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REVIEW ARTICLE

A review of studies on urban energy performance evaluation

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Abstract

Energy is a foundation for a city to create economic wealth, satisfy people's desires, and achieve benefits. However, the increasing mismatch between energy supply and demand and the worsening of environmental pollution have highlighted the importance of improving urban energy performance, so the number of studies related to urban energy performance evaluation is increasing. Based on describing the authors, numbers, regional sources, and themes of these studies, this paper reviews and analyzes the conceptions, evaluation indicators, influencing factors, evaluation methods, and evaluation systems related to urban energy performance. Most countries have expressed concern about this topic. Researchers in China, Belgium, and the USA have had the most achievements and collaborations. The concept of urban energy performance further extends to a comprehensive performance. It is measured based on an input-output process. In addition to the original evaluation indicators, new desirable outputs and undesirable outputs are included. Industrial structure, energy price, population density, home car ownership, climate factors, Gini coefficient, health expenditure level, and unemployment rate are regarded as influencing factors. Therefore, a new framework of evaluation indicators and influencing factors is constructed. Stochastic frontier analysis (SFA) and data envelopment analysis (DEA) are commonly used to evaluate. With changes in conceptions, evaluation indicators, and influencing factors, the evaluation method should rather focus on measuring multiple input-output variables, determining the evaluation results and the impacts of factors at the same analysis stage, and highlighting policy orientations. As an important management tool, the evaluation system would continue to be studied and developed.

Keywords Urban energy performance · Concept connotation · Evaluation indicator · Influencing factor · Evaluation method · Evaluation system · Review

Introduction

In recent years, urban energy consumption has increased dramatically with the rapid development of the economy and society (Grimm et al. 2008). According to statistics, global energy consumption increased from 11,588.4 million tons of standard coal in 2007 to 13,511.2 million tons of standard coal in 2017 (BP 2018), of which urban activity consumed 67% (Chen and Chen 2015). Energy is not only an important input element of economic growth, but also the heart and the lifeblood of urban industrial development and the material basis for human survival. Energy has played an irreplaceable role in social and economic development (Raggad 2018). However, the huge growth in urban energy consumption has also posed great challenges to the urban environment. Urban energy consumption has generated 70% of global greenhouse gas emissions (Chen and Chen 2015). At present, global greenhouse gas emissions are about 14% higher than the international annual standard level, and environmental pollution, global climate change, extreme weather, and other problems are becoming more and more serious.

Because it is difficult to increase energy supply, improving urban energy performance is one of the most important ways to solve these problems and has therefore become a major concern of researchers, urban managers, and residents. Urban energy performance has become a major sustainable

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development issue that is related to urban resources, environment, economy, society, management, and well-being. At the theoretical level, studies on urban energy performance evaluation could help to define scientifically the connotation of terms, expand the theoretical basis, and enrich the content framework for urban energy performance. At the practical level, they could effectively improve urban energy performance, propose ways and key points for improvement, and provide policy recommendations. However, the existing concept of urban energy performance has become divorced from the full scope of the concept because of changes in the social economy and the urban environment. Against this new background, there is a lack of indicators and influencing factors to evaluate urban energy performance. Existing evaluation methods need to be improved, evaluation systems need to be built, and the key points and difficulties of studies in this field need to be further sorted out and summarized.

Therefore, based on relevant studies on urban energy performance, this paper aims to review systematically current research trends, conceptual connotations, evaluation indicators, influencing factors, evaluation methods, and evaluation systems, after which future research directions will be proposed. Its innovations include: first, redefining the concept of urban energy performance from economic, environmental, and well-being perspectives. Second, a new framework of urban energy performance evaluation indicators and influencing factors is constructed. The framework reveals the content structure of urban energy performance evaluation indicators and influencing factors and defines the relationships between the various indicators and factors. Third, directions for improving urban energy performance evaluation and factor analysis methods are pointed out from three aspects: variable settings, the requirement for performance evaluation and factor analysis at the same stage, and the embodiment of policy effects. Fourth, the construction thought, system design, and realization approach for an urban energy performance evaluation system are proposed.

This paper is structured as follows: the second section presents the research trends. The third section systematically reviews the concepts, evaluation indicators, influencing factors, evaluation methods, and evaluation systems related to urban energy performance. The fourth section presents results and discussions. In this section, the limitations of existing studies are summarized from various aspects. The concept of urban energy performance is redefined, and a new framework of urban energy performance evaluation indicators and influencing factors is constructed. Improvement directions for evaluation and factor analysis methods are proposed, and the construction thought for an evaluation system is also presented. The fifth section is a summary of the main conclusions and the research prospects.

Research dynamics

The research theme of this paper is urban energy performance evaluation, and therefore "urban energy performance evaluation" was set as the literature retrieval search phrase. The "Web of Science" database has a convenient and customizable search function and was therefore chosen as the database source for literatures. A total of 412 papers were retrieved from 1986 to 2017 on April 3, 2018. The journals with the most publications were *Energy and Buildings*, *Energy Procedia*, *Applied Energy*, *Renewable & Sustainable Energy Reviews*, and *Energy*, which are devoted to studies of energy performance.

Table 1 summarizes the most published authors in the research field of urban energy performance evaluation. Grimmond CSB had the largest number of papers and a wide range of collaborations with authors from Singapore, Finland, the UK, the USA, Sweden, and other countries. The other authors had four or five papers each and came from Belgium, China, Spain, France, Italy, the USA, and South Korea. According to the authors in Table 1, China has the largest number of researchers active in the field, followed by Belgium and the USA. It is also apparent that China, Belgium, and the USA have the most training and support for researchers in this field. In addition, these authors often collaborate with each other and pay attention to developments in the energy and resource disciplines.

As shown in Fig. 1, the number of papers related to urban energy performance evaluation has increased year by year since 2007. Especially since 2015, the number of papers has increased significantly and is expected to continue to increase in the future. Urban energy performance evaluation has become a focus and a challenge for current research work.

The analysis results presented in Fig. 2 show that developed countries have conducted more extensive studies on urban energy performance evaluation and have paid more attention to the effects of urban energy use. The largest numbers of publications are from Italy and the USA, with these publications accounting for 33% of the total. As the largest developing country in the world, China not only has a huge land area and abundant energy, but also needs to consume a large amount of energy. It is therefore crucial to improve urban energy performance in China. Therefore, Chinese researchers have also carried out many studies on this topic.

According to the titles of 412 papers, 18 high-frequency words were extracted, as shown in Fig. 3. "City," "energy performance," and "performance evaluation" were the literature retrieval search terms and are shown in Fig. 3. These high-frequency words reflect the research emphases of urban energy performance evaluation from the aspects of research objectives, perspectives, contents, and means. "Green," "low carbon," and "sustainability" are core themes directing urban development and have therefore become the research

Table 1 The most published authors in the research field of urban energy performance evaluation

Name	Country	Affiliation	The number of papers
Grimmond CSB	Belgium	Laboratory of Hydrology and Water Management, Ghent University	9
Chen B	China	School of Environment, Beijing Normal University	5
Martilli A	Spain	Department of Environment, CIEMAT	5
Masson V	France	CNRM, Meteo-France and CNRS	5
Ulgiati S	Italy	Department of Sciences and Technologies, University "Parthenope" of Naples	5
Chen F	USA	Research Application Laboratory, National Center for Atmospheric Research	4
Lee SH	Korea/USA	School of Earth and Environmental Sciences, Seoul National University/Chemical Sciences Division, NOAA Earth System Research Laboratory	4
Geng Y	China	School of Environmental Science and Engineering, Shanghai Jiao Tong University/China Institute for Urban Governance, Shanghai Jiao Tong University	4
Hamdi R	Belgium	Royal Meteorological Institute	4
Liu GY	China	State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Beijing Normal University	4

objectives of urban energy performance evaluation. "Energy system," "energy consumption and saving," "energy efficiency," "environmental performance," "economic performance," "social effect," and similar phrases show that the evaluation perspective of urban energy performance is not simply to reduce energy consumption or to achieve economic growth unilaterally, but to integrate economic performance, environmental performance, and social impact effectively. These high-frequency words expand the research perspectives of urban energy performance evaluation. The phrases "evaluation model and system," "concept model," "evaluation method," "energy policy and strategy," "energy management," and "indicator framework" explain the research contents and research means of urban energy performance evaluation.

