https://doi.org/10.15302/J-LAF-1-020096 Received Date | 2024-02-26 Accepted Date | 2024-05-06

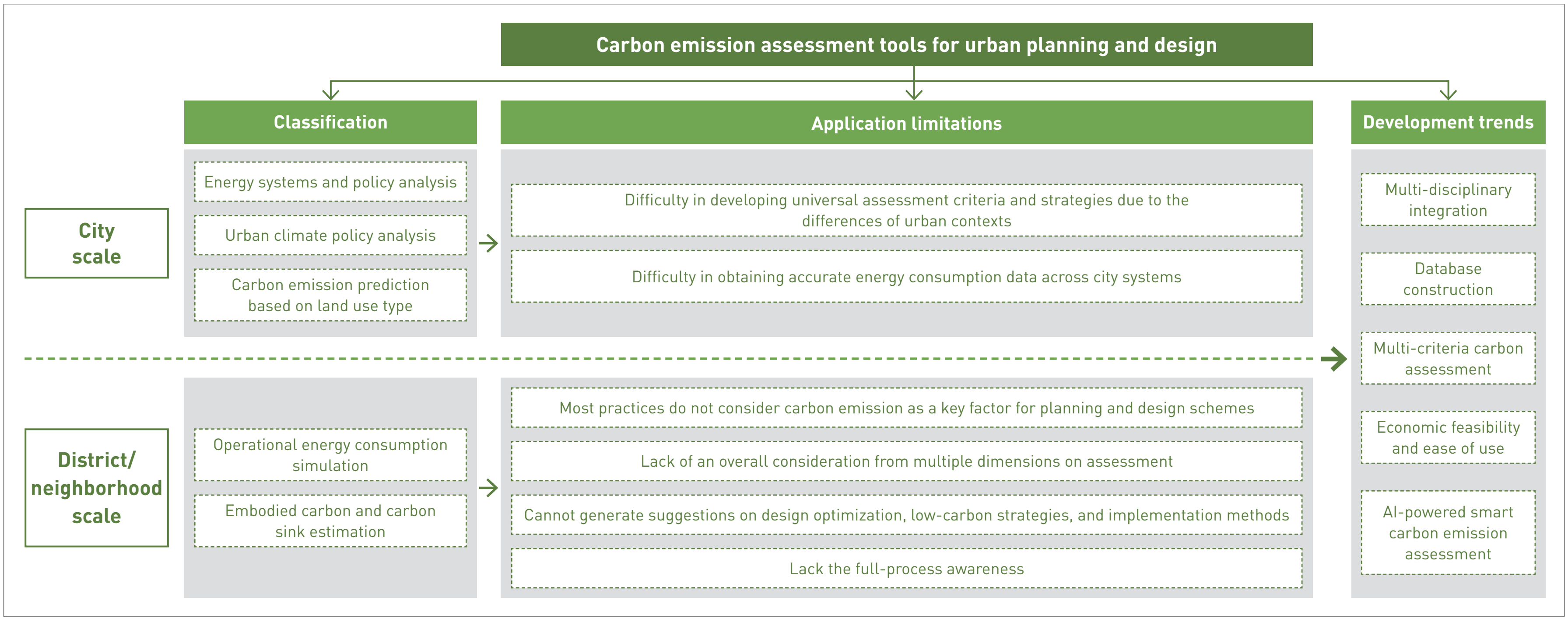
Towards Digitalized Urban Planning and Design of Low-Carbon Cities: Evolution and Application Review of Assessment Tools

Meng XU[1,2], Yue ZHONG[3], Yu YE[1,2,*]

1 College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China
2 Key Laboratory of Ecology and Energy-saving Study of Dense Habitat (Ministry of Education), Tongji University, Shanghai 200092, China
3 Arup International Consultants (Shanghai) Co., Ltd, Shanghai 200030, China

*CORRESPONDING AUTHOR
Address: 1239 Siping Road, Yangpu District, Shanghai 200092, China
Email: yye@tongji.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Facing the challenges of global climate change, the construction of low-carbon cities has become an inevitable pathway, where carbon emission assessment is a critical part to the transition towards digitalized urban planning and design of low-carbon cities. However, comprehensive review on carbon assessment tools applied to urban planning and design is absent. As a response, this paper selected and reviewed typical digital assessment tools of carbon emissions at both the city and district/neighborhood scales, and summarized their measuring dimensions and reference data. Currently, tools based on energy system planning and operational energy simulation dominate the field, while tools for carbon emission and carbon sink estimations based on land use types or materials are rapidly developing due to the increasing refinement of carbon emission assessments and shifts of decarbonization policies. At present, these tools are primarily used in energy planning and design, governmental decision-making, and building structural design and material choice, and their application in urban planning and design practice, especially in the early stages, remains limited. Hence, this study further underscored the limitations and potential development directions of existing carbon emission assessment tools by case studying low-carbon practices worldwide that have not utilized digital assessment tools—in the future, improving tools' flexibility and adaptability for diverse scenarios, building comprehensive databases, incorporating the calculation of operational carbon, embedded carbon, and carbon sinks, and aligning with the needs for multi-dimensional, multi-criteria, and full-process assessments should be put into more efforts.

KEYWORDS

Low Carbon Cities; Carbon Emission; Carbon Emission Assessment Tools; Urban Planning and Design; Digitalization; Carbon Sink

HIGHLIGHTS

- Summarizes five categories of carbon emission assessment tools at both city and district/neighborhood scales
- Summarizes the application scenarios, advantages and disadvantages, measuring dimensions, and reference data of the tools
- Points out the limitations of the tools and proposes the future development trend towards multi-disciplinary, multi-criteria, full-process, and intelligent estimations

RESEARCH FUNDS

- "An Intelligent Evaluation Model for Measuring Quality of Place With the Combined Application of Multi-sourced Urban Data and Deep Learning Algorithms", National Natural Science Foundation of China (No. 52078343)
- "2022 Industry-University Cooperation Collaborative Education Project", Ministry of Education and Shanghai Tongji Urban Planning and Design Institute Co., Ltd. (No. 220900155145615)
- Independent Research Project of "Key Laboratory of Ecology and Energy-saving Study of Dense Habitat (Tongji University)", Ministry of Education and Shanghai Tongji Urban Planning and Design Institute Co., Ltd. (No. KY-2022-LH-A02)

EDITED BY Tina TIAN, Yuting GAO

1 Introduction

With the promotion of carbon neutrality and carbon peaking goals, the construction of low-carbon cities and related quantitative assessments have become hot topics in the field of urban planning and design[1][2]. One important driver for promoting low-carbon concepts is global climate change. The Intergovernmental Panel on Climate Change (IPCC) points out that the net emissions of anthropogenic greenhouse gases have continued to rise over the past decade, with the average annual emissions higher than any previous decade[3]. Without additional climate change mitigation policies, global warming could lead to a temperature increase of 3.5°C by 2100[4]. Therefore, advancing the implementation of low carbon policies is of utmost urgency.

Currently, the focus of low-carbon urban construction at home and abroad has shifted from macro-level conceptual introduction and review towards the analysis of specific issues and the application of digital technologies at the micro level[5]~[7]. As the first step of carbon reduction actions, precise quantitative assessment of carbon emissions has increasingly been incorporated into urban planning and design. Analyzing the impact of urban spatial planning on carbon emissions and estimating the effectiveness of carbon-neutral action plans can help determine carbon reduction objectives and provide guidance for policy-making and planning design[8]. Emerging frameworks and tools for carbon emission assessment applicable at varied scales[9] enable digital carbon assessment for planning strategies and design schemes, progressively promoting the cross-integration of energy planning and urban planning design[10]~[12].

However, existing reviews on carbon assessment tools have several limitations. First, these reviews primarily focus on energy system planning and design, as well as life cycle assessments of buildings. Under climate policies, carbon emission has become a new quantitative indicator in urban planning and design practice. Since carbon assessment tools serving early-stage planning and design have been developed and applied in practice in recent years[13][14], there is a lack of comprehensive reviews on carbon assessment tools for urban planning strategies and design schemes[15][16]. Second, existing reviews often focus on a single scale or discipline, lacking cross-scale and interdisciplinary systematic analysis[13][14][17] from a macro-level comprehensive perspective that could better guide planners and designers in selecting appropriate carbon assessment tools based on specific usage scenarios and stages. Third, although the development of assessment tools sees a diversification trend, these tools are still less used in planning and design practice, the reasons behind which are worth exploring; in addition, the research on the application limitations and future development directions of different sorts of carbon assessment tools remains insufficient[18]~[20].

