, charters, and partnerships developed for higher education institutions, which can be considered to represent university leaders' intentions to help improve the effectiveness of Education for Sustainable Development. Ozawa-Meida et al. (2013) conducted a carbon footprint study based on consumption for a UK university, including scope 1, 2 and 3 emissions under the classification of the WRI/WBCSD Greenhouse Gas Protocol Corporate Standard. Their study can help provide a better understanding of major greenhouse gas emissions from a university and the actions that can be taken to reduce these emissions. Larsen et al. (2013) investigated carbon footprints in the Norwegian University of Science and Technology (NTNU) by applying a model called Environmental Extended Input-Output (EEIO) and identified key emission sources, which could be helpful for preparing an appropriate emissions reduction policy.

Similar activities have also been observed in China. For instance, Zhou and Shao (2005) studied the influence of ISO 14001 on creating a green university and presented the detailed procedures of establishing ISO 14001 within a university campus. Du et al. (2005) studied the current situation and development trend of ecological campus construction, the existing eco-schools are classified into three styles: landscape design style, ecological technique style, ecological education and management style. Lu et al. (2007) established an indicator system to evaluate the performance of one green university project and proposed recommendations for further greening the campus. Wang et al. (2010) reviewed all the Chinese practices on establishing green universities, including indicators, criteria, best practices and relevant policies. Zhu (2010) presented an innovative model for establishing green culture within a university campus, and sustainable development is the basement of green culture. Wang (2011) defined the concept of a green university and reviewed different indicator systems for assessing the overall performance of one green university project. On the basis of reviewing different green university initiatives, Shi (2010) proposed his ideas for how to develop a low carbon university, including various carbon emission reduction strategies and capacity building efforts. Geng et al. (2013) proposed an integrated model for green universities based on a case study of Shenyang University, this model can manage all the campus activities on a sustainable basis. Yuan et al. (2013) investigated the awareness of faculty, alumni and students' parents on sustainable development and their perceptions of green universities. The main focus of this study was placed on exploring the most important factors that contribute towards achieving 'Green University' goals from different stakeholders' points of view. These factors were broadly grouped into seven categories, i.e. management systems, environmental sustainability, sustainable curricula, research and development, staff development and rewards, student opportunities and social responsibility. Tan et al. (2014) analyzed the development of green campuses in China. It is found from the analysis that the development of energy and resource efficient campus has been expanded in a large scale in China, mainly aiming at the energy efficient technology application and campus energy management, and all these initiatives are strongly promoted by the national government with policy support and financial funding.

The concept of a low carbon campus is proposed based on previous studies. A low carbon campus is a campus with an elegant environment, harmonious and considerate management and low emissions, which is the most important factor. Moreover, the concept of scientific development is regarded as the guide; the development law of education and the growth law of talents are taken as principles; and the decrease of greenhouse gas emissions is the ultimate purpose.

Similar to a society, the operation and maintenance of a university is a process of socioeconomic metabolism, taking in various raw materials, energy and water and transforming them into wastes. Every part interacts with others through a complex network. To improve its sustainability, a comprehensive model is proposed so that various dimensions can be addressed in a systematic way. Fig. 1 presents such a model.

This comprehensive model aims to manage all the sustainable indicators by minimizing materials, energy and water use, which is also the definition of a low carbon campus. The model addresses all the issues related with a university's metabolism and ensures that the views and goals of different stakeholders are considered together. Such a holistic approach requires that all factors related to university operation should be considered in the decision-making process, avoiding the problems of a fragmented institutional framework.

3. Research method

Various methods have been proposed to evaluate the economic, ecological and environmental characteristics of a campus over several years, such as multi-objective linear programming (MOLP) and a fuzzy two-stage algorithm (Ho et al., 2014), life cycle assessment (LCA) and carbon footprint (Song et al., 2016), and ecological footprint evaluation (EFE) (Lambrechts and Van Liedekerke, 2014).

In recent years, EFE and related issues have become a popular research topic in the field of sustainable development. Jiang et al. (2004) calculated the ecological footprint of a small scale campus using questionnaire survey data. Gu et al. (2005a, b) calculated the ecological efficiency of Northeastern University and the universities in Shenyang using EFE and summarized the factors that affect the ecological efficiency of universities. Jiang et al. (2007) noted that the ecological situation of Heilongjiang Institute of Science and Technology is more optimistic using the EFE to calculate its ecological footprint. Wang and Chen, (2008) evaluated the ecological footprint and ecological efficiency of the new campuses of four universities in Fuzhou University City in 2006; they analyzed the main influencing factors according to the basic principle and calculation model of the EFE. Lu et al. (2008) used the EFE to analyze and calculate the ecological footprint of Henan University in 2006 based on 6 aspects (energy, food, water, waste, paper and traffic) to reveal the ecological efficiency of the university campus and its influencing factors; they proposed measures to

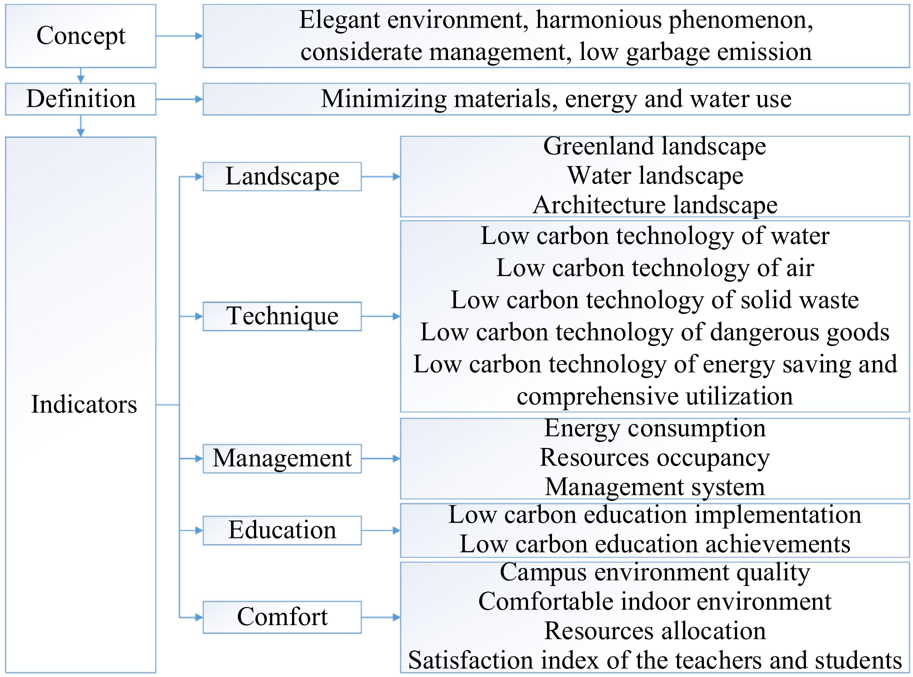

Fig. 1. A comprehensive model of a low carbon campus.

reduce the ecological footprint in the campus and recommendations to construct a resource-efficient school.