A comprehensive analysis of existing studies reveals that the number of studies on urban energy performance evaluation is relatively small. More studies focus on energy performance evaluation in other objects such as countries, regions, industries, enterprises, and buildings. Different kinds of energy performance include energy well-being performance and carbon emissions performance, and studies closely related to urban energy performance include various themes such as urban energy efficiency evaluation, urban sustainable performance, urban environmental efficiency evaluation, and low-carbon ecological city evaluation. Therefore, this study uses these earlier studies related to urban energy performance as literature analysis materials to analyze the conceptual connotations, evaluation indicators, influencing factors, evaluation methods, and evaluation systems involved in these studies in detail, and provide references for future studies on urban energy performance evaluation.

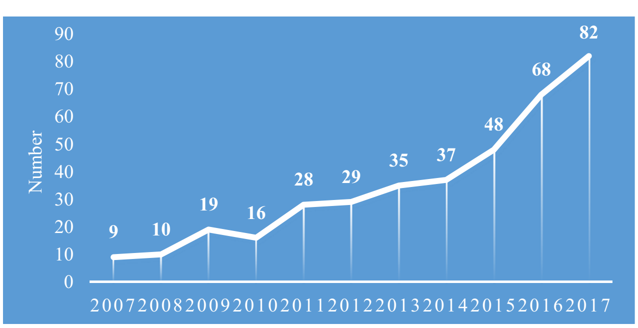


Fig. 1 Number of published papers related to urban energy performance evaluation from 2007 to 2017

Literature review

Connotations of the urban energy performance concept

The core of urban energy performance is "performance," a term that has mostly been used in management. The concept of performance has been understood from three main points of view. The first view was that performance was the result of work. The second view regarded performance as a process of work behavior. The third view was a quality-oriented view (Yan 2014). As a multi-dimensional concept, performance included not only task performance, but also contextual performance. In other words, performance measurement involved not only measuring the various activities that convert raw materials into products or services, but also quantifying other behaviors and results that help to achieve good task performance (Borman et al. 2001). Therefore, urban energy performance mainly measures the behavior and results of urban energy use. In addition, energy "contextual performance" must be considered. This is determined based on the

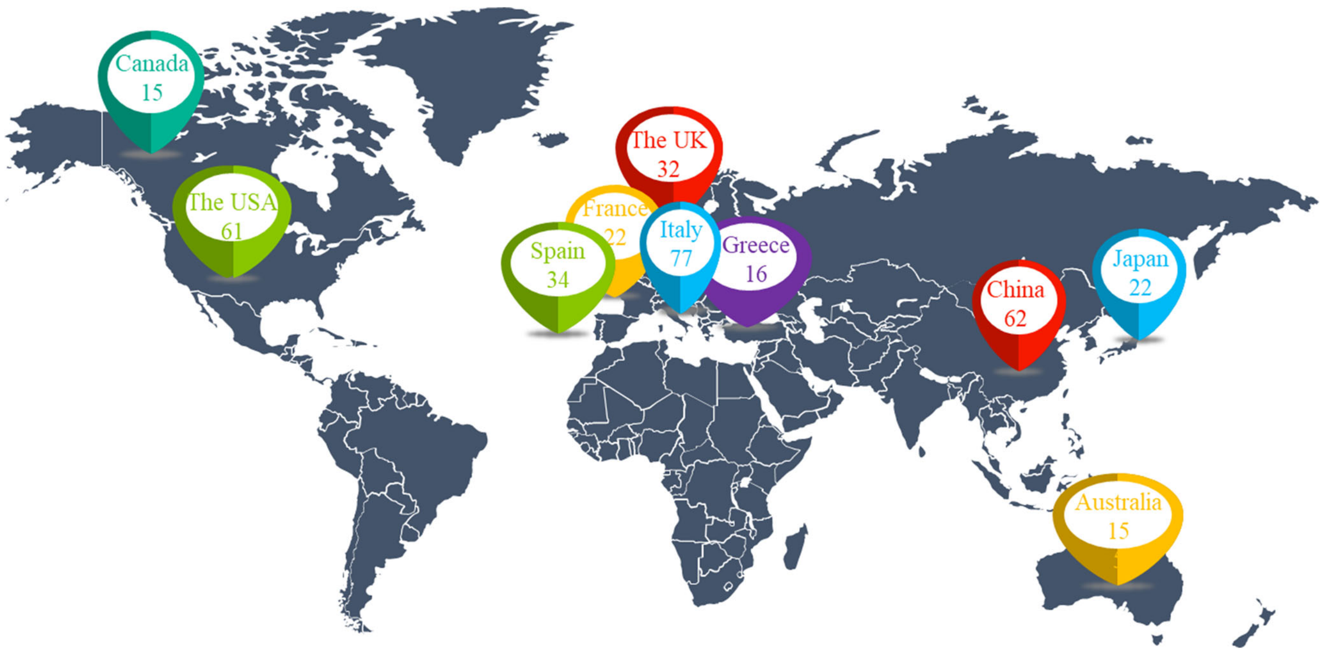
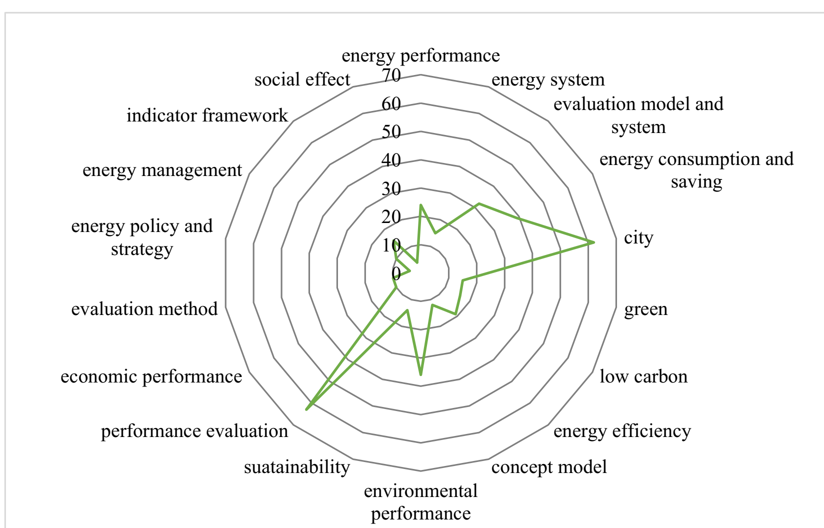


Fig. 2 Distribution of the countries with the most publications

comprehensive urban goals of economic development, social progress, environmental quality, and social well-being.

The definition of energy performance originated from energy efficiency. Patterson believed that energy efficiency referred to producing the same number of services or useful outputs using less energy (Patterson 1996). Hence, the primary problem became how to define effective output and energy input. Four kinds of energy efficiency indices were produced, including the thermodynamic index, the physical-thermodynamic index, the economic-thermodynamic index, and the economic index. Among these, the economic-thermodynamic index was most commonly used. In other words, the concept of energy efficiency was expressed through energy intensity. However, this definition still needed to be expanded to measure heterogeneous energy, to sum energy consumption, and to define the scope of energy inputs and the types of outputs. In addition, energy intensity included a large number of industrial structural factors, the substitutions between elements and the changes in energy input structure, and it was not sufficient to explain changes in the technical efficiency of energy production. Therefore, it was inadequate to use the ratio of energy to economic output to represent energy efficiency. On this basis, researchers started from the basic meaning of efficiency and transformed the measurement of energy efficiency into the distances from samples to the production frontier. Accordingly, researchers further suggested that the concept of energy performance was influenced by many input variables, output variables, and factors. As part

Fig. 3 High-frequency words in the titles of studies related to urban energy performance evaluation



of this trend, the content of energy performance also changed and expanded. Energy well-being performance, carbon emissions performance, energy saving and emissions reduction performance, and environmental performance emerged. Energy well-being performance took human well-being as the output (Dietz et al. 2012; Knight and Rosa 2011); carbon emissions performance and energy saving and emissions reduction performance viewed the carbon dioxide emissions produced by energy consumption as an undesirable output (Wang et al. 2015a; Zhou et al. 2016); and environmental performance comprehensively considered the economic, social, resource, and environmental benefits of the energy consumption (Wu et al. 2017). The concept of energy performance has been used to define national, regional, industrial, enterprise, and building energy performance. However, a concept of urban energy performance has not been proposed.