To address the aforementioned limitations, this paper systematically categorizes, reviews, and compares the functional features, assessment dimensions, and applicable scenarios of existing assessment tools for digitalized low-carbon urban planning and design, and discusses their application shortcomings in planning and design practice. Finally, the paper summarizes the development trends of various assessment tools and points out potential development directions to provide references for future research and practice of low-carbon planning and design.

2 Research Methods

Typical carbon assessment tools as the research subjects in this study were selected through the literature screening and validation by Google Scholar. Google Scholar offers extensive coverage, including both Chinese and English literature in the Architecture category from core-collection journals (e.g., SCI, A&HCI) and non-core collection journals, as well as conference papers.

First, initial searching was conducted by using both Chinese and English keywords, including "carbon assessment tools," "carbon emission evaluation," "low carbon urban planning," "low carbon urban design," "low-carbon city," "urban energy planning," "carbon-neutral city," "碳评估工具," "低碳评估指标体系," "碳评估工具综述," "零碳城市," "零碳规划," "减碳技术," and "碳中和城市规划." This study retrieved literature published after January 1, 1980 to December 31, 2023. And then frequently mentioned carbon assessment tools were selected from the search results. Citation counts and frequency of mentions reflect, to a certain extent, the gained attention and application of the tools. Meanwhile, the relatively new tools that were less mentioned in the retrieved literature were compared with conventionally typical tools, to select the relatively mature, highly innovative ones that can represent recent development trends. Finally, the obtained tools were preliminarily categorized, and tools with well-documented official descriptions in each category were retained for the final analysis.

3 Research Results

3.1 Overview of Assessment Tools

A total of 19 assessment tools were finally selected for the study, which are categorized into two major types by scale and function (Table 1). 1) Urban-scale tools that mainly aid in the formulation of larger-scale planning policies, by predicting carbon emissions, financial costs, and environmental impacts under different energy planning and master planning policy measures or various scenarios based on macroeconomic data and energy consumption data. 2) District-/neighborhood-scale tools that are mainly used to evaluate planning and design schemes at smaller scales[21] by predicting carbon emissions based on information such as building form and attributes, and climatic data.

The development and evolution of carbon assessment tools are closely related to the development of low-carbon policies and associated demands (Fig. 1). Carbon assessment tools at both city and district/neighborhood scales have been initially developed since the 1980s, witnessing a significant increase in number over the past decade, especially the district-/neighborhood-scale assessment tools. This reflects the trend of refined low-carbon assessments and the shift in decarbonization policy focus—from reducing energy demand and the carbon intensity of energy systems towards decreasing embodied carbon emissions and promoting ecological restoration to enhance carbon sinks[22].

3.2 City-Scale Carbon Assessment Tools

City-scale carbon assessment tools can be roughly classified into three categories by function: energy system and policy analysis, urban climate policy analysis, and carbon emission prediction based on land use types.

1) Tools for energy system and policy analysis. These tools are used to assess carbon emissions under different energy planning strategies and scenarios, predicting funding, costs, and the impact of environmental changes, primarily in areas of energy system, electricity, heating and cooling, etc.

2) Tools for urban climate policy analysis. These tools are of high comprehensiveness and typically used for cross-sectoral planning in construction, transportation, industry, etc.; although the numerical values used in calculations are relatively coarse, they can provide an overall picture to help decision-makers choose effective climate intervention measures.

3) Tools for carbon emission prediction based on land use types. These tools predict a city's carbon emissions under different development scenarios based on the changes of land use types of real plots, reflecting high-precision geographic spatial distribution characteristics and interactions by analyzing energy consumption data of different land use types. In recent years, many researchers have started exploring more refined carbon emission prediction methods[23], but which are still in early stages and require users

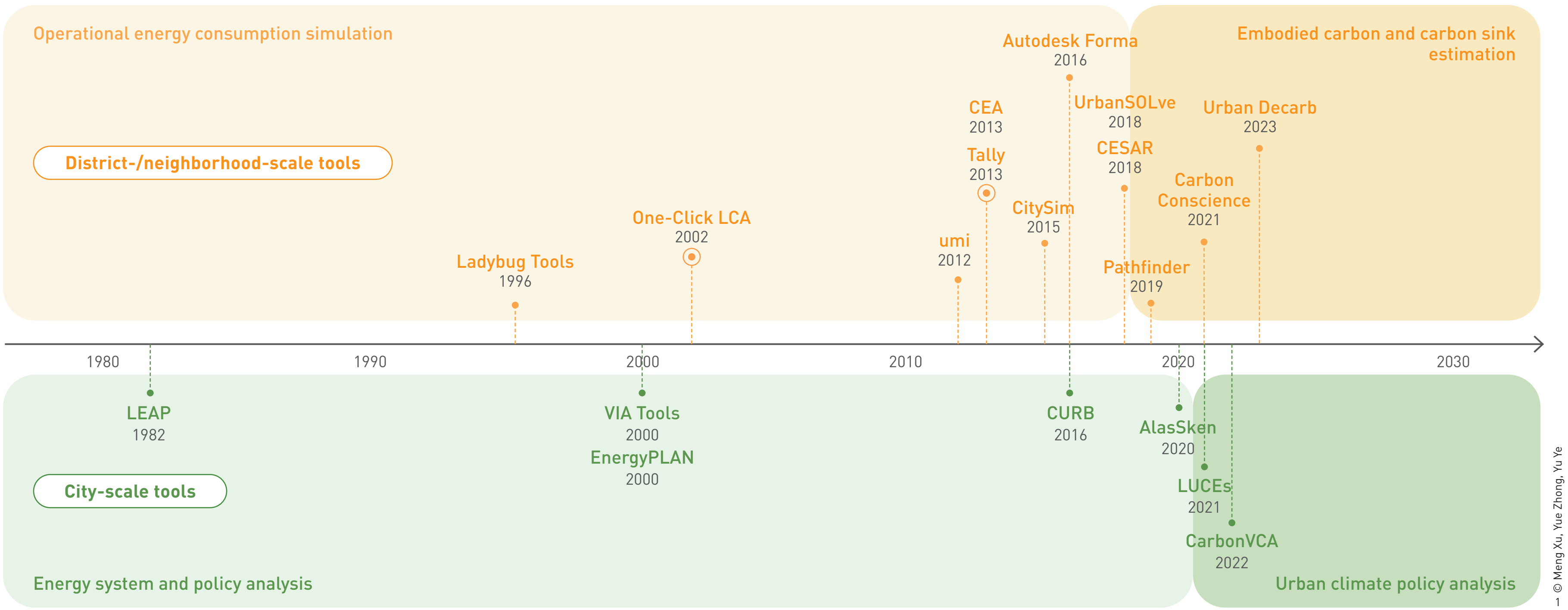
Table 1: Overview of carbon assessment tools