LCA is widely used as an effective tool to analyze potential environmental impacts by identifying the emissions of the development process. LCA refers to the assessment of environmental factors and their potential effects on the entire process of a product's lifecycle (i.e., from the acquisition of raw materials to their production, utilization, and final deposition). LCA emphasizes that the effects of production, use, waste, and recycling must be considered at the beginning of a design period of any product or project (Sharma et al., 2011). In its practical application, LCA is used to minimize environmental impacts, shorten the design period, and lower the relevant costs. Many studies have evaluated products and processes using the LCA method (Basset-Mens and Van der Werf, 2005; Chen et al., 2012; Gonzalez-García et al., 2013).

EFE provides a method for calculating the impact of human activities on the ecological environment; however, it does not have a specific boundary. LCA is able to provide a scientific research boundary, but it minimizes the contributions of environmental resources and labor services. Therefore, to take advantage of both methods, the calculation of environmental impact using LCA is introduced into the EFE to evaluate the low carbon campus in this paper. Furthermore, most previous EFE studies, which considered the analyzed systems as "black boxes", merely reflect the general performance of the assessed systems; however, the question of which steps contribute to higher or lower sustainability remains unanswered. Thus, life cycle thinking is also adopted in this case study to analyze each step of a low carbon campus to find the key points of optimization of the system.

3.1. Overview and calculation method of EFE

EFE is effective for macroscopically analyzing the relationship between a nation's trade and ecological environment. Each type of economic and social behavior has its own ecological footprint. EFE determines the relationship between human development and the ecological environment in a new perspective and is simple to calculate and easy to use. The ecological footprint of a region is the area of the bio productive land that is needed to produce all the resources consumed by the people in this region and to absorb all the wastes produced by these people (Wackernagel et al., 1999).

The main factors of the EFE calculation method are as follows:

3.1.1. Ecological productive area

The following land types are considered in EFE: fossil energy, arable land, forest, pasture, built area and sea. Each type of land has its own ecological functions. The ecological productive area represents the areas occupied by different productive lands. The equation is as shown below:

$$A_j = \sum_{j=1}^{n} \frac{C_j}{P_j} \tag{1}$$

A_j is the ecological productive area (hm^2),
C_j is the resource consumption of item j (kg or t), and
P_j is the annual average productivity in the world of item j (kg/hm^2 or t/hm^2).

3.1.2. Equivalence factor

To align the measurement units, all six land types must be converted using an equivalence factor. The equivalence factor is the ratio of the average productive capacity of an area and the world. It represents the ecological productive capacity of the land. EFE is usually applied in macroscopic research. To make this method suitable for evaluating microcosmic objects, the national average ecological productive capacity should be calculated instead of the global average ecological productive capacity (Gu et al., 2005a, b). Such an approach can improve the accuracy of the research results (see Table 1).

Table 1
Equivalence factors based on the world (Wackernagel et al., 1999; Wackernagel and Rees, 1998).

Land type	Fossil energy	Arable land	Forest	Pasture	Built area	Sea
Equivalence factor	1.1	2.8	1.1	0.5	2.8	0.2

The formula of the equivalence factor is as follows:

$$EQ_j = \frac{Q_j}{Q_g}\ (j = 1, 2, 3, 4, 5, 6) \tag{2}$$

Q_j is the average productive capacity of an area (kg/hm^2 or m^3/hm^2) and
Q_g is the average productive capacity of the ecological system at the national level (kg/hm^2 or m^3/hm^2).

3.1.3. Ecological footprint

The ecological footprint can be obtained by combining the ecological productive area and the equivalence factor; the formula for the ecological footprint is as follows:

$$EF = \sum_{j=1}^{6} A_j \times EQ_j \tag{3}$$

3.1.4. Yield factor

Because of differences among geographical position, climate and the development level of productivity, there is a huge difference in the ecological capacity of different places. Therefore, the area values of different production capacities cannot be directly compared. This problem can be solved by correcting the yield factor. The yield factor, which is equal to the ratio of the average productive capacity and the annual average productivity, is used to horizontally compare the ecological footprint of different countries and regions.

The formula for the yield factor is as follows.

$$YF_j = \frac{P_g}{P_j}\ (j = 1, 2, 3, 4, 5, 6) \tag{4}$$

P_g is the average productive capacity or waste absorption capacity of the ecological system of the measurement coverage (kg/hm^2 or t/hm^2) and
P_j is the annual average productivity of a nation (kg/hm^2 or t/hm^2).

3.1.5. Ecological carrying capacity

EFE redefines ecological carrying capacity by considering differences among the region, the composition of the population, and the effect of productivity. The expected area of the ecological productive land that can be used in a certain area is the ecological carrying capacity.

The formula for the ecological carrying capacity is as follows:

$$EC = \sum_{j=1}^{6} A_j \times YF_j \times EQ_j \tag{5}$$

EC is the ecological carrying capacity (global hectare),
A_j is the ecological productive area (hm^2),
YF_j is the yield factor, and
EQ_j is the equivalence factor.

3.1.6. Ecological deficit and ecological remainder

The ecological deficit indicates that the ecological carrying capacity is insufficient, and the ecological remainder indicates that the ecological space provides a surplus.

The formula for the ecological carrying capacity is as follows:

$$ED\ /ER = EF - EC \tag{6}$$

ED indicates ecological deficit (when $EF \geq EC$), and
ER indicates ecological remainder (when $EF \leq EC$).

3.2. Comprehensive calculation method for EFE and LCA

Both EFE and LCA evaluate the impact of human activities on the environment. EFE is a method that can only calculate the impact of human activity on the ecological environment, while LCA is a method that can only offer the scientific research boundary of ecological impact. The two theories can be used as evaluation tools for different dimensions. Far better research results could be obtained by combining the advantages of both methods.