The above analyses show that the definition of urban energy performance should be combined with the substitution and influence of energy and other inputs, rather than taking only economic output as an output indicator. Therefore, whether from the performance standpoints or from the research trends in energy performance, the concept of urban energy performance has subverted the view that energy performance is equivalent to energy efficiency. Energy performance has been transformed into a comprehensive concept that measures energy consumption processes and results, energy economic performance, and energy contextual performance and is influenced by variable factors.

Urban energy performance evaluation indicators and influencing factors

Existing studies on urban energy performance are relatively few. Table 2 summarizes the evaluation indicators and influencing factors related to urban energy performance from three existing perspective studies related to urban energy performance.

As shown in Table 2, the evaluation indicators and influencing factors in different research contents are different. National energy performance is mainly evaluated based on a country's overall energy consumption and economic output. To consider the roles of other input-output elements, variables such as capital, labor, and carbon dioxide emissions are included, which fully reflect the sustainability of national environmental development. The influencing factors are focused on industrial structure, energy price, territorial area, population, and energy imports and exports at the national macro level. The variables of evaluating regional energy performance are similar to those at the national level. Their points of difference are that the undesirable outputs of regional energy performance evaluation take regional characteristics and data availability into account and add sulfur dioxide emissions, exhaust emissions, and other variables. The choice of influencing factors for regional energy performance is more targeted, and the influencing factors are chosen based on the research emphasis. For example, to study regional economic, energy, and carbon emissions performance in China under market-oriented reform, Lin and Du (2015) selected the degree of marketization in different regions as the main influencing factor and set energy price, energy consumption structure, industrial structure, foreign trade openness, policy, and province as control variables. Within the scope of regional energy performance evaluation, energy price, energy consumption structure, the degree of openness, and environmental regulation were common influencing factors. Industrial energy performance can also be measured by energy, capital, labor, and industrial outputs. Its factors include the level of economic development, industrial structure, population density, and energy price. The energy performance of enterprises and buildings is evaluated from a more micro perspective. The energy consumed by enterprises is mainly used in production activities, and therefore enterprise energy performance is closely related to the level of energy use, production activity level, product mix, non-energy inputs, and the external environment. Building energy performance is measured by the energy consumption and utility of the building, which are related to building area, energy-consuming facilities, location, price, energy consumption behavior, policies, and other variables. By analyzing the energy performance of different subjects, it can be concluded that the energy performance of countries, regions, industries, enterprises, and buildings is mostly analyzed by the utility level of their outputs from the economic perspective.

As for other categories of energy performance, energy well-being performance pays more attention to the improvements in well-being obtained from energy consumption, and therefore energy well-being performance is measured by the levels of energy consumption and social well-being. The level of energy consumption is mainly determined by the per capita ecological footprint or actual energy consumption, whereas measurements of the level of social well-being can be derived from an objective or a subjective perspective. Objective well-being indicators include the index of sustainable economic welfare (ISEW) (Menegaki et al. 2017), the genuine progress indicator (GPI) (O'Mahony et al. 2018), the average life expectancy (Dietz et al. 2012; Jorgenson et al. 2014), and the human development index (HDI) (Koohi et al. 2017). Subjective well-being indicator refers mainly to life satisfaction (Knight and Rosa 2011). The influencing factors of energy well-being performance include the degrees of economic development, political democracy, and income equity, the level of industrial structure, and the health level. The evaluation of energy security performance focuses on energy availability, diversity, affordability, technology and efficiency, environmental sustainability, regulation and governance, and other aspects. In the context of increasing energy consumption and

Table 2 Evaluation indicators and influencing factors summarized from existing studies related to urban energy performance

Perspective	Category	Authors	Study descriptions	Evaluation indicators and influencing factors
The energy performance studies of different objects	National energy performance	Ang et al. (2015)	The comparison of energy performance in multiple regions	Energy consumption; economic value added
		Wang et al. (2017c)	The energy and carbon emissions performance and its decline potential of APEC countries	Energy consumption; capital; labor; gross domestic product (GDP); carbon dioxide emissions; energy intensity; industrial structure; carbon emissions intensity
		Chang et al. (2016)	The estimation of sustainable energy consumption and carbon emissions performance in Baltic States	Energy consumption; capital; labor; GDP; carbon dioxide emissions
		Cengiz et al. (2018)	The urban energy performance evaluation of OECD countries	Energy consumption; GDP; the real price of household and industrial energy; the area of country; industrial added value share; service industry added value share
		Song et al. (2017)	The measurement of energy performance through the energy triple dilemma index	Energy security; energy capital; environmental sustainability
		Alp and Sözen (2014)	The energy performance of Turkey and the comparison with other EU Member States	Total primary energy production; the net imports of natural gas; the net imports of primary energy; the net imports of crude oil and petroleum products; total power generation; the domestic consumption of primary energy; final energy consumption; population
	Regional energy performance	Wang et al. (2012)	The comparative analysis of regional energy and carbon emissions performance	Labor; capital stock; energy input; GDP; carbon dioxide emissions; sulfur dioxide emissions
		Lin and Du (2015)	China's regional economic, energy, and carbon dioxide emissions performance under market-oriented reform	GDP; carbon dioxide emissions; capital; labor; energy consumption; the degree of marketization; energy price; energy consumption structure; industrial structure; foreign trade openness; policy; province
		Li and Lin (2017)	The relationships between energy and carbon dioxide emissions performance with regional integration in China	GDP; labor input; energy input; capital input; carbon dioxide emissions; regional integration; international openness; ownership; environmental regulation; energy price; human capital; fiscal expenditure
		Wu et al. (2017)	The measurement of regional energy and environmental performance in China	Labor; capital investment; energy; GDP; waste gas
	Industrial energy performance	Li et al. (2016)	Industrial energy pollution performance in China's regions	Labor; capital stock; total energy consumption; industrial added value; sulfur dioxide emissions; carbon dioxide emissions; chemical oxygen consumption
		Zhou et al. (2016)	Industrial energy saving and emissions reduction in China's cities	Urban industrial labor; fixed capital; electricity consumption; regional industrial output value; sulfur dioxide and industrial solid waste emissions
		Wang and Zhao (2017)	The regional energy environmental performance and investment strategy in China's nonferrous metals industry	Total energy consumption; labor; capital stock; nonferrous metal industry output value; carbon dioxide emissions; the level of economic development; industrial structure; population density; energy price
		Fei and Lin (2017)	Regional input-output efficiency and energy carbon emissions performance in China's agriculture	Capital; labor; energy; agricultural output; carbon dioxide emissions
		Lin et al. (2007)	The grey correlation analysis of economy, energy use and carbon emissions in Taiwan's industrial sector	Industrial economic level; industrial energy consumption; carbon dioxide emissions
	Enterprise energy performance	Boyd et al. (2008)	Energy performance evaluation of manufacturing enterprises	The level of energy use; production activity level and type; non-energy inputs; external factors (climate, material quality)
				Annual energy consumption; production capacity; annual total working hours

Table 2 (continued)