Category	Applicability	Tool	Developed year	Function description	Advantages/disadvantages	Source
City-scale tools						
Energy system and policy analysis	· Energy system simulation · Energy planning for heating and cooling, etc.	LEAP	1982	Scenario-based energy-environment econometric model	Simply consider energy system planning, poor guidance for urban spatial planning and design	Ref. [32]
		EnergyPLAN	2000	Design and evaluation tool for smart energy systems based on renewable energy		Ref. [46]
Urban climate policy analysis	· Comprehensive assessment of macro-level climate measures · Urban planning for buildings, transportation, industry, etc.	CURB	2016	Energy, emissions, and financial evaluation tool for different intervention measures	Outstanding comprehensiveness, applicable to global cities	Ref. [30]
		VIA Tool	2020	Evaluation tool for identity barriers and opportunities of integrated, cross-scaled climate strategies	Assess the implementation process and effects of climate measures, not supporting quantitative carbon emission assessment	Ref. [47]
		ALasSken	2020	Evaluation tool for the impact of urban climate measures and prediction of greenhouse gas emissions	Limited data and calculation methods, only applicable to cities in Finland	Ref. [31]
Carbon emission prediction based on land use types	· High-precision simulation of land-use type changes · Study and decision-making for residential, industrial, and other land-use types	LUCEs	2021	Urban-scale land-use carbon emission estimation model	High precision, but require extensive datasets of land use and energy consumption	Ref. [48]
		CarbonVCA	2022	Carbon emission calculation and prediction tool for actual micro-scale plots		Ref. [45]
District-/neighborhood-scale tools						
Category	**Applicability**	**Tool**	**Developed year**	**Function description**	**Advantages/disadvantages**	**Source**
Operational energy consumption simulation	· Quantifying carbon emissions and other sustainability indicators for early stages of planning and design · High-precision prediction on operational energy consumption for buildings and districts	Ladybug Tools	1996	Workflow for predicting operational energy loads through microclimate simulation	Suitable for small-scale site operational energy consumption simulation, not involving regional energy demands and energy system types	Ref. [33]
		umi (Urban Modeling Interface)	2012	Energy demand-and-supply analysis tool, including operational energy, embodied energy related to energy systems and building materials	Applicable for early and later stages of planning and design, supporting the analysis of operational energy consumption, embodied carbon emissions, daylighting, and other environmental performance	Ref. [25]

(Continued)

Table 1: Overview of carbon assessment tools (Continued)

District-/neighborhood-scale tools						
Category	**Applicability**	**Tool**	**Developed year**	**Function description**	**Advantages/disadvantages**	**Source**
Operational energy consumption simulation	· Quantifying carbon emissions and other sustainability indicators for early stages of planning and design · High-precision prediction on operational energy consumption for buildings and districts	CEA (City Energy Analyst)	2013	Tool for predicting spatio-temporal distribution changes in urban energy demand and optimizing energy system design	Highly integrated with geographic information systems, suitable for early stages of planning and design, with high-precision prediction	Ref. [34]
		CitySim	2015	Tool considering renewable energy conversion systems, energy demand for buildings, and high-precision supply simulation	Simulate energy consumption of large-scale areas with a high precision, not suitable for early stages of planning and design	Ref. [35]
		Autodesk Forma	2016	Cloud-based sustainability analysis tool	Suitable for early stages of planning and design, not considering building energy systems, user behaviors, etc.	Ref. [49]
		CESAR	2018	Building stock modeling tool for bottom-up prediction for energy transition strategies	Suitable for energy planning and design, supporting current energy demand analysis and future demand estimation	Ref. [26]
		UrbanSOLve	2018	Simulation tool for sunlight exposure and energy performance to assist block design decisions	Only suitable for early stages of planning and design, not considering building energy systems user behavior, etc.	Ref. [50]
Embodied carbon and carbon sink estimation	· Predicting carbon footprints based on land use type and materials · Urban spatial design such as buildings and landscapes	One-Click LCA	2002	Comprehensive toolset for building life cycle assessment, embodied carbon estimation, and design optimization	Simply measure building embodied carbon, applicable for multiple stages of design (including early ones)	Ref. [36]
		Tally	2013	Design decision tool for life cycle assessment of buildings by quantifying implicit environmental impact of building materials	Simply consider building embodied carbon	Ref. [51]
		Pathfinder	2019	Quantitative tool for greenhouse gas emissions and carbon sink potential in landscape and site design projects	Simply quantify landscape embodied carbon	Ref. [52]
		Carbon Conscience	2021	Assessment tool for embodied carbon emissions based on land use type and materials	Simply measure embodied carbon of buildings and landscapes, not considering other urban infrastructure	Ref. [29]
		Urban Decarb	2023	Integrated carbon assessment tool for evaluations of buildings, landscapes, infrastructure systems, etc.	Suitable for early stages of planning and design, supporting the evaluation of the entire urban system, but over-emphasizing scenario interactions and lacking detailed quantitative data	Ref. [28]



1. Development trends of carbon assessment tools (One-Click LCA and Tally, marked by circles, are early-developed tools for embodied carbon assessment of buildings).

having a high level of expertise (academic researchers mainly).

In summary, city-scale carbon assessment tools guide government policy-making by predicting carbon emissions. With the increasing trend of refined assessment of carbon emissions, predictions based on macro statistical data are relatively mature, whereas those upon local urban spatial characteristics requiring further efforts.

3.3 District-/neighborhood-Scale Carbon Assessment Tools

Over the past decade, carbon assessment tools at the district-/neighborhood-scale have become a focus of attention for universities and research institutions[10]. They combine energy system analysis and energy demand prediction to evaluate the carbon emissions and environmental performance of planning and design schemes[11][12][24]. Such tools can generally be divided into two categories: operational energy consumption simulation, and embodied carbon and carbon sink estimation.

1) Tools for operational energy consumption simulation. These tools are often developed in earlier years, and mainly used to predict the operational energy consumption of buildings and districts based on climate data and building forms and attributes. Some of such tools can assist early-stage design schemes from multiple sustainable dimensions (including carbon assessment), while others focus on predicting energy consumption and optimizing energy systems at the district/neighborhood scale and support high-precision real-time prediction of operational carbon emissions, considering urban morphological factors in energy consumption calculations.

2) Tools for embodied carbon and carbon sink estimation. Although a few operational energy consumption simulation tools (such as umi[25] and CESAR[26]) also support embodied carbon assessment, they can simply quantify the embodied energy consumption generated by building construction and renovation, yet without considering landscapes and other urban environmental factors. As full-life-cycle assessment of urban construction has been paid more and more attention[23], emerging carbon assessment tools increasing target assessing embodied carbon from operational carbon. They can predict embodied carbon and carbon sinks of projects at various scales based on data of land use types and materials[19][27], offering a more comprehensive perspective for the environmental impacts of large-scale urban planning and design projects. Among them, Urban Decarb[28] can conveniently perform comparative analysis of the differences of carbon emissions and costs between various design schemes, and are suitable for diverse types of design projects. The Carbon Conscience tool developed by Sasaki[29] can calculate the embodied carbon generated by buildings

and landscapes separately, supporting not only the estimation of carbon emissions and environmental impacts per unit under given land use scenarios at the early planning stages but also the calculation of carbon emissions and carbon sinks by building types, structures, materials, etc., at later design stages.

In summary, there is still a lack of comprehensive assessment tools at the district/neighborhood scale that consider both operational carbon and embodied carbon, while also integrating data of climate, energy systems, land use types, and materials.

3.4 Measuring Dimensions and Reference Data

Based on the energy demands, carbon emissions, and sustainable development elements of different sectors in cities, the study summarizes the 12 and 9 measuring dimensions of the city-scale and district-/neighborhood-scale carbon assessment tools, respectively (Table 2).

For the city-scale tools, building, industrial and manufacturing, commercial and business, and transportation are the main sectors of urban carbon emissions[19], which also constitute common dimensions among the carbon assessment tools. Other major dimensions include electricity, sewage treatment, and solid waste management.

City-scale carbon assessment tools quantitatively evaluate the above dimensions mainly based on macro energy consumption data in economy and land use. Both such types of data have long updating cycles and low accessibility that would fundamentally affect the accuracy and applicability of assessment results.

1) Economic energy consumption data are typically sourced from annual government statistical reports, and often updated every 2 or 3 years, resulting in a certain lag in data acquisition[30][31]. So for the globally universal tools, such as LEAP[32] and CURB[30], timely data acquisition and updates across global cities poses a significant challenge. To ensure data accuracy, these tools require users to input data from various sectors of the case city. On the contrary, tools developed for a specific country or region, such as ALasSken[31], are easier to access and update data from the government, and they are usually equipped with built-in databases that do not require additional data input from the user. Additionally, tools like LEAP allow users to develop extra functional programs based on cities' realities and specific assessment needs, enhancing the applicability of assessment tools.

2) Land use energy consumption data consist of land use type data and carbon emission coefficient for land use types. Land use type data also come from government agencies and are annually updated. However, carbon emission coefficients must be precisely measured based on the specific land use situations of the given city, which is crucial for the accuracy of carbon emission predictions.