3.2.1. Recycle factor (RF)

The recovery factor of some recyclable materials, such as structural steel, rebar, sintered brick, and aluminum are shown in Table 2.

The average of the recovery factors of the four materials, which is 0.74, was used in this paper.

The energy contained in a building material can be reused in the recycling process. Such energy also affects the value of the ecological footprint. However, many ecological footprint calculation methods ignore this type of energy. For instance, the energy consumption at the production stage is considerably large, but the recycle ratio is the highest in common construction materials.

Material recycling and reuse consumes part of this energy. According to statistics, removed metal materials, such as structural steel, require between 20% and 50% of their primary energy consumption of production in further processing. In the current literature, the agreed upon value is 40%.

Thus, RF is added into the ecological footprint in this paper. This adjustment is expected to obtain accurate results.

RF is calculated as follows:

$$RF = (1 - R) \times (1 - q) \tag{7}$$

RF is the recycle factor,
R is the recovery factor, and
q is the energy consumption ratio of recycling reproduction.

Table 2
Recovery factors of construction materials (Scheuer et al., 2003).

	Structural steel	Rebar	Sintered brick	Aluminum
Recovery factor	0.9	0.5	0.6	0.95

Table 3
Service lives of common construction materials (Zhu and Chen, 2010).

Construction material	Roof brick	Dope	Plastic floor
Service life (a)	30	10	17

3.2.2. Maintenance factor (MF)

In LCA, the energy consumption and CO_2 emissions of the operational process account for 90% of the gross values (Zhu and Chen, 2010). Thus, the consumption of energy and resources during the entire usage period represents the majority of the total ecological footprint of the construction materials. If a material can be replaced, the ecological footprint should be calculated.

The service lives of common construction materials, such as roof bricks, dope, and plastic floors, are shown in Table 3.

MF is calculated as follows:

$$MF = \frac{T_b}{T_m} \quad \text{(when the result is a whole number);} \tag{8}$$

$$MF = 1 + \left[\frac{T_b}{T_m}\right] \quad \text{(when the result is not a whole number)} \tag{9}$$

MF is the LCA maintenance factor,
T_m is the service life of the construction material (a), and
T_b is the service life of a public building (a, generally thought to be 70 years).
The average value of 5 is used in this paper.

3.2.3. Life cycle ecological footprint

Based on exploring the important factors of life cycle ecological footprint, we emphasize the need to incorporate RF and MF in calculating the ecological footprint of buildings in low carbon campus.

The life cycle ecological footprint is calculated as follows.

$$EF_w = \sum_{j=1}^{n} A_j \times EQ_j \times MF \times (1-R)(1-q) \tag{10}$$

4. Various innovation efforts in TJPU

Based on the requirements, concept and definition of a low carbon campus, TJPU was designed in 2004; the design also considered public opinion and previous experience. TJPU locates in the xiqing district of tianjin, covers an area of 2.3 million square metres, almost 30,000 students are studied at here. A map with more information is shown in Fig. 2. The design ideas and various innovation efforts are shown in Fig. 3. TJPU has obtained certain social, economic and environmental achievements, and it was used as the case study because of its representativeness and data availability.

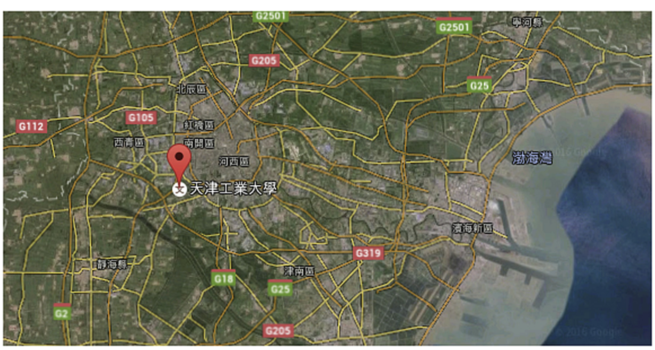

Fig. 2. A map with more information around TJPU.

4.1. LED semiconductor lighting system

The LED semiconductor lighting system has numerous advantages. The system's test results passed international identification, which means that the system reached international advanced levels. It has a service life of more than 20 years, which lowers its cost. High luminous efficiency is another feature; for example, a

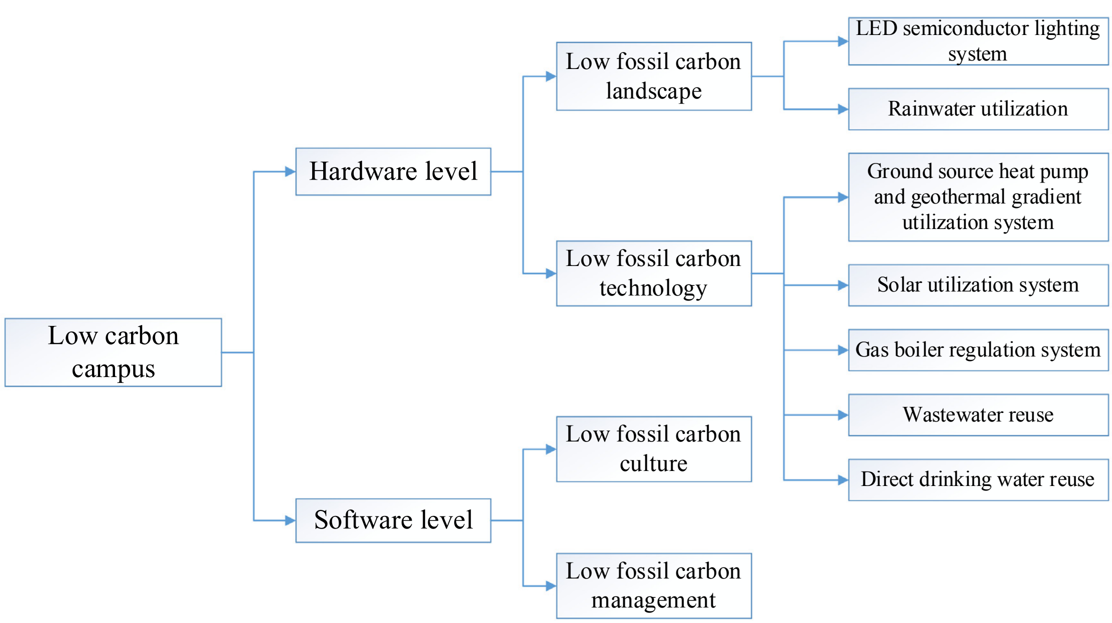

Fig. 3. Various innovation efforts of the low carbon campus in TJPU.