Perspective	Category	Authors	Study descriptions	Evaluation indicators and influencing factors
		Boyd and Zhang (2013)	Energy performance improvement of US cement industry based on Energy Star energy performance index	
		Boyd (2017)	The energy performance indicator analysis of manufacturing enterprises	Product mix; process input selection; scale; climate
	Building energy performance	Bruegge et al. (2016)	The attention degree of housing market to energy-saving houses	Housing price
		Middelkoop et al. (2017)	Residents' willingness to adopt household energy performance policies	Residents' willingness to improve energy efficiency; natural and social background; behavior process; motivation; policy guidance
		Wang (2012)	The energy performance of hotel building in Taiwan	Total building area; the number of floors; construction year; hotel rating; hotel location; room number; average room area; the building area percentage of catering facilities; the building area percentage of retail stores; annual occupancy rate; average house price; housing fee income; catering income; total income; staff number; personnel density; the total number of customers; foreign guests; group guests; domestic guests; Chinese guests; North American guests; Japanese guests; European guests
The energy performance studies of different types	Energy well-being performance	Knight and Rosa (2011)	Environmental well-being performance in 105 countries	Per capita ecological footprint; average life satisfaction; per capita GDP; political democracy score; Gini coefficient; social trust level; climate; region
		Dietz et al. (2012)	The relationships between environmental well-being benefits and Kuznets curve	Per capita GDP; per capita ecological footprint; average life expectancy
		Jorgenson et al. (2014)	The relationships between energy consumption, social well-being and economic development in central and eastern European countries	Average life expectancy; per capita energy consumption; per capita GDP; the degree of democratization; government health expenditure; Gini coefficient; the proportion of manufacturing output value to GDP; the proportion of export value to GDP
		Išljamović et al. (2015)	National well-being evaluation	Per capita GDP; unemployment rate; energy use; consumer price index; per capita health expenditure; the number of nurses and midwives; the number of doctors; the number of sick beds; the development level of information and communication technology; democratic index; ecological footprint; environmental performance index
	Energy security performance	Zhang et al. (2017)	The measurement of provincial energy security performance in China	Energy availability and diversity; the affordability and balance of energy consumption; technology and efficiency; environmental sustainability; governance and innovation
		Martchamadol and Kumar (2013, 2014)	National and provincial energy security performance indicators	Per capita primary energy consumption; per capita final energy consumption; per capita electricity consumption; primary energy intensity; ultimate energy intensity; transmission loss; crude oil storage and production ratio; natural gas storage and production ratio; coal storage and production ratio; industrial energy intensity; agricultural energy intensity; commercial energy intensity; per capita household energy consumption; per capita household electricity consumption; traffic energy intensity; the proportion of renewable energy generation to total power generation; the share of non-carbon energy in the total energy supply; the share of

Table 2 (continued)

Perspective	Category	Authors	Study descriptions	Evaluation indicators and influencing factors
				renewable energy in the final energy consumption; the dependence on net energy import; per capita carbon dioxide emissions; carbon dioxide emissions for per unit gross regional product; household electricity consumption; the share of income for electricity; energy consumption for per household
		Sovacool (2013); Sovacool et al. (2011)	National energy security performance	The availability of energy; the purchase ability of energy; the development and efficiency of technology; environmental sustainability; regulation and governance
	Carbon emissions performance	Shao et al. (2014)	The carbon emissions performance and its decomposition of industrial energy consumption in Tianjin, China	Economic scale; energy efficiency; industrial structure; energy structure
		Wang et al. (2015a)	The measurement and decomposition of energy saving and emissions reduction performance in Chinese cities	Labor; capital; energy input; GDP; sulfur dioxide emissions; income level
		Hu et al. (2017)	The measurement and development of total-factor carbon emissions performance	Construction engineering; employment; industrial added value; carbon dioxide emissions
The studies related to urban energy performance	Urban energy efficiency	Hang et al. (2015)	Urban energy efficiency in China	Labor; capital stock; energy consumption; GDP; sulfur dioxide emissions
		Keirstead (2013)	The energy efficiency of British cities	Regional area; population; total energy consumption; household annual income; refrigeration days; heating days; retail area; office area; factory area; warehouse area; other area; the proportion of families with two cars; the percentage of employment in family; life expectancy; per capita added value; carbon emissions; the proportion of people with easy access to services
		Wang et al. (2017b)	The driving factors of urban energy efficiency	Per capita carbon emissions; per capita GDP; climate; population; region; market scale; market attraction; economic vitality; human capital; business environment; the difficulty of business; academic resource; research background; research achievements; the potential of leading culture; cultural resource; tourist facilities; the attraction to tourists; the degree of mutual communication; working environment; living cost; safety; living environment; living facilities; urban transportation service; the convenience of traffic; international traffic network; international transportation infrastructure; ecological degree
		Wang et al. (2017a)	Urban energy efficiency and marginal carbon emissions reduction cost in China	Labor; GDP; capital stock; urban energy consumption; carbon dioxide emissions
	Urban sustainability performance	Kourtit et al. (2017)	The sustainability analysis of the world cities	Labor input; carbon dioxide emissions; GDP; life satisfaction; the percentage of renewable energy use
		Kılkıs (2016)	The evaluation indicators for sustainable development of energy, water and environment systems in eastern and southern Europe cities	Energy consumption and climate; energy and carbon dioxide emissions reduction measures; the potential and utilization of renewable energy; water and environmental quality; carbon dioxide emissions and industry situation; urban planning and social well-being; research, development, innovation and sustainability policy

Table 2 (continued)

Perspective	Category	Authors	Study descriptions	Evaluation indicators and influencing factors
		Munier (2011)	The selection method of urban sustainability performance evaluation indicators	The frequency of excessive air quality; the number of cars; per capita residential water consumption; adult literacy rate; the birth weight; crime rate; employment degree; the degree of construction license; unemployment rate; the proportion of the workers in the environment renovation; the average greening space of the residents; the cost compensated for environmental degradation; the social effect of changing per unit GDP; the number of low-income families; per capita public health investment; the regional maximum population loaded permanently
	Urban environmental efficiency	Wang et al. (2015b)	The analysis on urban environmental efficiency	Labor; energy; fixed capital; GDP; sulfur dioxide emissions
		Üstün (2015)	Urban environmental efficiency evaluation in Turkey	The total amount of water resources; the total environmental budget; the total amount of collected solid waste; the number of people receiving sewage treatment services; the number of people receiving drinking water supply; the maximum concentration of PM10; the maximum concentration of sulfur dioxide
	Low-carbon ecological city evaluation	Yu (2014)	The analysis of low-carbon city evaluation	The effective use of resources; friendly environment; sustainable economy; harmonious society
		Lin et al. (2014)	The indicator system model of low-carbon city	Energy structure; industrial structure; sector energy intensity of per unit GDP added value; per capita GDP; the solid waste disposal structure; the per capita solid waste production; the per capita waste water production; animal husbandry structure; agricultural planting structure; the per capita livestock breeding; the per capita agricultural planting area; the amount of fertilizer used in per unit agricultural land; per capita processing industrial output; per capita forest area; forest structure
		Zhou et al. (2015)	The evaluation tool of low-carbon city in China	Energy and climate; water quality; air quality; waste; transportation; economic health; land use and new urban area; population characteristics and social health
		Tan et al. (2015)	The development of low-carbon indicator framework	Energy; economy; technology development; society and life; carbon emissions and environment; waste; urban accessibility

environmental problems, studies on carbon emissions performance are increasing in number. The core point of carbon emissions performance measurement is to incorporate carbon dioxide and other pollutants into the outputs and to take energy, labor, and capital as input variables. Economic scale, industrial structure, and income level have important impacts on carbon emissions performance.

Some researchers have studied urban energy efficiency and urban environmental efficiency from the perspective of total-factor inputs and outputs, but some researchers studied these questions from a broader perspective including urban area, population, family income, family refrigeration and heating days, the number of employees in the home, the number of families with two cars, and life expectancy. Urban sustainable performance evaluation and low-carbon ecological city evaluation comprehensively consider resources, environment, economy, society, lifestyle, technology, and urban accessibility and focus on renewable energy use, urban planning, social well-being, transportation convenience, research development and innovation policy, and waste disposal.