At the district/neighborhood scale, simulation tools for operational energy consumption are mainly used to predict energy demand and usually combined with microclimate and thermal comfort assessments. Some tools can support energy system analysis and renewable energy assessments. Tools for early stages of planning and design also include other sustainable analysis modules (such as daylighting), providing designers with a more comprehensive lenses. In contrast, the embodied carbon and carbon sink estimation tools measure narrower dimensions, primarily focusing on buildings and landscapes, with less consideration of transportation, infrastructure, etc.

The tools for operation energy consumption simulation mainly refer to building form and attributes data and climate data, and the ones for embodied carbon and carbon sink estimation primarily refer to data of the land use types, materials, and structures of buildings, landscapes, and infrastructure (Table 3).

1) Climate data and building form and attributes data are accessible from meteorological statistics websites, OpenStreetMap, and official databases of cities[33]. Usually these data are input by users; in cases where the data do not align with the reality, designers need to validate and adjust by collecting data from additional sources such as satellite images, so as to improve data accuracy. The tools mainly for energy system optimization and demand-supply analysis (e.g., CEA[34], CitySim[35], CESAR[26], etc.) can utilize the information of building energy supply system types and user behavior data to conduct high-accuracy energy consumption calculation and prediction. These data can be extracted from OpenStreetMap, but which usually does not cover all the urban areas of a given city, requiring the supplement with census data for some tools[26].

2) There is no directly available data of land use type, site area, materials, site management, etc., for the embodied carbon and carbon sink estimation tools, which requires an integration of multidisciplinary knowledge with existing research and practical experiences. Meanwhile, databases need to be continuously updated with new knowledge and experience to meet the diverse project needs. For example, Carbon Conscience has established separate specialized building and landscape datasets[36]—the building dataset references existing tools for full-life cycle assessment of buildings, while the landscape dataset is derived from relevant academic research papers. In the absence of direct reference data, drawing on data sources from first-hand academic

Table 2: Summary of dimensions of carbon assessment tools

City-scale tools											
Tool	**Buildings**	**Industrial and manu-facturing**	**Commercial and trading**	**Transportation**	**Electricity**	**Heating and cooling**	**Sewage treatment**	**Solid waste recycling and treatment**	**Agriculture, forestry, animal Husbandry, and Fishery**	**Warehousing**	**Tele-communications**
LEAP	√	√	√	√							
EnergyPLAN		√	√		√	√					
CURB	√		√		√		√	√			
VIA Tools	√	√	√		√	√	√	√	√		
ALasSken	√	√	√				√	√	√		√
LUCEs	√	√	√	√					√	√	
CarbonVCA	√	√		√							

District-/neighborhood-scale tools								
Tool	**Operational energy demand**	**Microclimate and thermal comfort**	**Energy system design**	**Renewable energy**	**Daylighting**	**Embodied carbon in buildings**	**Embodied carbon and carbon sinks in landscapes**	**Embodied carbon in infrastructure**
Ladybug Tools	√	√		√				
umi	√				√	√		
CEA	√		√	√				
CitySim	√	√	√	√				
Autodesk Forma	√	√			√			
CESAR	√	√				√		
UrbanSOLve	√							
One-Click LCA						√		
Tally						√		
Pathfinder							√	
Carbon Conscience						√	√	
Urban Decarb						√	√	√

Table 3: Summary of referencing data for the district-/neighborhood-scale assessment tools

Category	Tool \ Data	Climate data	Building form	Building attribute	Building energy system	User behavior	Building material and structure	Land use type, area, and material
Operational energy simulation	Ladybug Tools	√	√					
	umi	√	√	√			√	
	CEA	√	√	√	√	√		
	CitySim	√	√	√	√	√		
	Autodesk Forma	√	√	√			√	
	CESAR	√	√	√	√	√	√	
	UrbanSOLove	√	√	√				
Estimation of embodied carbon and carbon sinks	One-Click LCA						√	
	Tally						√	
	Pathfinder							√
	Carbon Conscience						√	√
	Urban Decarb						√	√

research effectively improves the accuracy of embodied carbon and carbon sink estimations.

4 Discussion

4.1 Application Limitations of Carbon Assessment Tools

Carbon assessment tools have developed rapidly with a variety of measuring dimensions, but their application in specific planning decisions and design practices is still limited. Compared with district-/neighborhood-scale tools, city-scale carbon assessment tools see relatively mature applications, primarily for energy planning and climate planning decision-making, with less application in the early stages of planning and design. Therefore, this study collects and compares authentic cases of low carbon practices that do not utilize assessment tools, in order to identify the shortcomings of existing assessment tools.

Due to the significant disparity between countries and cities, it is challenging to develop universal standards and strategies of carbon emission assessment. This often necessitates the creation of context-specific assessment frameworks and standards[37], leading to the limited application of existing city-scale tools in urban planning decision-making. Cities in China and abroad have constructed their own assessment frameworks and implementation methods of low-carbon construction. For example, Tianjin, as one of China's low-carbon pilot cities, proposed its low-carbon assessment framework and indicators for urban planning with both carbon reduction and carbon sink goals[38], and explored a carbon reduction roadmap integrated with its existing territorial spatial planning framework[39]. Similarly, Malaysian cities have proposed their own frameworks and assessment systems of low-carbon city, to bridge the gap between government policies and the green city rating tools available in the market, so as to better guide cities in implementing carbon reduction measures[40]. However, the inability to obtain accurate data from other case cities makes these tools fail to be employed in broader regions.

At the district/neighborhood scale, carbon emissions are typically assessed alongside indicators such as microclimate/thermal comfort and daylight potential. Multi-dimensional assessment tools like Ladybug Tools[33] have already been effectively utilized at early stages of planning and design. Additionally, tools for embodied carbon and carbon sink estimation have become increasingly mature in the context of building materials and structural design, but their application in comprehensive urban planning and design is just beginning and gradually being incorporated into practice projects, such as Carbon Conscience[29].

The following limitations of district-/neighborhood-scale assessment tools are worth discussing.

First, most planning and design practices still do not consider carbon emission as a key factor yet; instead, treating it only as one of the evaluation options after the completion of design scheme.

Second, most tools focus on a single aspect of carbon emissions (operational carbon, or buildings' embodied carbon). However, urban planning and design requires an overall consideration on carbon emissions and carbon sinks from multiple urban systems, such as buildings, landscapes, and transportation; also, combined use of multiple tools would easily ignore the correlations between data. Therefore, a holistic approach to the assessment is necessary to help identify trends of correlations between various components. For example, the Lihu New City Planning Project in Wuxi improved existing assessment models and constructed a new carbon-neutral assessment system, which can simultaneously assess carbon emissions and carbon sinks[41]; in the case of the planning of Jinan Western New District, a planning scheme assessment was conducted on the accessibility of road network and the carbon emission potential of transportation[42]. These cases mark the gap of multi-dimensional carbon emission assessments for spatial planning and design among current assessment tools.

Third, most of the existing tools focus on qualifying carbon emission, and cannot offer design optimization suggestions, low-carbon strategies, and recommended implementation methods based on the assessment results. However, practical technical roadmaps and pathways in critical to its implementation. For example, the and practical cases of seven communities, including the Xietu community and other six communities in Shanghai developed their low-carbon renewal strategies and implementation paths by using traditional methods such as status surveys, carbon emission baseline assessments, and data analysis[43].

Finally, the district-/neighborhood-scale tools generally lack the full-process awareness and the monitoring and verification of carbon emissions during project management and operation. Some cities are currently exploring this. For instance, the Shanghai Digital Jianghai Industrial Park has constructed an overall control mechanism: by building a digital twin platform for intelligent carbon reduction, carbon emission data can be collected and fed back from aspects of building energy use, transportation, carbon sinks, etc., forming a technical framework of carbon reduction in urban neighborhoods covering the full-process from planning, construction to management and operation[44].

In summary, both city- and district-/neighborhood-scale carbon assessment tools should improve their comprehensiveness and flexibility to make them suitable for more diverse scenarios and to assist planning and design practices more accurately and efficiently.

4.2 Trends of Carbon Assessment Tool Development

Based on the above comparative analysis, this paper summarizes the future development trends of assessment tools for digitalized low-carbon urban planning and design as follows.

First, enhancing tools' practicality by promoting the interdisciplinary integration, to provide optimized, cohesive design solutions for carbon emission issues. At both the city and district/neighborhood scales, future efforts could delve into the development of comprehensive digital assessment tools that integrate knowledge from architecture, planning, landscape, transportation, structural engineering, MEP (mechanical electrical, and plumbing), and sustainability.