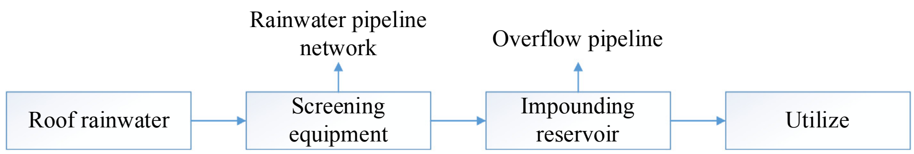

Fig. 4. Process flow for roof rainwater collection and utilization.

30 W LED light has an equivalent brightness to a 150 W traditional light source. The small size and handiness of LED provide it with tremendous flexibility.

4.2. Rainwater utilization

Part of the building roof has a device for rainwater collection and reuse. Rainwater is easy to collect with relatively good water quality, so it can be collected for reuse. As shown in Fig. 4, roof rainwater enters the screening equipment through the downpipe; the portion of water that is needed is sent to the impounding reservoir, which is used for the campus's daily water use, while the other part is discharged to the municipal pipeline network and eventually goes into the rainwater pipeline network.

4.3. Ground source heat pump and geothermal gradient utilization system

During the construction process, geological data were relatively lacking, and there were no successful cases. Therefore, subsequent investigations and scientific analyses were made on campus. A pair of geothermal wells was completed in August 2007. Gradient utilization schemes were adopted to use the geothermal resources. The geothermal water experienced a heat exchange: the tail water temperature was 41 °C with a flow rate of 100 m^3/h, and the temperature decreased to 8 °C through secondary use. The primary heat exchanger provides the basic heat load for heating; the secondary water source heat pump provides the heating energy for the supplementary load. Gradient utilization for geothermal water fully uses the geothermal energy resources supply, maximizing the investment benefit and achieving the goal of sustainable development. This system was honored as the tracking project of the United Nations Development Program.

4.4. Solar utilization system

Tianjin belongs to a second class solar energy resource rich region; the annual solar irradiation range is 5425.1 MJ/m^2, and the annual sunshine hours are 2610–3090. Solar is inexhaustible and clean energy with very low running costs. Based on a full investigation and research, the 1500 m^2 glass vacuum tube collector system was installed on the roof of the students' apartments. After several years of operation, the system effect is very good. Teachers and students are also very satisfied with the system, and its saves operating costs of more than one million yuan every year.

4.5. Gas boiler regulation system

January is the coldest month in Tianjin. Schools have a winter vacation during this time to prevent low temperature operation of the system. Therefore, the cutting peak design method was applied to reduce the designed cooling load. Two 2800 kW gas-fired hot water boilers were placed in the equipment station as winter heating system peak heat sources in response to extreme temperatures. The system can also effectively reduce the initial investment costs.

4.6. Wastewater reuse

A variety of renewable water treatment technologies are utilized to achieve safe and effective wastewater use on campus, such as laboratory wastewater and domestic sewage (Bonnet et al., 2002).

The treatments shown in Fig. 5 and Fig. 6 are used to make the laboratory wastewater meet the emission requirements.

The renewable water reuse project, which focuses on the treatment of domestic sewage, is a supplement to ecological water for environmental sustainability (see Fig. 7).

4.7. Direct drinking water reuse

There are two types of direct drinking water supply: decentralized and centralized, which are separately shown in Fig. 8 and Fig. 9, respectively.

4.8. Low carbon culture

Hardware technology is indispensable, and environmental awareness is also of great importance. Improving students'

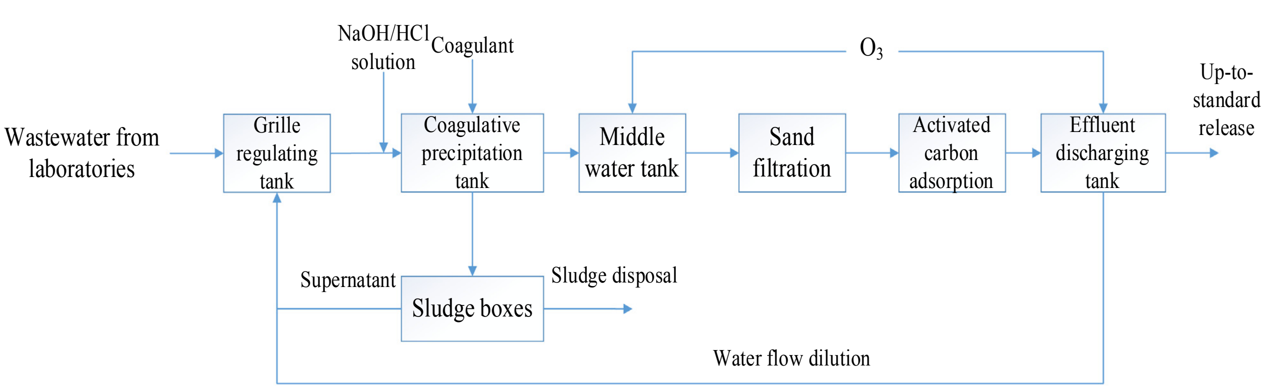

Fig. 5. Process flow of laboratory wastewater treatment.

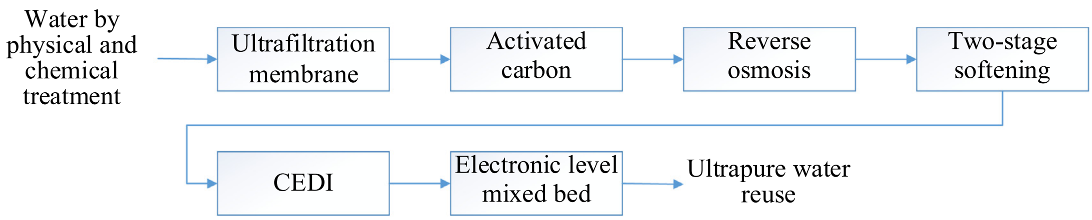

Fig. 6. Process flow for the integrated safe rescue of the multi-level membrane for laboratory wastewater.