Through a detailed analysis and summary of these evaluation indicators and influencing factors, it can be concluded that the research perspective, purpose, objective, and content are the important bases for setting up evaluation indicators and

Table 3 Evaluation methods used in existing studies related to urban energy performance evaluation

Sources	Evaluation methods	The characteristics of evaluation methods
Boyd et al. (2008)	Stochastic frontier analysis (SFA)	It comprehensively considered evaluation indicators and influencing factors. It could effectively measure the differences between actual and optimal performance.
Zhang et al. (2017)	Fuzzy analytic hierarchy process; preference sequence structure assessment	They could reflect decision preferences.
Middelkoop et al. (2017)	Multiple logistic regression analysis	This method analyzed the micro variables of natural and social background, behavior process, motivation and policy.
Fei and Lin (2017)	Non-radial direction distance function	It could measure operational and environmental efficiency, and energy and environmental performance. It could analyze the decline potential of energy intensity and carbon emissions intensity.
Song et al. (2017)	Random multiple criteria acceptability analysis	It could use different preferences as input data to construct the new sorting schemes. The interval decision matrix was incorporated into this method.
Cengiz et al. (2018)	Bayesian stochastic frontier analysis; Bayesian network method	Bayesian stochastic frontier analysis method took into account the measurement errors of the efficiency estimation. Bayesian network method could analyze the relationships between variables and efficiency.
Wang et al. (2017c)	Non-radial distance function model with variable scale returns of global production technology	It could accurately describe the actual production technology. It applied the intertemporal data. It combined with the scale of global production technology.
Ang et al. (2015)	Spatial decomposition analysis	It could compare the specific differences of energy consumption or carbon emissions in different regions.
Li et al. (2016)	Pollution efficiency index; energy efficiency index; the Luenberger productivity index	They could measure the energy performance and pollution performance. The third method reflected changes in intertemporal production and the index was divided into efficiency change and technology change.
Lin et al. (2007)	Grey relational analysis	It comprehensively considered the dynamic network relationship of energy system, economy system and environment system.
Wang and Zhao (2017)	Non-radial data envelopment analysis model	It could deal with energy efficiency and environmental efficiency. It could adjust inputs, undesirable outputs and desirable outputs. It could make full use of the information of production factors.
Zhou et al. (2016)	Non-radial direction distance function; the Malmquist index	The first method could be applied to the situation of reducing inputs and undesirable outputs in different proportions. The second method could reflect dynamic changes in performance values.
Wang et al. (2017a)	Improved SBM model	It considered the relationships between desirable outputs and undesirable outputs. It could directly handle the redundancy of excessive inputs and insufficient outputs.
Wang et al. (2017b)	Data envelopment analysis (DEA); K-means clustering analysis method	The first method could determine the energy efficiency. The second method could classify efficiency level by the classification method.
Keirstead (2013)	Ratio method; regression analysis; DEA	The advantages and disadvantages of different methods were reflected.
Hang et al. (2015)	Energy inefficiency index	The technical heterogeneity was considered. The non-radial slack variables were added. The undesirable outputs were added. This method could decompose the inefficient sources.
Kourtit et al. (2017)	Multi-period data envelopment analysis	It considered dynamic changes in different periods.
Wang et al. (2015b)	Meta-frontier data envelopment analysis	It could consider the heterogeneity of production technology in different regions.
ÜSTÜN (2015)	CCR model; BCC model	They could get the efficiency values. These method could help to deduce conclusions. There was no constraint on the variable forms of the inputs and outputs.

influencing factors. The content and structure of framework for urban energy performance evaluation indicator and influencing factor needs further analysis and determination.

Methods of evaluating urban energy performance

Single-factor evaluation method

The energy performance evaluation method is derived from the single-factor evaluation method, that is, the ratio of energy consumption to GDP. This method reflects the interaction and constraint relationships between energy and economy and is easy to understand and use. In view of the impacts of climate, energy price, and population on energy performance, Nagata (1997) proposed the concept of real and single energy intensity, which effectively removed the impacts of the above factors on measuring energy performance.

Total-factor evaluation method

The single-factor evaluation method considers only a single input factor. It is obvious that this method has some defects, and therefore the total-factor evaluation method was proposed. Besides energy input, the total-factor evaluation method can also deal with other input variables, output variables, and various influencing factors. The total-factor evaluation method is not confined to any specific evaluation method, leaving the selection free to be based on actual needs and different variables. Table 3 summarizes the evaluation methods used in existing studies related to urban energy performance evaluation.

Through the above analysis, it could be concluded that SFA, fuzzy comprehensive evaluation method, DEA, regression analysis, and the Malmquist-Luenberger index are commonly used in studies related to urban energy performance evaluation. The fuzzy comprehensive evaluation method includes many specific methods. The core of these methods is to set up reasonable weights for different evaluation indicators, where the indicator weights are set to reflect decision preferences according to the actual situation and experts' opinions. Similarly, the specific regression analysis method should be selected according to the research purpose, independent variable attributes, dependent variable attributes, and data sample conditions. SFA and DEA aim to reflect performance values by measuring the gap between target and actual energy inputs or the gap between expected and actual outputs. The fundamental difference between these two methods is whether the parameters of the variables can be estimated. DEA is a non-parametric analysis method, but SFA is a parametric method (Moutinho et al. 2018).

DEA was first proposed by Charnes et al. (1978) on the basis of Färe and Lovell's (1978) study. After developments and improvements, CCR model, BCC model, Russell model, quasi-fixed inputs model, and SBM model were gradually developed into Shephard input distance function model, the directional distance function (DDF) model, the DDF + SBM model, multi-period data envelopment analysis, meta-frontier data envelopment analysis, and the Malmquist-Luenberger index. These models developed from models that included only desirable outputs to ones that included both desirable and undesirable outputs, and then to ones that considered different regions, periods, and technological developments. As shown in Fig. 4, on the assumption that all inputs could be adjusted in a radial direction, Charnes et al. (1978) and Banker et al. (1984) proposed classical DEA models, called CCR model and BCC model. These two models stipulated that all inputs could be scaled down proportionately without reducing the outputs. CCR model stipulated that the scale returns were constant, but BCC model permitted variable scale returns. Because the weak efficiency problem exists when CCR model and BCC model are used for calculation, the efficiency might be overestimated, in which case the recognition ability of these models might be weakened. Therefore, the DEA model (Färe and Lovell 1978; Tone 2001) that allows all inputs to be contracted in different proportions was proposed because this model could also directly deal with the redundancy of over-specified inputs and output shortages. Due to transaction costs and regulations, not all inputs could be adjusted to the optimal level. Therefore, Ouellette and Vierstraete (2004) modified the DEA model according to the quasi-fixed input hypothesis. This means that the energy input could be adjusted and the other inputs would remain quasi-fixed in the short term. With the aggravation of environmental pollution, the DEA model, which could deal with reductions in energy inputs and pollutants simultaneously, was proposed. It calculated energy performance based on Shephard distance function (Färe et al. 1996). However, the model still had some problems dealing with bad outputs, and it did not conform to actual production rules. Hence, DDF was proposed to deal with the pollutant problem (Chung et al. 1997; Färe and Grosskopf 2004). For piecewise linear production frontiers, the measured efficiency would be overestimated when nonzero slack variables existed in the constraint conditions. SBM directional distance function was proposed to solve this problem (Fukuyama and Weber 2009). Because of temporal and regional differences, the DEA model was developed into the multi-period data envelopment analysis model and the meta-frontier data envelopment analysis model. The Malmquist-Luenberger index, which consisted of an efficiency change index and a technological progress index, was used to measure total-factor productivity changes for two different periods. The efficiency change index could further be divided into pure