Second, database construction is the key to improving the application breadth and result precision of carbon assessment tools. For city-scale tools, the open access to data from multiple sources can facilitate the database building that contain assessment standards and strategies for different countries and cities, thereby increasing the tools' flexibility and competitiveness and minimizing the waste of resources and time caused by duplicated development. Although the district-/neighborhood-scale tools share some energy and material data, establishing comprehensive and continuously updated databases remains challenging. In addition, studies using cross-scale data for refined assessments at both scales offer a new perspective for carbon assessment. For example, city-scale tools are used in bottom-up digital carbon assessments of micro sites based on land use data[45]; using city-scale data (e.g., census data), district-/neighborhood-scale tools are employed in site-specific carbon assessments through a combination with GIS[26][34].

Third, the research on multi-criteria low-carbon assessment needs to be deepened. The use of multi-criteria assessment methods—such as considering the complexity of circular economy and carbon tracking, and the dynamics of carbon sinks influenced by climate change and vegetation growth cycle—can maximize the simulation performance of carbon emissions of authentic projects.

Fourth, improving the economic feasibility and convenience of carbon assessment tools. In the application of carbon assessment tools, calculating the payback period and costs will help investors balance different factors to ensure that the selected solution meets the low-carbon and energy-saving requirements and is economically viable. In addition, visualized forms and displays can help investors and designers better understand the carbon emissions between different design schemes, facilitating option comparison and decision-making.

Fifth, with the advancement and widespread application of artificial intelligence (AI) technology, carbon assessment tools will also usher in the iterative innovation of intelligence in digital future. With the help of AI algorithms, large amounts of data can be processed quickly, greatly enhancing the efficiency of calculations related to energy simulation. AI can also be utilized for environmental predictions, such as forecasting climate changes by training past climate data, to better help decision makers formulate and implement low-carbon policies.

4.3 Research Limitations

This study collected carbon tools through literature screening on Google Scholar. This may have led to the exclusion of some emerging carbon assessment tools, especially those that are less mentioned in the literature but have recently arisen owning to the advent of AI. Also, in studying global low-carbon urban planning and design cases, the methods of literature review and information searching were mainly used, where a systematic approach to comprehensively examine the application cases of carbon assessment tools needs more efforts in future research.

5 Conclusions

This study systematically categorized and compared the characteristics and application of the carbon assessment tools for digitalized low-carbon urban planning and design. Overall, the application of these tools at multiple stages of planning and design is of great significance to the construction of low-carbon cities. At the policy-making stage, carbon assessment tools can predict the city's carbon emissions under different development scenarios, visions, and measures, helping decision-making on carbon reduction options. At the early stages of planning and design, many assessment tools can measure the carbon emissions of conceptual design schemes from the beginning of the project, including embodied carbon, and life-cycle carbon sinks and operational carbon. At the mid-to-late stages, many carbon assessment tools can quickly and accurately simulate the carbon emissions of design schemes. At the post-construction stage, some carbon assessment tools can continuously track the operational carbon of the project, providing constructive suggestions for future design optimization. In the future, carbon assessment tools will see advance in global applicability, multidisciplinary coverage, full life-cycle calculation, economic balance, and data visualization. The combination of AI and other intelligent technologies will greatly increase the efficiency of carbon assessment in practice and enable carbon assessment tools to better support urban planning and design practices.

ACKNOWLEDGEMENTS

The authors would like to express sincere gratitude to fellow student Yuxuan Liu for her contribution in tool retrieval and case collection.

Competing interests | The authors declare that they have no competing interests.

REFERENCES

[1] Wang, Y., Bian, T., & Huang, X. (2021). Research on time–space differences in the prediction of carbon peaking of China's comprehensive economic zones. *Landscape Architecture Frontiers*, 9(6), 24–43.

[2] Hewlett, M. (2014). Eco-low carbon urban planning methodology. *Landscape Architecture Frontiers*, 2(3), 70–75.

[3] Intergovernmental Panel on Climate Change (IPCC). (2022). Summary for Policymakers. *Climate Change 2022: Mitigation of Climate Change. Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–48). Cambridge University Press.

[4] Intergovernmental Panel on Climate Change (IPCC). (2023). 2023: Sections. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 35–115). IPCC.

[5] Yang, L., & Li, Y. (2013). Low-carbon city in China. *Sustainable Cities and Society*, (9), 62–66.

[6] Jiang, W., & Kang, W. (2019). A review on the low-carbon city study: Development and trends. *Chinese Journal of Urban and Environmental Studies*, 7(2), 1950006.

[7] Mauree, D., Naboni, E., Coccolo, S., Perera, A. T. D., Nik, V. M., & Scartezzini, J.-L. (2019). A review of assessment methods for the urban environment and its energy sustainability to guarantee climate adaptation of future cities. *Renewable and Sustainable Energy Reviews*, (112), 733–746.

[8] Wang, S., Gao, S., Huang, Y., & Shi, C. (2020). Spatiotemporal evolution of urban carbon emission performance in China and prediction of future trends. *Journal of Geographical Sciences*, 30(5), 757–774.

[9] Lai, S., Lu, J., Luo, X., & Ge, J. (2022). Carbon emission evaluation model and carbon reduction strategies for newly urbanized areas. *Sustainable Production and Consumption*, (31), 13–25.

[10] Huang, Z., Yu, H., Peng, Z., & Zhao, M. (2015). Methods and tools for community energy planning: A review. *Renewable and Sustainable Energy Reviews*, (42), 1335–1348.

[11] Markovic, D., Cvetkovic, D., & Masic, B. (2011). Survey of software tools for energy efficiency in a community. *Renewable and Sustainable Energy Reviews*, 15(9), 4897–4903.

[12] Torabi Moghadam, S., Delmastro, C., Corgnati, S. P., & Lombardi, P. (2017). Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches. *Journal of Cleaner Production*, (165), 811–827.

[13] Ng, S. T., Chen, Y., & Wong, J. M. W. (2013). Variability of building environmental assessment tools on evaluating carbon emissions. *Environmental Impact Assessment Review*, (38), 131–141.

[14] Fenner, A. E., Kibert, C. J., Woo, J., Morque, S., Razkenari, M., Hakim, H., & Lu, X. (2018). The carbon footprint of buildings: A review of methodologies and applications. *Renewable and Sustainable Energy Reviews*, (94), 1142–1152.

[15] Li, L. (2021). Integrating climate change impact in new building design process: A review of building life cycle carbon emission assessment methodologies. *Cleaner Engineering and Technology*, (5), 100286.

[16] Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on Life Cycle Assessment, Life Cycle Energy Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Applied Energy*, (143), 395–413.

[17] Albuquerque, F. D. B., Maraqa, M. A., Chowdhury, R., Mauga, T., & Alzard, M. (2020). Greenhouse gas emissions associated with road transport projects: Current status, benchmarking, and assessment tools. *Transportation Research Procedia*, (48), 2018–2030.

[18] Gao, H., Wang, X., Wu, K., Zheng, Y., Wang, Q., Shi, W., & He, M. (2023). A review of building carbon emission accounting and prediction models. *Buildings*, 13(7), 1617.

[19] Udara Willhelm Abeydeera, L. H., Wadu Mesthrige, J., & Samarasinghalage, T. I. (2019). Global research on carbon emissions: A scientometric review. *Sustainability*, 11(14), 3972.

[20] O'Regan, A. C., & Nyhan, M. M. (2023). Towards sustainable and net-zero cities: A review of environmental modelling and monitoring tools for optimizing emissions reduction strategies for improved air quality in urban areas. *Environmental Research*, (231), 116242.

[21] Chan, E., Conejos, S., & Wang, M. (2017). Low Carbon Urban Design: Potentials and Opportunities (pp. 75–88). In: S. Dhakal & M. Ruth (Eds.), *Creating Low Carbon Cities*. Springer.

[22] Arup. (2022). *Reduce, restore, remove: A call to action*.

[23] Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P.-S. (2022). Strategies to achieve a carbon neutral society: A review. *Environmental Chemistry Letters*, 20(4), 2277–2310.

[24] Gao, S., & Zhang, H. (2020). Urban planning for low-carbon sustainable development. *Sustainable Computing: Informatics and Systems*, (28), 100398.