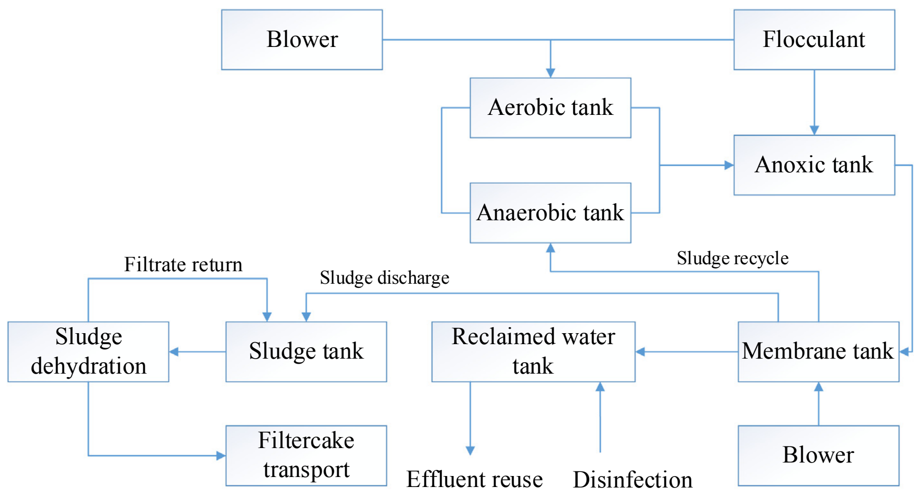

Fig. 7. Process flow for centralized reclaimed water reuse.

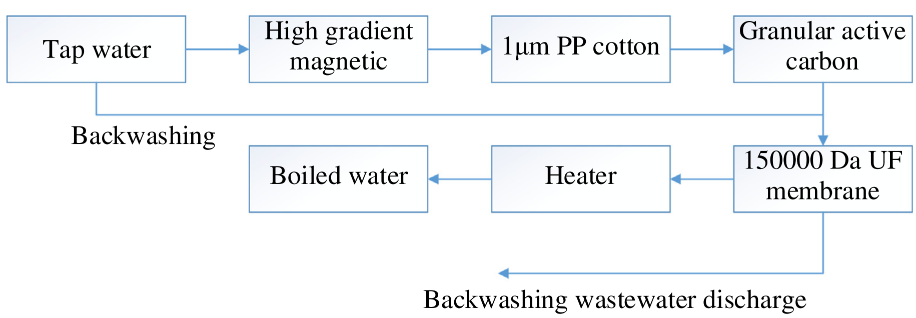

Fig. 8. Process flow for decentralized direct drinking water.

systemic knowledge structure is also an area of focus. In class, the knowledge of environmental protection and sustainable development were promoted. After class, a variety of lectures were held. Both of these methods were beneficial for regulating energy savings management as students were encouraged to increase awareness of energy savings. The theme of campus culture construction was established in TJPU to guarantee the healthy development of a low carbon culture (Karol, 2006). Through the installation of smart meters in student dormitories, students can realize a self-management mechanism that helps students to form good habits of environmental protection behavior.

4.9. Low carbon management

Facing the reality of the huge campus energy consumption, an excellent low carbon management operation system was established in TJPU, which laid a solid foundation for the design of a low carbon campus. Vast relative rules were proposed to establish strong security. Moreover, a low carbon campus digital platform has been in use since October 2011. In total, 526 instruments have been installed in public areas, including recycled water meters, electric meters, hot water meters and steam meters, which can calculate the energy consumption and accurately determine all types of expense. Various management activities did not conform with the sensors and the dynamic environment information. The reasons for this were analyzed and the preventive measures were formulated to improve the sustainable development of the internal control mechanism.

5. Data analysis

The design of a low carbon campus is not an easy project; three phases, namely, the construction phase, application phase and the demolition phase, are included. Campus buildings can also be considered products of the production process, so that LCA can be used to analysis them. Unlike other industrial goods, buildings are

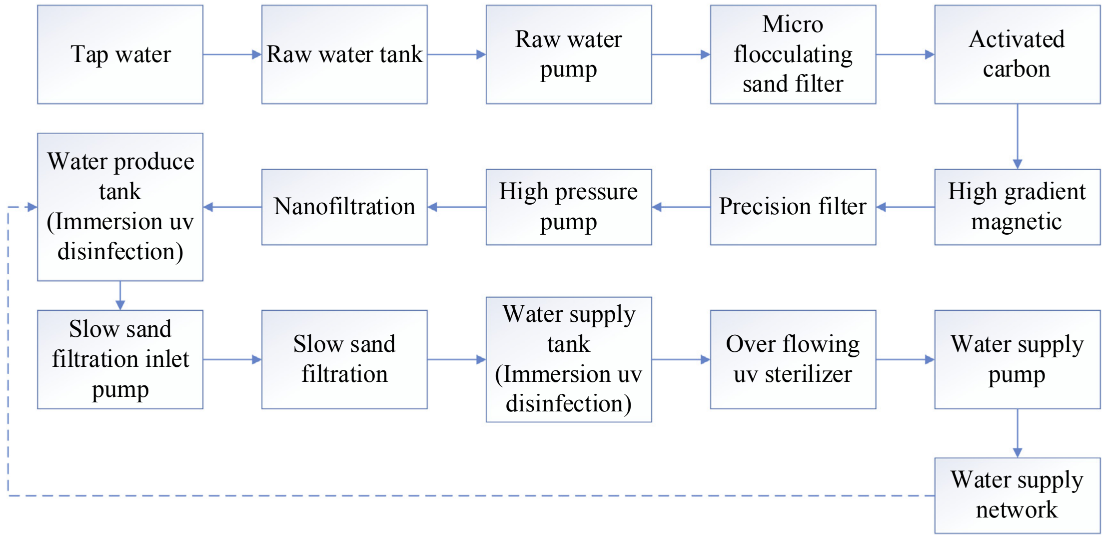

Fig. 9. Process flow for centralized direct drinking water.