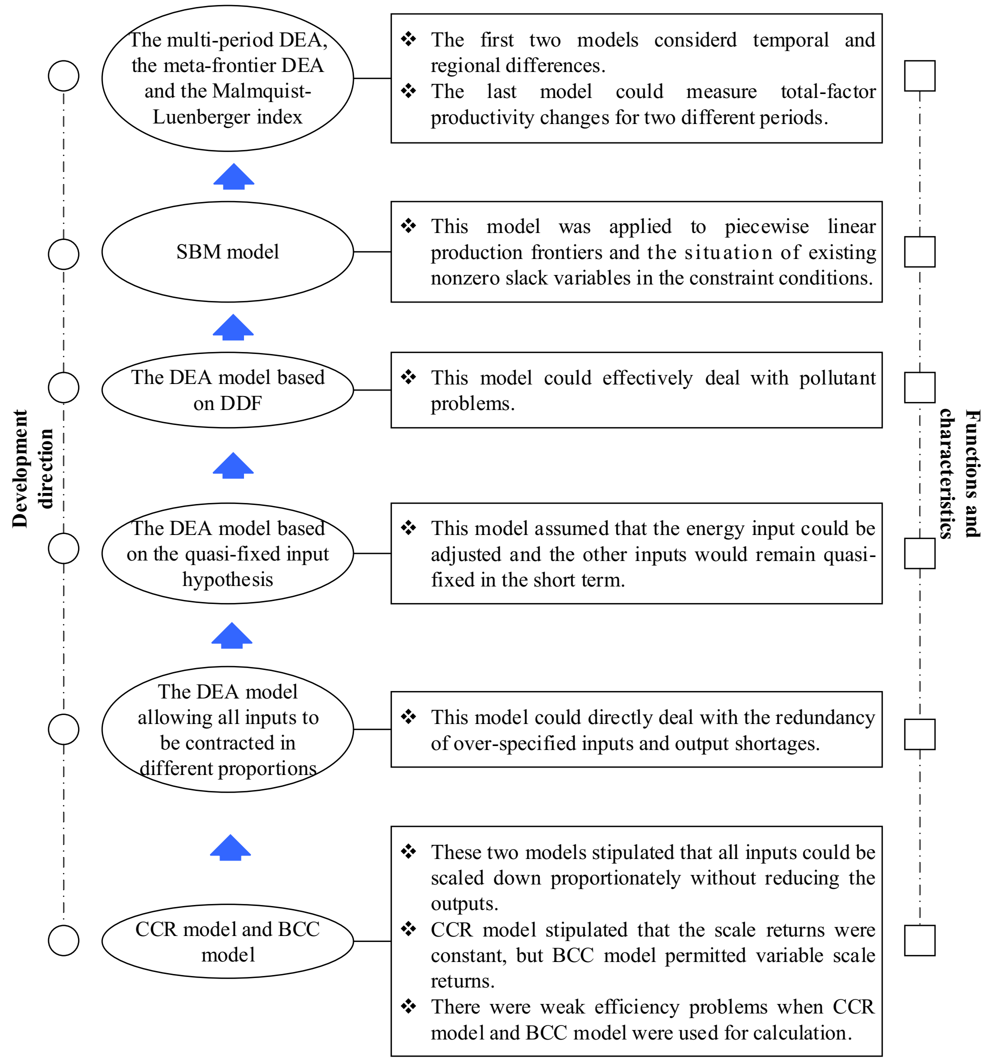


Fig. 4 The development and changes of DEA method

technical efficiency change and scale efficiency change (Chung et al. 1997).

Unlike DEA, the SFA method could set parameters and separate out random factors. The initial SFA model was proposed by Aigner et al. (1977) . With extensions in research practice, the parameter estimation of non-efficiency items, the panel data model, and the time-varying performance model were also expanding. Battese and Coelli (1992) proposed the SFA model for panel data, which set the non-efficiency term to obey a truncated normal distribution. In 1995, the improved SFA model was proposed (Carrer et al. 2015), with performance measurement and factor analysis incorporated into the same model. SFA needs to assume an equation form when constructing the production frontier and uses maximum likelihood estimation method to estimate the parameters. A diversity of equation forms increases the risks of using SFA, and therefore it is important to determine the equation form reasonably and accurately. To solve the problems of multiple inputs and outputs effectively, Yin et al. (2017b) applied the ray stochastic frontier model. The development and changes of SFA method are shown in Fig. 5.

Evaluation system

Against the background of the "smart city" and "Big Data information technology," all kinds of computer tools have been applied to the city in both macro and micro aspects. Urban energy performance covers a huge amount of data and information and is closely related to the economic, social, ecological, environmental, and well-being aspects of a city. Therefore, it is necessary to evaluate and monitor these aspects through an urban energy performance evaluation system and to strengthen further the comprehensive management and sustainable use of urban energy. Energy performance evaluation systems have been applied in various fields, including the international energy performance architecture index, the Energy Star Program in the USA, the Energy-Related Products directive in the European Union, the Energy

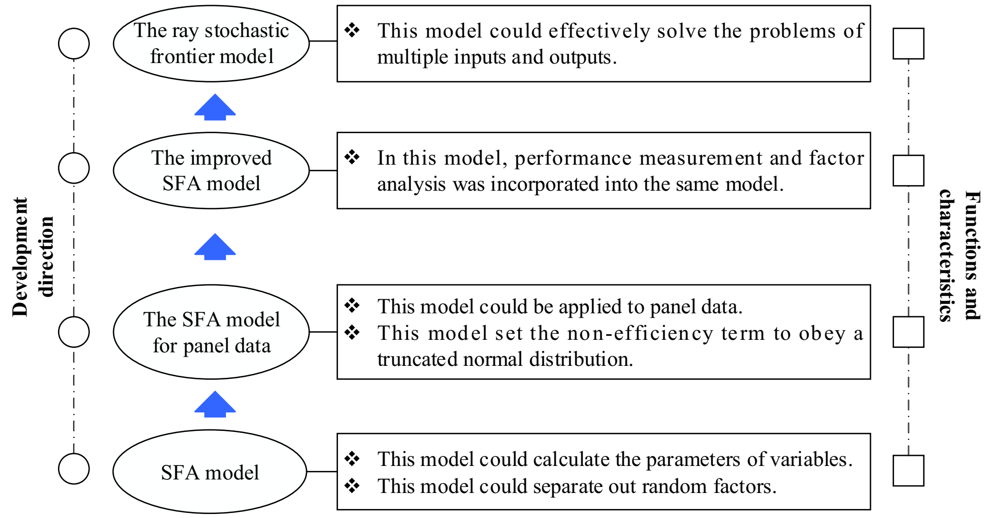


Fig. 5 The development and changes of SFA method

Performance Certification in the European construction industry (Pagliaro et al. 2015), and the Energy Saving Trust in the UK. These energy performance evaluation tools used in countries, enterprises, and products have played outstanding roles and provide important references for constructing urban energy performance evaluation systems.

Results and discussions

Extension of the urban energy performance concept

By reviewing existing studies related to urban energy performance, combining the evolution of the energy performance concept and the characteristics of urban energy consumption activities, it has become clear that the concept of urban energy performance needs to be redefined from the following three aspects. First, because the city is the main energy user, the measurement scope of urban energy performance should be based on the processes of production activities and production results. Second, the measurement of urban energy performance is not reflected by the performance of energy tasks (such as economic output tasks), but should include "task performance" and "contextual performance" (including energy environmental performance and energy well-being performance). Third, urban energy performance is measured based on inputs and outputs. Within the total-factor evaluation framework, urban energy performance is influenced by many input indicators, output indicators, and other factors (Knight and Rosa 2011; Wang et al. 2015a; Wu et al. 2017). Therefore, urban energy performance is defined as the level of producing optimal outputs based on energy and other inputs through urban development activities under the influences of certain social regulations and factors. Based on the above analysis and definition, future studies of urban energy performance should take the economy, the environment, and social well-being as perspectives and pay more attention to integrated performance on the economy, the environment, and social well-being.