[25] Fonseca, J. A., & Schlueter, A. (2015). Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts. *Applied Energy*, (142), 247–265.

[26] Wang, D., Landolt, J., Mavromatidis, G., Orehounig, K., & Carmeliet, J. (2018). CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies. *Energy & Buildings*, (169), 9–26.

[27] Han, Y., Zhang, S., & Yin, L. (2019). Quantifying the carbon storage capacity and its spatial distribution patterns of green spaces in a metropolitan area: A case study of Seoul, South Korea. *Landscape Architecture Frontiers*, 7(2), 55–65.

[28] Henning Larsen. (2023, April 20). *Urban Decarb: New Digital Tool Brings Carbon into Focus on the Urban Scale*.

[29] Sasaki. (2021). *Introducing the carbon conscience App*.

[30] The World Bank. (2016, September 22). *The CURB tool: Climate action for urban sustainability*.

[31] Carbonneutralfinland. (2023). *Municipalities' greenhouse gas emission scenario tool has been updated – agricultural actions included*.

[32] Stockholm Environment Institute. (2022). *LEAP: The Low Emissions Analysis Platform* [Software version: 2020.1.107]. Somerville, MA, USA.

[33] Natanian, J., & Auer, T. (2020). Beyond nearly zero energy urban design:

A holistic microclimatic energy and environmental quality evaluation workflow. *Sustainable Cities and Society*, (56), 102094.

[34] Chair of Architecture and Building Systems, ETH Zurich. (n.d.). *City Energy Analyst (CEA)*.

[35] Mutani, G., Coccolo, S., Kaempf, J., & Bilardo, M. (2018). *CitySim Guide: Urban Energy Modelling by Mutani, Guglielmina*. Createspace Independent Publishing Platform.

[36] One-Click LCA. (2023). *One-Click LCA for construction and manufacturing*.

[37] Yu, D., Zhou, X., Qi, H., & Qian, F. (2023). Low-carbon city planning based on collaborative analysis of supply and demand scenarios. *City and Built Environment*, 1(1), 7.

[38] Lu, L., Tian, Y., Zhang, L., & Liu, Y. (2011). Study on low-carbon assessment indicator system of urban planning of Tianjin. *City Planning Review*, 35(S1), 26–31.

[39] Lin, C., Zhu, W., Zhang, Y., & Wu, C. (2022). Methods and practice of territorial spatial planning toward the goal of "peak carbon emissions and carbon neutrality": The case study of Tianjin. *Urban Planning Forum*, (S2), 229–234.

[40] Ministry of Energy, Green Technology and Water (KeTTHA), & GreenTech Malaysia. (2017). *Low Carbon Cities Framework (Version 2)*.

[41] Wu, Z., Zhao, Z., Gan, W., Zhou, S., Dong, W., & Wang, M. (2023). Achieving carbon neutrality through urban planning and design. *International Journal of Environmental Research and Public Health*, 20(3), 2420.

[42] An, Q., Sheng, S., Zhang, H., Xiao, H., & Dong, J. (2019). Research on the construction of carbon emission evaluation system of low-carbon-oriented urban planning scheme: Taking the West New District of Jinan City as example. *Geology, Ecology, and Landscapes*, 3(3), 187–196.

[43] Yu, X., He, J., Zhu, D., & Wang, D. (2022). Path and practice of low-carbon urban renewal: A case study of seven communities in Shanghai. *Urban Planning Forum*, (4), 111–119.

[44] Wu, H., Lin, C., Chen, Y., & Weng, T. (2022). Technical framework and implementation strategy for carbon reduction in urban districts based on whole process management and control: The case of Shanghai Jianghai Digital Industrial Park. *Urban Planning Forum*, (S2), 59–65.

[45] Yao, Y., Sun, Z., Li, L., Cheng, T., Chen, D., Zhou, G., Liu, C., Kou, S., Chen, Z., & Guan, Q. (2023). CarbonVCA: A cadastral parcel-scale carbon emission forecasting framework for peak carbon emissions. *Cities*, (138), 104354.

[46] EnergyPLAN. (2022). *EnergyPLAN—Advanced analysis of smart energy systems*.

[47] C40 Cities Climate Leadership Group. (2020). *Vertically-integrated climate action tools*.

[48] Zhou, Y., Chen, M., Tang, Z., & Mei, Z. (2021). Urbanization, land use change, and carbon emissions: Quantitative assessments for city-level carbon emissions in Beijing–Tianjin–Hebei region. *Sustainable Cities and Society*, (66), 102701.

[49] Autodesk. (2024). *Autodesk Forma: Cloud-based software for early-stage planning and design*.

[50] Nault, E., Waibel, C., Carmeliet, J., & Andersen, M. (2018). Development and test application of the UrbanSOLve decision-support prototype for early-stage neighborhood design. *Building and Environment*, (137), 58–72.

[51] Building Transparency. (2023). *Tally*.

[52] Climate Positive Design. (n.d.). *Measure + improve our carbon impact*.

https://doi.org/10.15302/J-LAF-1-020096 收稿日期 | 2024-02-26 录用日期 | 2024-05-06 中图分类号 | TU986 文献标识码 | A

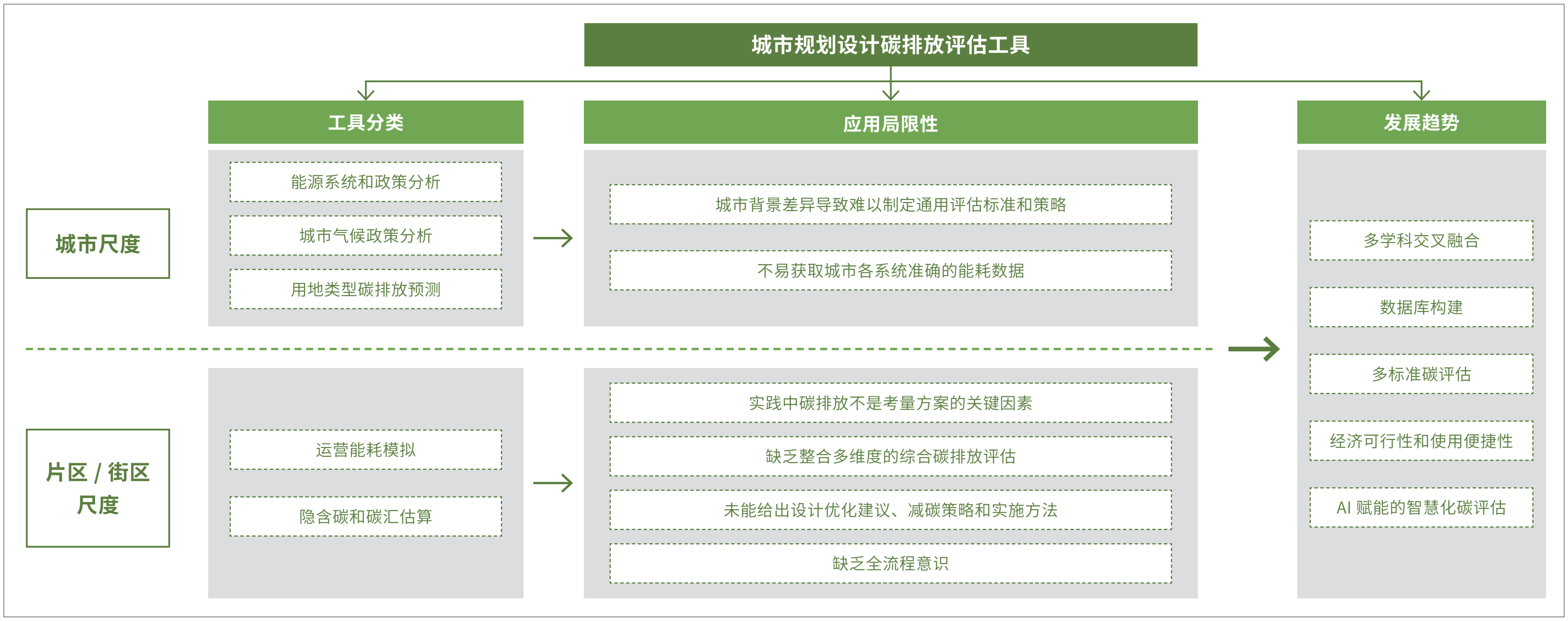
迈向数字化的低碳城市规划设计：碳排放评估工具演进与应用回顾

徐萌[1,2]，仲玥[3]，叶宇[1,2,*]