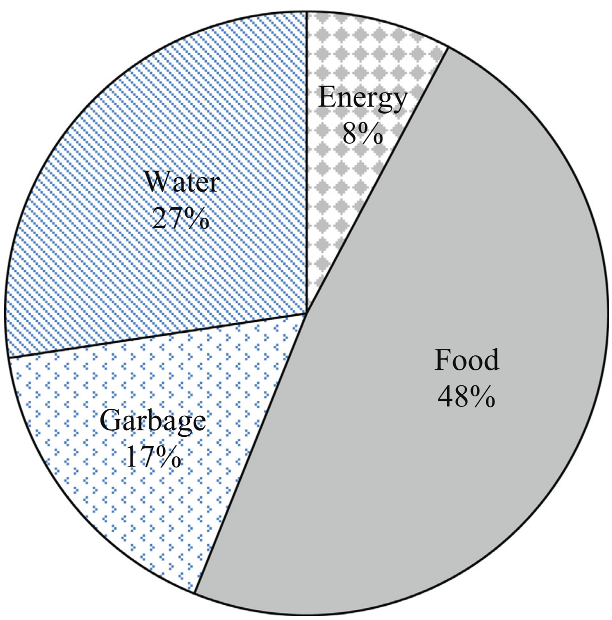

Fig. 10. Ecological footprint composition of TJPU.

special products. They are large in scale and are used for several decades; there is no doubt that they require high resource consumption. Almost no studies have undertaken a whole analysis for all three phases. To facilitate a horizontal comparison, only the ecological footprint of the operation phase is analyzed in this paper. All consumption data are from the logistics department of TJPU, other relevant factors are based on the following papers, Rees (1992), Wackernagel et al. (1999), Gu et al. (2005a, b).

5.1. Traditional ecological footprint calculation

According to the characteristics of universities, component analysis, which mainly considers energy (including electricity, coal, and water), transportation (including school official vehicles, private cars, and public transport), and daily life (including food and garbage), is used in this paper (Xie et al., 2008).

Because of the remote location and strict control of TJPU, few vehicles visit the campus, so the proportion of transportation ecological footprint is very small and can be reasonably neglected. According to the consumption data, the energy ecological footprint, food ecological footprint, garbage ecological footprint and water ecological footprint of TJPU during 2014 were obtained, which are shown in Table 4, Table 5, Table 6, and Table 7, respectively. The price of water in Tianjin is 4.9 CNY per ton, the price of electricity is 0.49 CNY per KW·h at the same condition, and the power costs of water accounted for approximately 25% of the total water costs. The calculation results of the above components and some relevant ecological footprint situations in universities around the world are summarized in Table 8.

Because the ecological footprint is not easily understood, a person's average index, which represents the per capita ecological footprint, is used to build a standard and analyze the conclusion. The total number of students in TJPU in 2014 was 28,380, so the per capita ecological footprint was 0.16 hm^2/per, and the same data for some other universities around the world are shown below. The global average ecological footprint is 2.7 hm^2/per (see Table 9).

5.2. Ecological carrying capacity calculation

The national average production capacity is 0.677 tons/ha (Ling and Jin, 2011), and the following data are from the National Bureau of Statistics (see Table 10).

Because built area comes from arable land, the yield factor of the built area is equal to that of the arable land. The fossil energy mainly refers to the absorption of greenhouse gas by the forest. Therefore, the yield factor of the fossil energy is equal to that of the forest.

EC can be calculated to be 11,905 using formula (5).

5.3. EFI calculation

EFI is the percentage difference between the ecological carrying capacity and the ecological footprint in the ecological carrying capacity; , the formula is as follows:

$$\mathrm{EFI} = \frac{EC - EF}{EC} \tag{11}$$

Table 4
Energy ecological footprint.

Type	Consumption (t)	Carbon emission factor	C-CO_2 transformation factor	Unit CO_2 emissions(t)	Average productivity of fossil energy land (t/hm^2)	Equivalence factor	EF (hm^2)	Land type
Natural gas	1057.2	0.409	3.67		5.2	1.1	335.7	Fossil energy
Electric power	0.053//GW·h			964	5.2	2.8	27.7	Built area

Table 5
Food ecological footprint.

Component	Consumption (kg)	Annual average productivity in the world (kg/hm^2)	Equivalence factor	EF (hm^2)	Land type
Grain	363,750	2744	2.8	371.2	Arable land
Vegetable	326,300	18,000	2.8	50.8	Arable land
Fruit	8020	18,000	2.8	1.2	Arable land
Legume	44,240	1856	2.8	66.7	Arable land
Beef and mutton	29,820	33	0.5	451.8	Pasture
Pork	46,910	74	0.5	317.0	Pasture
Egg	64,400	400	0.5	80.5	Pasture
Poultry	56,280	33	0.5	852.7	Pasture
Milk	2130	502	0.5	2.1	Pasture
Aquatic product	8000	29	0.2	55.2	Sea
Total	949,850			2249.2	

Table 6
Garbage ecological footprint.

Component	Emissions (t)	CO_2 emissions of a unit of garbage (t)	CH_4 emissions of a unit of garbage (t)	GWP coefficient of CH_4	GWP equivalent of CH_4 (t)	Total CO_2 of a unit of garbage(t)	Average productivity of fossil energy land (t/hm^2)	Equivalence factor	EF (hm^2)	Land type
Garbage	6000	0.0649	0.0236	23	0.5428	0.6077	5.2	1.1	771.3	Fossil energy

Table 7
Water ecological footprint.

Component	Water consumption (m^3)	Unit power consumption (KW·h/m^3)	Total electricity consumption of water supply (GW·h)	Relative CO_2 emissions (t)	Average productivity of fossil energy land (t/hm^2)	Equivalence factor	EF (hm^2)	Land type
Water	2,501,100	2.5	6.25	6027.65	5.2	1.1	1275.1	Fossil energy

Table 8
Ecological footprint of TJPU compared with worldwide universities.

Component	University of Colorado at Boulder		University of Redlands		Peaking University		TJPU	
	EF (hm^2)	Proportion (%)	EF (hm^2)	Proportion (%)	EF (hm^2)	Proportion (%)	EF (hm^2)	Proportion (%)
Energy	4858.00	87.27	1155.90	50.09	17,343.23	54.30	363.40	7.80
Food	574.10	10.31	113.40	4.91	14,120.84	44.21	2249.20	48.28
Garbage	–	–	289.50	12.54	177.94	0.56	771.30	16.56
Water	56.50	1.01	–	–	211.43	0.66	1275.10	27.37
Transportation	78.00	1.40	749.00	32.46	88.19	0.28	–	–
Total	5566.60	100.00	2307.80	100.00	31,941.63	100.00	4659.00	100.00

EFI is the ecological footprint index;
EF is the ecological footprint; and
EC is the ecological carrying capacity.

The relationship between EFI and the sustainability level are shown in Table 11.