Construction of new framework for urban energy performance evaluation indicators and influencing factors

Through the analysis described in Section 3.2, the evaluation indicators and influencing factors used in studies related to urban energy performance were set up based on the research objects and purposes, ignoring multi-dimensional standards related to the economy, the environment, and social well-being. For example, national, regional, industrial, and enterprise energy performance as well as urban energy efficiency paid more attention to energy economic performance (Boyd et al. 2008; Cengiz et al. 2018; Lin and Du 2015). Carbon emissions performance, urban environmental efficiency, and low-carbon ecological city evaluation paid more attention to energy environmental performance (Lin et al. 2014; Üstün 2015; Wang et al. 2015a). Energy well-being performance and urban sustainability performance measured energy performance from the social well-being perspective (Jorgenson et al. 2014; Munier 2011). Therefore, based on conceptual contents and the existing urban energy performance evaluation indicators and influencing factors, a new framework for urban energy performance evaluation indicators and influencing factors is constructed and is shown in Fig. 6.

The idea of constructing the framework is as follows: based on the conceptual contents of urban energy performance and current urban development goals, the economy, the environment, and social well-being are proposed as perspectives for future studies on urban energy performance evaluation and factor analysis. Therefore, in Fig. 6, urban energy

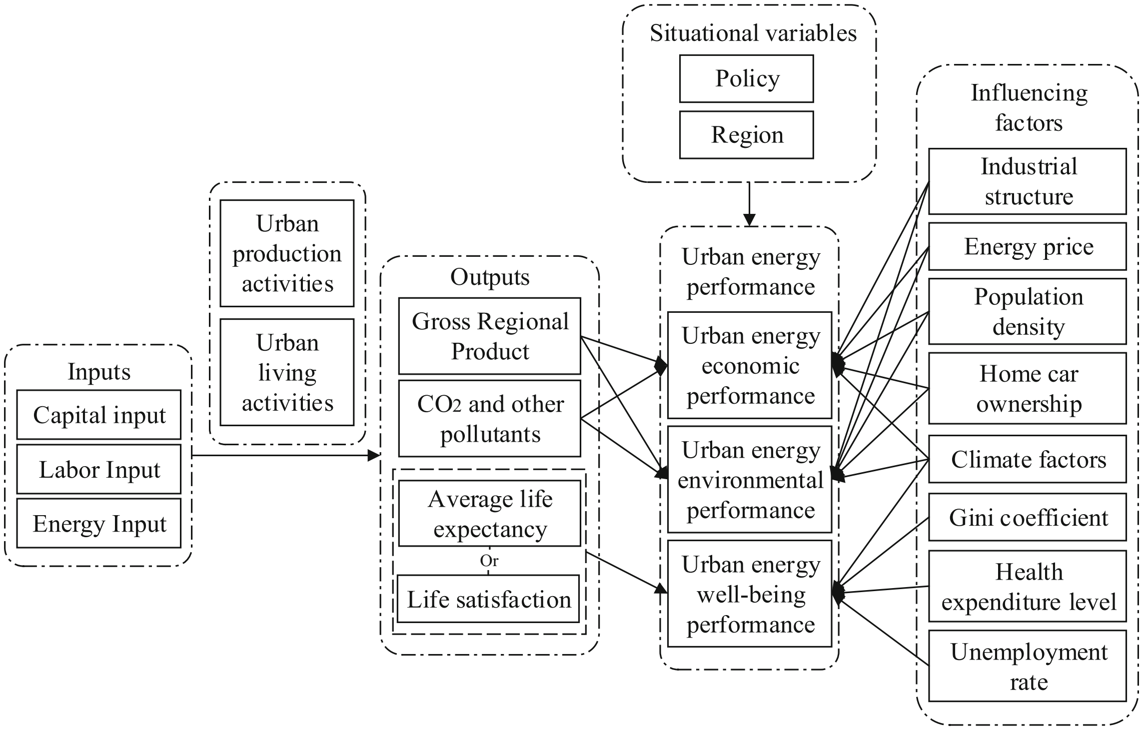


Fig. 6 New framework for urban energy performance evaluation indicators and influencing factors

performance includes urban energy economic performance, urban energy environmental performance, and urban energy well-being performance, which breaks through the limitation of purely studying urban energy economic performance. Production and living activities are taken as the carriers of inputs and outputs, which mainly reflects the dynamic process of transferring energy and other inputs to outputs through a series of activities.

According to analyses of evaluation indicators and influencing factors used in studies related to urban energy performance evaluation, the framework of urban energy performance evaluation indicators and influencing factors can be divided into two modules: the evaluation indicator module and the influencing factor module. In other words, it is not only necessary to evaluate urban energy performance using evaluation indicators, but it is also important to explore performance differences based on influencing factors. Capital, labor, and energy are set as input elements, and gross regional product, carbon dioxide emissions, other pollutants, and average life expectancy (or life satisfaction) are taken as output elements. The first three output elements are used to reflect energy economic performance and energy environmental performance and life expectancy (or life satisfaction) is used to reflect energy well-being performance. Among these output elements, gross regional product and life expectancy (or life satisfaction) are desirable outputs, and the other outputs are undesirable outputs (Dietz et al. 2012; Knight and Rosa 2011; Wang et al. 2012; Wu et al. 2017; Yang et al. 2018). Policy and region are situational variables (Lin and Du 2015). The influencing factors include industrial structure, energy price, population density, home car ownership, climate factors, Gini coefficient, health expenditure level, and unemployment rate. The first five factors help to explore differences in energy economic performance and energy environmental performance (Cengiz et al. 2018; Keirstead 2013), whereas the last four factors contribute to exploring differences in energy well-being performance (Išljamović et al. 2015; Knight and Rosa 2011).

Directions for improvement in urban energy performance evaluation methods

A review of relevant evaluation methods reveals that DEA and SFA are the most widely used. Different evaluation methods have certain limitations due to their own variables and function forms, but they are also being improved as the field is studied further. Based on the new framework of urban energy performance evaluation indicators and influencing factors, the directions for future improvement of urban energy performance evaluation methods can be foreseen as described below.

First, to make the framework of evaluation indicators and influencing factors more consistent with actual urban development, undesirable outputs are included in the measurement. As the urban energy performance range expands, the average life expectancy or life satisfaction, which embodies urban energy well-being performance, is also included in the framework. Therefore, future urban energy performance evaluation methods should focus on dealing with multiple desirable and undesirable outputs on the premise of ensuring the evaluation model's rationality and robustness.

Second, previous studies related to urban energy performance evaluation and influencing factors have been carried out in two stages, which undoubtedly increases errors in evaluating performance and analyzing performance differences. The improved SFA method creatively integrated energy performance evaluation and factor analysis into the same evaluation model, but this method was limited to a single output. The DEA model considered multiple outputs, but it did not include the functions described above (Carrer et al. 2015). Furthermore, future urban energy performance methods should gradually integrate performance evaluation and factor analysis into the same method model.

Third, as important situational variables, policy and region play irreplaceable roles. Therefore, future urban energy performance evaluations should make policy orientation clearer. The first point is to integrate undesirable outputs into the evaluation model, which makes it possible to evaluate the economic and environmental effects of policies and to define the degree and scope of policy implementation (Wang and Zhao 2017). The second point is to set the weights for input and output variables and to compare the differences in output expansion and pollutant discharge before and after implementing energy consumption constraints, so as to estimate indirectly the effectiveness of changing energy policies (Wang et al. 2017a; Zhou et al. 2016). The third point is to estimate indirectly the opportunity cost caused by environmental controls by comparing the output differences under pollutant constraints. The opportunity cost is the potential economic loss caused by environmental policy implementation. Urban energy performance measured under these various adjustment methods would objectively reflect the regulatory roles of policies, which would provide an important reference for rational formulation of energy conservation and emissions reduction targets and paths. In addition, regional differences would lead different cities towards different production frontiers, making the performance analysis more reasonable.

Construction of an urban energy performance evaluation system

At present, there are relatively few evaluation systems for energy performance, and there are even fewer studies on urban energy performance evaluation systems. Therefore, an urban energy performance evaluation system would have substantial application prospects. Based on extensive analysis of existing energy performance evaluation systems, this paper proposes a construction thought for an urban energy performance evaluation system, as shown in Fig. 7.