1 同济大学建筑与城市规划学院，上海 200092
2 同济大学高密度人居环境与生态节能教育部重点实验室，上海 200092
3 奥雅纳工程咨询（上海）有限公司，上海 200030

*通讯作者
地址：上海市杨浦区四平路1239号
邮编：200092
邮箱：yye@tongji.edu.cn

图文摘要



摘要

面对全球气候变化带来的挑战，低碳城市建设成为不可避免的趋势。在向数字化低碳城市规划设计方向转型的过程中，碳排放量化评估是关键一环。然而，目前缺乏对应用于城市规划设计的碳排放评估工具的综合阐述和分析。因此，本文分别在城市尺度和片区 / 街区尺度上对多种典型的数字化碳排放评估工具进行了综述，并总结了工具评估的维度和参考依据。总的来说，现阶段基于能源系统规划和运营能耗模拟的评估工具仍占主导；随着碳排放预测的精细化发展趋势和脱碳政策重点的转变，基于用地类型和材料的碳排放预测和碳汇估算工具也发展迅速。然而，这些工具目前主要应用于能源规划设计、政府决策、建筑结构设计和材料选择，在城市规划设计实践项目中的应用有限，特别是在初期阶段。因此，本研究继而通过分析未应用数字化评估工具的低碳实践案例，指出了现有碳排放评估工具的应用局限性和潜在的发展方向：未来，应提高工具的灵活性和场景适应性，构建完善的数据库，兼顾运营碳、隐含碳和碳汇计算，契合多维度、多标准、全流程的评估需求。

关键词

低碳城市；碳排放；碳排放评估工具；城市规划设计；数字化；碳汇

文章亮点

- 从城市和片区／街区两个尺度总结了五类碳排放评估工具
- 梳理归纳了碳排放评估工具的适用场景、优缺点、维度和参考数据
- 指出了碳排放评估工具的应用局限性，提出了其多学科、多标准、全流程、智慧化的发展趋势

基金项目

- 国家自然科学基金面上项目“基于多源数据和深度学习的公共空间品质评价模型与设计支持研究”（编号：52078343）
- 上海同济城市规划设计研究院有限公司2022年教育部产学合作协同育人项目（编号：220900155145615）
- 教育部重点实验室及上海同济城市规划设计研究院有限公司联合自主课题“高密度人居环境生态与节能”（编号：KY-2022-LH-A02）

编辑 田乐，高雨婷

1 引言

随着碳中和碳达峰目标的推行，低碳城市建设和量化评估成为城市规划和设计领域的关注焦点[1][2]。其中全球气候变化是推行低碳理念的一个重要原因。政府间气候变化专门委员会指出，人为温室气体净排放总量在过去十年间持续上升，平均年温室气体排放量高于之前任何十年[3]；如果没有实施额外的气候变化缓解政策，2100年全球变暖导致的升温可能达到3.5℃[4]。因此推进低碳政策的实行刻不容缓。

目前，国内外低碳城市建设的重点已从宏观层面的概念梳理逐渐转向微观层面的具体问题分析和数字化技术的运用[5]~[7]。作为减碳行动的第一步，碳排放精准量化评估也逐渐被纳入到城市规划和设计中。通过分析城市空间规划对碳排放的影响，进而估算碳中和行动计划的效果，有助于确定碳减排目标，为政策制定和规划设计提供指引[8]。近些年涌现出应用于各个尺度的多样化碳排放评估框架和工具[9]可对规划策略和设计方案进行数字化碳排放评估，逐步实现了能源规划设计和城市规划设计的交叉整合[10]~[12]。

然而，现有的碳排放评估工具（下文简称为“评估工具”）相关综述研究主要存在以下几点局限性。首先，对评估工具的综述主要关注能源系统规划设计和建筑全生命周期评估两方面。气候政策导向下的碳排放是城市规划和设计实践的新兴量化指标，而服务于前期规划和设计的评估工具也在近几年才被研究开发并开始运用到实践中[13][14]，因此对城市规划策略和设计方案的评估工具的综合阐述存在空白[15][16]。第二，现有的综述研究往往聚焦单一尺度或学科，缺乏跨尺度、跨学科的系统分析[13][14][17]以提供宏观的综合视角，并更精准地指导规划设计师根据使用场景和阶段选取合适的评估工具。第三，评估工具虽呈多样化发展趋势，但仍未广泛应用到规划设计实践中，这背后的原因是值得探索的，而且目前对于各类评估工具的应用局限性和未来发展方向的研究仍旧匮乏[18]~[20]。

针对以上研究局限性，本文从功能特点、评估维度和适用场景等方面对数字化低碳城市规划设计评估工具进行系统性梳理和比较研究，并根据评估相关工具在规划设计实践中的具体应用情况探讨其存在的不足；最后，本文将总结各类评估工具的发展趋势，指明潜在发展方向，为未来低碳城市规划设计研究和实践提供参考。

2 研究方法

本文利用谷歌学术进行文献筛选和验证，从现有文献中选取典型的评估工具作为研究对象。谷歌学术文献覆盖度高，不仅涵盖中、英文文献，而且可以检索建筑学科内除SCI、A&HCI等核心期刊外的其他期刊和会议论文。

首先，研究在谷歌学术中检索了1980年1月1日至2023年12月31日发表的文献，检索关键词包括“carbon assessment tools”“carbon emission evaluation”“low carbon urban planning”“low carbon urban design”“low-carbon city””urban energy planning”“carbon-neutral city”“碳排放评估工具”“低碳评估指标体系”“碳排放评估工具综述”“零碳城市”“零碳规划”“减碳技术”“碳中和城市规划”。鉴于文献引用量和提及频率在一定程度上反映了相应工具的受关注度和应用情况，随后在检索结果中选取多次被提及的评估工具。此外，本文将检索到的文献中提及频率较低的新兴工具与以往的典型工具进行比较，在其中选取了部分创新性强、代表近期发展趋势且开发相对成熟的工

具。最后，对所得工具进行初步分类，每类中官方介绍较为详细、完善的工具被保留并用于最终分析。

3 研究结果

3.1 评估工具概述

本文共检索到19个评估工具，按照尺度和功能将其划分为两大类（表1）：第一类工具主要用于辅助城市尺度的规划政策制定，基于宏观经济数据和能耗数据，预测不同能源规划和总体规划的政策措施下或多种情景下的碳排放量、资金成本消耗和环境影响等；第二类工具主要用于评估片区／街区尺度的规划设计方案[21]，基于建筑形态和属性、气候数据等信息进行碳排放预测。

碳评估工具的开发和演进与低碳政策及相关需求的发展息息相关（图1）。首先，城市和片区／街区尺度上的碳评估工具从20世纪80年代开始出现，在近十年显著增多。片区／街区尺度的评估工具近些年的发展增速尤为明显，这反映了低碳评估精细化发展趋势，以及脱碳政策重点的转变，即由减少能源需求和能源系统的碳排放强度转向减少隐含碳排放和修复生态环境以增加碳汇[22]。

3.2 城市尺度碳评估工具

按照功能，城市尺度的碳评估工具主要分为能源系统和政策分析、城市气候政策分析和基于用地类型的碳排放预测三类。

1）能源系统和能源政策分析类工具：这类工具用于评估不同能源规划战略和情景下的碳排放，预测资金、成本和对环境变化的影响，主要涉及能源系统及电力、供热制冷等相关领域。

2）城市气候政策分析类工具：这类工具的综合性较强，通常涉及建造业、交通运输、工业等跨系统规划。虽然计算结果的精度存疑，但可以综合考量整体图景，帮助决策者选择有效的气候干预措施。

3）基于用地类型的碳排放预测类工具：这类工具基于真实地块的土地利用类型变化来预测城市在不同发展情景下的碳排放水平，可通过分析不同用地类型的能耗数据反映高精度的地理空间分布特征和相互作用。近年来，大量研究学者着手探索更加精细化的碳排放预测方法[23]，