In this case, the EFI is 0.61, which indicates that the low carbon campus is in a state of strong sustainability.

6. Discussions

6.1. Ecological footprint analysis

The ecological footprint of TJPU is as follows (see Fig. 10):

This figure shows the ecological footprint composition of TJPU. It can be observed that the food ecological footprint accounted for the largest proportion at 48%, followed by the water, waste, and energy ecological footprints.

Based on Table 8, Fig. 11 compares the ecological footprint of

Table 9
Per capita ecological footprint of universities around the world (Zhou, 2012).

Country	School name	Year	Ecological footprint (hm^2)	Per capita ecological footprint (hm^2/per)	The ratio to the global average ecological footprint	Computation method
USA	University of Illinois at Chicago	2008	97,601	2.66	0.99	W&R
	Colorado College	2001	5603	2.24	0.83	W&R
	Ohio State University at Columbus	2007	650,666	8.66	3.21	Janis
	Marlboro College	2010	971	2.49	0.92	W&R
Australia	Newcastle University	1999	3592	0.19	0.07	Flint
UK	Holme Lacy College	2000/2001	296.07	0.56	0.21	W&R
Canada	University of Toronto Mississauga	2005/2006	8744	1.07	0.40	Stewart&Loo
	British Columbia Institute of Technology	2006/2007	16,590	0.49	0.18	W&R, John, Bareett et al.
	Kwantlen University College	2005	3039	0.33	0.12	Stewart&Loo
Spain	Univ Polytechnic Valencia	2006	19,562	0.43	0.16	W&R
		2007	20,166	0.44	0.16	
		2008	18,894	0.41	0.15	
		2009	22,426	0.49	0.18	
China	Northeastern University	2003	24,787	1.06	0.39	Li Guangjun&Gu Xiaowei
	Shenyang University	2003	17,218	1.27	0.47	Li Guangjun&Gu Xiaowei
	Liaoning University	2003	11,862	0.85	0.31	Li Guangjun&Gu Xiaowei
	Suzhou University Of Science And Technology	2007	15,115	0.97	0.36	Li Guangjun&Gu Xiaowei
	Nanchang Hangkong University	2008	10,763	0.59	0.22	Li Guangjun&Gu Xiaowei
	Environmental Management College	2008	2447	0.43	0.16	Li Guangjun&Gu Xiaowei
	University of Kaohsiung	2003	1921	0.6	0.22	Cai Yunzhang

TJPU with those of other universities.

As shown in Fig. 11, the ecological footprint of TJPU has the following characteristics:

(1) The total ecological footprint is small, which indicates that various efforts at TJPU do work. The energy ecological footprint of other universities is more than 50%, even up to 87%, while the energy ecological footprint of TJPU is only 7.8%, significantly lower than that of other universities. TJPU is at the forefront of the four universities in terms of energy utilization.

(2) The proportion of food ecological footprints of TJPU and Peking University is significantly higher than that of the two foreign universities. Due to the high rear service socialization degree in foreign universities, foreign schools do not provide accommodations. Most students live near the school or in convenient community housing. However, in China, most of the students live on campus, resulting in differences in the statistical results, which is also related to the eating habits of different areas and needs to be further studied.

(3) The total amount and proportion of the waste ecological footprint in TJPU are higher than those of the other three universities, which is related to the good habit of garbage classification in foreign countries and the garbage classification model application in recent years in Peking University. Garbage disposal methods need to be improved in TJPU, and low carbon education and low carbon management still need to be promoted.

(4) The total amount and proportion of the water ecological footprint in TJPU are higher than those of the three other universities. Further investigation indicated that although there were some water saving facilities, they did not work. Further analysis was performed on rainwater utilization, direct drinking water reuse, and wastewater reuse. Essential facilities were put into service from December 2014 to December 2015, and some achievements can be shared. The direct drinking water supply demonstration project saved 1.92 million KW·h of electric energy, the wastewater reuse demonstration project saved 0.36 million m^3 of water, and the rainwater utilization purification demonstration project saved 0.14 million m^3 of water. The data are from the logistics department of TJPU. The calculation method is the same as that for Table 4 and Table 7. The results show that the annual

Table 11
Ecological footprint index.

Level	EFI	Sustainability level
1	$0.5 < EFI \le 1$	Strong sustainability
2	$0 < EFI \le 0.5$	Weak sustainability
3	$-1 < EFI \le 0$	Unsustainable
4	$EFI \le -1$	Strong unsustainability

Table 10
Yield factor of ecological productive land in Tianjin in 2014.

Land type	Fossil energy	Arable land	Forest	Pasture	Built area	Sea
Area (10,000 ha)		165.66	26.18	29.93		11.74
Production (10,000 tons)		719.23	8.10	120.44		40.82
Average ecological productive capacity (tons/hectares)		4.34	0.31	4.02		3.48
Yield factor	0.46	6.41	0.46	5.94	6.41	5.14

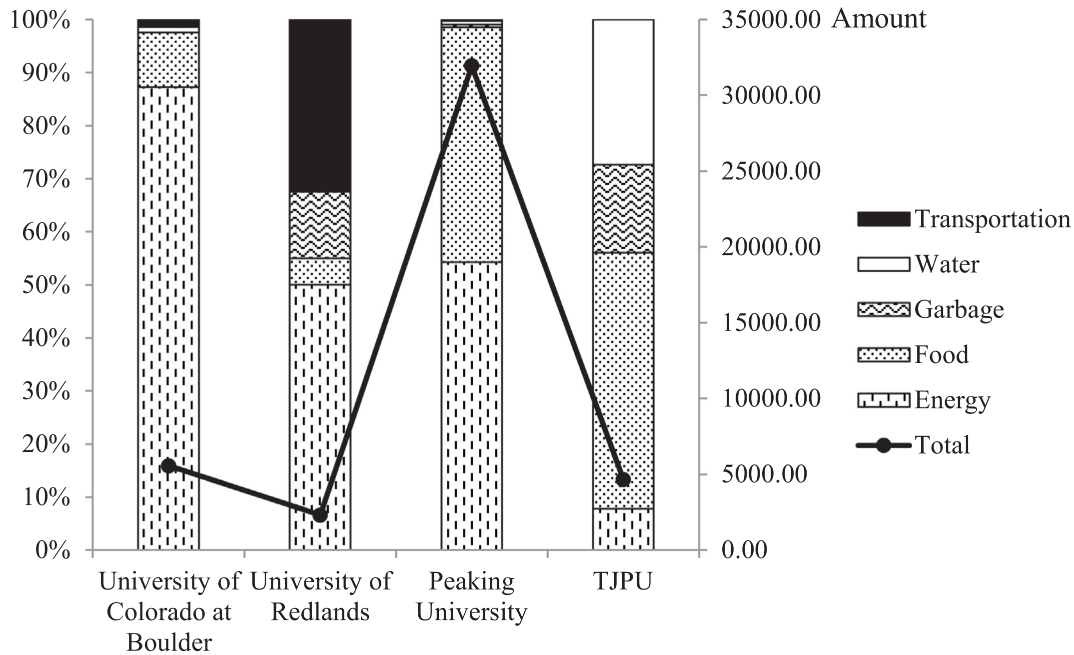

Fig. 11. Ecological footprint of TJPU compared with other universities worldwide.