In the system planning stage, the needs of the users are collected. Combining with the basic requirements of the information management system, the design objectives for the urban energy performance evaluation system are put forward. Regional management institutions, urban government management institutions, urban planners, urban energy management institutions, urban energy management researchers, and urban residents are the main users of the urban energy performance evaluation system. Therefore, while maintaining scientific rigor and rationality, the system should be both convenient and easy to operate. The primary requirement of the urban energy performance evaluation system is to assist users in intuitively obtaining evaluation results for urban energy performance and the effects of different influencing factors.

In the analysis stage, it is necessary to analyze the structures, functions, and construction tools provided by existing energy performance evaluation systems, to compare the advantages and disadvantages of existing systems, and to determine a logical framework for constructing the urban energy performance evaluation system (Chang and Yu 2001).

In the system design stage, the functions of the urban energy performance evaluation system are initially set as login, information storage, information and data addition, information and data modification, information and data editing, urban energy performance calculation, urban energy performance comparison, urban energy performance query, urban energy performance analysis in different regions, chart export, and other functions. At the same time, based on the design pattern of a stand-alone system, the modules of the urban energy performance evaluation system are envisaged as a database, a distributed component server, and a human-computer interaction interface. After comparing the functions of several software development tools, the development tools for the urban energy performance system can be finally determined (Soutter et al. 2009; Yin et al. 2017a).

In the system development phase, the system interface is designed with reference to existing evaluation systems and focuses on attractiveness and practicality. In addition, according to the selected evaluation indicators, influencing factors, and method model, the parameters used to edit the program are calculated.

According to the arrangement and design of the first four stages, the developed urban energy performance evaluation system needs to be tested. The system would be improved according to the suggestions of different users.

Conclusions and prospects

Based on the query results from Web of Science, this paper has analyzed the authors, numbers, regions, and themes of the studies related to urban energy performance evaluation and has reviewed conceptual connotations, evaluation indicators, influencing factors, evaluation methods, and evaluation systems used. Therefore, the following conclusions can be summarized.

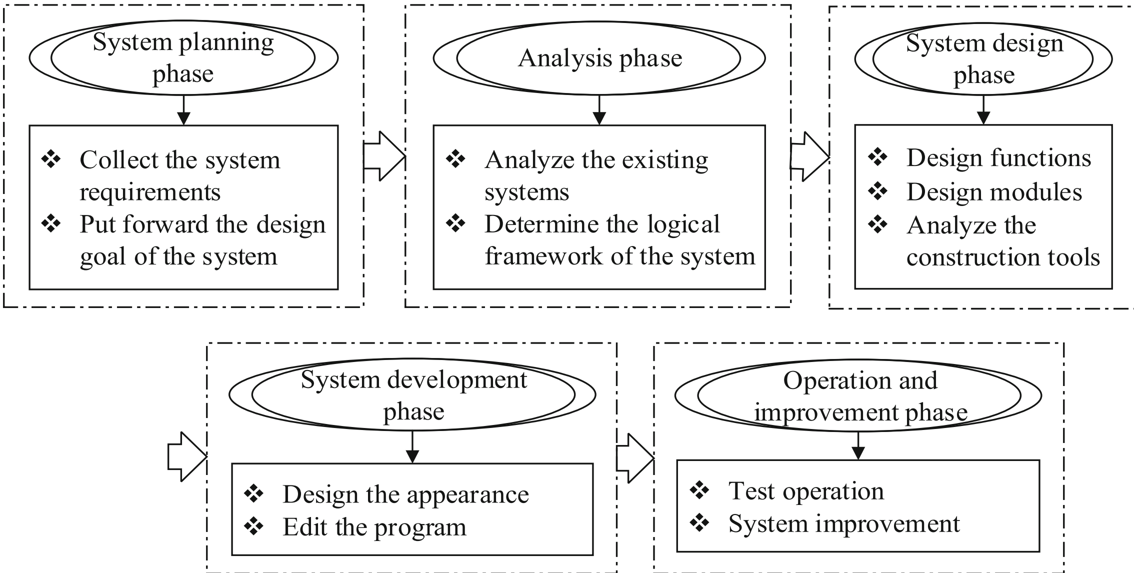


Fig. 7 Construction thought for an urban energy performance evaluation system

First, with the intensification of urban energy use and environmental problems, the number of studies on urban energy performance evaluation has increased year by year. In recent years, the growth trend has become more rapid, indicating that the attention paid to urban energy performance evaluation is increasing. The authors with the largest numbers of urban energy performance evaluation studies are from China, Belgium, and the USA. These countries provide more support to researchers in this field, and mutual collaboration occurs among these authors, which provides conditions for further studies. Italy, China, and the USA are the countries with the largest numbers of publications. It was apparent that developed countries and countries with higher energy consumption pay more attention to the issue of urban energy performance. High-frequency words such as “green,” “low carbon,” and “sustainability” reflect the goals and themes of studies on urban energy performance evaluation. Terms such as “energy performance,” “energy system,” “energy consumption and conservation,” “energy efficiency,” “environmental performance,” “economic performance,” and “social effect” expand the research perspectives of urban energy performance evaluation. The research content and the means of urban energy performance evaluation are illustrated by high-frequency words such as “city,” “performance evaluation,” “evaluation model and system,” “concept model,” “evaluation method,” “energy policy and strategy,” “energy management,” and “indicator system.”

Second, from the review results, the concept of urban energy performance lies in “performance” and should highlight the roles of urban production and living activities, the measurement datum of input-output, the measurement range of energy performance, and the regulating effects of other control variables. The evaluation indicators related to urban energy performance are identified in this paper and mainly include energy, capital, and labor inputs, economic outputs, average life expectancy (or life satisfaction), carbon dioxide emissions, and other pollutants. The influencing factors include industrial structure, energy price, population density, home car ownership, climate factors, Gini coefficient, health expenditure level, and unemployment rate. The evaluation indicators and influencing factors are different under different objects, contents, and objectives, but existing urban energy performance measurements fail to incorporate these evaluation indicators and influencing factors into the same framework.

Third, SFA, fuzzy comprehensive evaluation, DEA, regression analysis, and the Malmquist-Luenberger index are often used in studies related to urban energy performance evaluation. SFA and DEA are most commonly used to measure performance based on the gap between target and actual energy inputs or the gap between target and actual outputs. The difference between these two methods is that the former is a parametric method, but the latter is nonparametric. The fuzzy comprehensive evaluation method measures performance by assigning weights to the variables, and the regression analysis method uses various measurement models based on independent, dependent, and control variables. The Malmquist-Luenberger index is mainly used to reflect dynamic change trends. Each method has its own advantages and disadvantages. An evaluation system is the most convenient tool for urban energy performance information storage and calculation, but there is no professional evaluation system for urban energy performance.

Based on the above conclusions, future studies should focus on the following aspects. First, increases in urban energy consumption and in environmental, ecological, and social problems have led to a situation where traditional energy economic performance is no longer applicable to current demands for urban energy performance evaluation. Future studies should be guided by the actual development goals and development conditions of cities and expand their research perspectives and themes on urban energy performance evaluation.

Second, in future studies, the definition of the urban energy performance concept and the construction of a framework for urban energy performance evaluation indicators and influencing factors should regard the research perspectives of urban energy performance evaluation as a benchmark, enrich the contents, structure, and categories of concept, and include a comprehensive set of evaluation indicators and influencing factors. In addition, such studies should integrate the different variables into the same framework to evaluate urban energy performance with proper consideration of variable endogeneity problems.

Third, with the complexity of new frameworks for urban energy performance evaluation indicators and influencing factors, future urban energy performance evaluation methods should measure multiple inputs and multiple outputs, incorporate performance evaluation and factor analysis into the same method model, and reflect the regulatory roles of policies. Scientific evaluation results and performance differences would provide important references for policy formulation.

Fourth, in the era of Big Data and information, computer information management tools are already supporting all aspects of urban production and life. Therefore, future research and application of urban energy performance evaluation systems should be applied to manage basic information, energy consumption data, evaluation indicator data, influencing factor data, and evaluation results. Performance evaluation, performance analysis, and other functions also would be embedded in the evaluation system to meet the needs of urban development decision-makers and system users.

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