reduction of the water ecological footprint is 255 hm^2, accounting for 20.00% of the previous water ecological footprint, which shows that the demonstration projects had relatively good effects. It is recommended to continue these projects and to apply them in conditional schools to effectively improve water use.

(5) The proportion of the traffic ecological footprint in the University of Redlands is larger than that of the University of Colorado Boulder and Peking University, which is related to the vast campus area of the University of Redlands. Compact layout and concentrated function are characteristics of campuses in China; most goods and services can be met on campus; and the daily travel rate of teachers and students is not high. Therefore, in this paper, the traffic ecological footprint of TJPU can reasonably be neglected.

(6) The per capita ecological footprint of TJPU is in the leading position in the world. The main reason for this lies in the rational use of energy technology to greatly reduce the energy ecological footprint. The energy ecological footprint occupies more than 50% of the whole ecological footprint in the other universities.

Specific goals and clear thinking are the key factors regarding to the success of TJPU. Therefore, firstly specific goals should be set up in the universities that want to construct a low carbon campus. For instance, the discharge of wastewater was reduced by 20% this year, and so on. Secondly, a clear thinking is essential. As shown in Fig. 3, various innovation efforts of the low carbon campus in TJPU can be referred.

6.2. Indicator analysis

The purpose of performing the ecological footprint and EFI was to have a clear view of the institution's ecological impact to serve as a base for further policy planning in the future and to raise awareness among teachers and students (see Table 12). The possibilities for using ecological footprint and EFI in operations, policy and education will be discussed.

Regarding operations, university staff members had the impression that a clear view of the inputs and outputs of the institution was missing and expressed the desire for clear, quantitative data about different aspects of operations. In expressing this purpose, the ecological footprint and EFI also served as a baseline for further policy development regarding the institutions' operations. To guide further initiatives within campus operations, a set of scenarios was developed to lower the ecological footprint. The scenarios indicated that priority should be given to energy use. The scenarios and initiatives for this component could not be identified within the scope of the project but will be developed in the future.

Regarding policy development and management, the ecological footprint and EFI have led to defining qualitative and quantitative indicators for the quality monitoring system. Within operations, a qualitative indicator would be "preparing an internal environmental care system," measured within the sustainability assessment based on the Auditing Instrument for Sustainability in Higher Education (AISHE), which KHLeuven used on a regular base (Lambrechts and Ceulemans, 2013). Quantitative indicators to integrate into operations were defined as follows: the amount of water used (m^3, measured by the financial department using invoices), the amount of waste (kg, different categories), and the amount of energy use (gas, electricity). All of these indicators could be measured by the logistics department, with the exception of students' mobility, as this indicator would require a periodic survey.

Table 12
Results of traditional and revised indicator system.

Indicators	Result 1	Result 2
EF (hm^2)	4659	3634
EC (hm^2)	11,905	9286
EFI	0.61	0.61
Per capita ecological footprint (hm^2/per)	0.16	0.13

Result 1: results without considering potential environmental services (traditional EFI indicator).
Result 2: results with considering potential environmental services (revised EFI indicator).

Regarding education, qualitative indicators are linked to the use of AISHE, while quantitative indicators were defined as follows: the number of courses with clear reference to ecological footprint and EFI and the number of students involved in research and outreach projects regarding sustainable development. The possibilities and utility of these quantitative indicators were discussed, as stakeholders tended to have a preference toward a qualitative approach within education and research. Regarding the use of ecological footprint for educational purposes, stakeholders discussed how the ecological footprint could be used with students. Different possibilities were expressed: students could calculate their own personal footprint or the ecological footprint results could be used in courses to further develop awareness initiatives by students. It was noted that the ecological footprint should not be considered an ultimate goal of a university's efforts to incorporate ecological indicators. Instead, it serves as a basis to raise awareness and to guide the integration of sustainability. When using ecological footprint for educational purposes, it should be used as a starting point and should go beyond the mere results of numbers and global hectares. In doing this, the ecological footprint can contribute to the acquisition of key competences for sustainable development, i.e., systems thinking, future thinking, critical thinking about values and responsibility, and taking personal action (Lambrechts et al., 2013).

7. Conclusions

The steady growth of the world's economy and population, especially in developing countries, is increasing the demand for awareness of environmental protection. At the same time, in the current context of a shortage of resources and environmental pollution, we hope to reduce resource consumption and impacts on the environment. The sustainability of low carbon society is not only the final and fundamental target for governments to construct an environmentally friendly society but is also the common goal of humans all over the world.

Combined with the current goal of a low carbon campus, the concept and definition of a low carbon campus are proposed in this paper along with a comprehensive model to manage all of the indicators. The "life cycle" idea is also introduced in the paper to diagnose the key points of system optimization. Important factors of the construction materials such as RF and MF must be taken into account when evaluating the campus. The integrated EFE and LCA model enables a broader view of the sustainability of a system, and it is important for developing new and revised indices, such as EFI, and to improve sustainability evaluations of the campus from various viewpoints. The per capita ecological footprint of TJPU considering potential environmental services is 0.13 hm^2/per, and the EFI is 0.61; therefore, TJPU is in a state of strong sustainability development. Improvements in energy technology are the most important point for the optimization of this low carbon campus; water technology also plays an important role. Therefore, effective energy and water technology in TJPU can be generalized all over the world. Relative experiences such as comprehensive model and evaluation method can be expanded to other low carbon campus, together contribute to the sustainable development of universities and country. This paper is also leading a trend to address low carbon campus, which is beneficial for journal of cleaner production.

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