表 1：碳评估工具概览

城市尺度工具						
分类	**适用范围**	**工具名称**	**开发年份**	**功能描述**	**优劣势**	**来源**
能源系统和政策分析	· 能源系统仿真模拟 · 供热制冷等能源规划	LEAP	1982	基于情景分析的能源－环境计量经济模型	只考量能源系统规划，缺乏对城市空间规划设计的指导	参考文献 [32]
		EnergyPLAN	2000	基于可再生能源的智慧能源系统的设计和评估工具		参考文献 [46]
城市气候政策分析	· 综合性强的宏观气候措施影响评估 · 建筑、交通、工业等方面的城市规划	CURB	2016	针对不同干预措施的能源、排放和资金评估工具	综合性强，可应用于全球城市	参考文献 [30]
		VIA Tool	2020	纵向一体化气候战略的障碍和机遇评估工具	评估气候措施实施过程和效果，不涉及碳排放量化评估	参考文献 [47]
		ALasSken	2020	城市气候措施影响评估和温室气体排放预测工具	数据和计算方法局限，只适用于芬兰各城市	参考文献 [31]
基于用地类型的碳排放预测	· 高精度用地类型变化模拟 · 住宅、工业等用地类型研究及决策制定	LUCEs	2021	城市尺度土地利用碳排放量估算模型	精细化程度高，但需要庞大的土地利用和能耗数据集	参考文献 [48]
		CarbonVCA	2022	针对真实微观地块用地类型的碳排放核算和预测工具		参考文献 [45]

（续表见下页）

表 1：碳评估工具概览（接上表）

片区／街区尺度工具						
分类	**适用范围**	**工具名称**	**开发年份**	**功能描述**	**优劣势**	**来源**
运营能耗模拟	· 量化规划设计初期阶段的碳排放和其他可持续指标 · 高精度预测建筑和片区的运营能源消耗	Ladybug Tools	1996	基于微环境模拟的运营能源负荷预测工作流	适用于小尺度地块运营能耗模拟，未涉及区域能源需求和能源系统类型	参考文献 [33]
		umi (Urban Modeling Interface)	2012	能源需求和供应分析工具，包括能源系统和建筑材料相关的隐含能源	服务于规划设计初期和后期阶段，兼顾运营能耗、建筑隐含能耗、日光照明等多方面环境表现	参考文献 [25]
		CEA (City Energy Analyst)	2013	区域能源需求的时空分布变化预测和能源系统优化设计工具	和地理信息系统结合程度高，适用于规划设计初期阶段，可进行高精度预测	参考文献 [34]
		CitySim	2015	考量可再生能量转换系统、针对建筑的能源需求和高精度供应模拟的工具	以较高的精度模拟大规模区域的能耗，不适合规划设计初期阶段	参考文献 [35]
		Autodesk Forma	2016	基于云计算的可持续性分析工具包	适用于规划设计初期阶段，未将建筑能源系统、使用者行为等数据纳入分析	参考文献 [49]
		CESAR	2018	针对能源转型策略的、自下而上的建筑存量建模工具	适用于能源规划设计，兼顾当前能源需求识别与未来能源需求预测	参考文献 [26]
		UrbanSOLve	2018	辅助街区设计决策的日照和能耗表现模拟工具	只适用于规划设计初期阶段，未将建筑能源系统、使用者行为等数据纳入分析	参考文献 [50]
隐含碳和碳汇估算	· 根据用地类型和材料预测碳足迹 · 建筑、景观等城市空间设计	One-Click LCA	2002	综合性的建筑全生命周期评估、隐含碳估算和设计优化工具集	只衡量建筑的隐含碳，适用于多个设计的阶段（包括初期设计）	参考文献 [36]
		Tally	2013	量化建筑材料隐含环境影响，可进行全生命周期评估的设计决策工具	只考虑建筑的隐含碳	参考文献 [51]
		Pathfinder	2019	景观和场地设计项目的温室气体排放量和封存潜力量化工具	只量化景观的隐含碳	参考文献 [52]
		Carbon Conscience	2021	基于用地类型和材料的隐含碳排放评估工具，可衡量隐含碳成本、植物固碳量等	只衡量建筑和景观的隐含碳，未将其他城市基础设施纳入分析	参考文献 [29]
		Urban Decarb	2023	一体化碳评估工具，可面向建筑、景观和基础设施系统等进行评估	适用于规划设计初期阶段，面向整个城市系统的评估，但侧重场景交互，缺乏详细的量化数据	参考文献 [28]

但其发展尚处于起步阶段，对使用者的专业水平要求较高，目前主要服务于研究人员。

综上，城市尺度碳评估工具通过预测碳排放对政府部门的政策制定起到指导作用。碳排放预测呈现精细化趋势，基于宏观统计数据的预测相对成熟，而基于微观地块和城市空间特征的碳排放预测仍待探索。

3.3 片区／街区尺度碳评估工具

近十年来，片区／街区尺度的碳评估工具已成为高校和研究机构关注的重点[10]，结合能源系统分析和能源需求预测评估规划设计方案的碳排放和环境表现[11][12][24]。现有的碳评估工具大致可分为运营能耗模拟与隐含碳和碳汇估算两大类。

1）运营能耗模拟类工具：此类工具出现较早，主要根据气候信息和建筑特征等数据预测建筑和片区的运营能耗。其中，一部分工具致力于从多个可持续维度的评估（包括碳评估）来辅助早期方案设计；另外一部分工具侧重于片区／街区尺度的能耗预测和能源系统优化，可支持高精度实时运营碳排放的预测，并将城市形态作为重要因素纳入能耗计算。

2）隐含碳和碳汇估算类工具：虽然有少数运营能耗模拟类工具（如umi[25]和CESAR[26]）也兼具隐含碳评估的功能，但其只量化建筑建设和改造产生的隐含能源消耗，不涉及景观等其他城市环境和设施。随着城市建设的全生命周期评估成为热点话题[23]，新兴碳评估工具将焦点从运营碳转向隐含碳，可根据用地类型和材料等数据预测各尺度项目的隐含碳和碳汇[19][27]，尤其更全面地考量大尺度的城市规划设计项目的环境影响。其中，Urban Decarb[28]可便捷地比对各种设计方案在碳排放和造价方面的差异，适用于各类设计项目；由Sasaki开发的Carbon Conscience工具[29]可分别测算建筑和景观产生的隐含碳，在规划初期阶段以每单位特定用地估算碳排放量和环境影响生成用地方案，在设计深化阶段则可以根据建筑类型、结构和材料等信息计算碳排放和碳汇。

综上，目前在片区／街区尺度上仍缺乏综合考量运营碳和隐含碳，同时集成气候、能源系统、用地类型和材料等数据的综合性评估工具。

3.4 评估维度及参考数据

根据城市各系统的能源需求、碳排放量和可持续发展要素等，研究分别以12个和9个评估维度总结上述城市尺度和片区／街区尺度碳评估工具（表2）。

在城市尺度上，建筑、工业、商业和交通运输是城市碳排放的主要来源[19]，也构成碳评估工具的共性维度。其他主要维度包括电力、污水处理和固体垃圾管理等方面。

城市尺度的碳评估工具主要依照宏观经济能耗数据和土地利用能耗数据对以上各维度进行量化评估。这两类数据都具有更新周期长、数据开放度低的特点，会从根本上影响评估的准确性和适用性。

1）经济能耗数据通常来源于政府部门的统计报告（以年为单位），数据更新的周期往往为2~3年，因此数据获得存在一定的滞后性[30][31]。因此，对于应用于全球城市的工具（如LEAP[32]和CURB[30]）而言，及时获取和更新全球城市的数据是一个巨大挑战。为了保证数据的准确性，应用于全球城市的工具需要使用者输入案例城市各系统数据；对比之下，仅针对某一国家或地区的工具（如ALasSken[31]）从政府部门获取和更新数据较为容易，且工具通常自带部分数据库，无需用户额外输入。此外，LEAP等工具还允许使用者根据城市实际情况和具体评估需求开发额外的功能程序，提升了评估工具的适用性。

2）土地利用能耗数据包含用地类型和用地类型碳排放系数两类数据。用地类型数据同样来源于城市政府部门，以年为单位更新；而碳排放系数则需根据案例城市的具体用地情况详细测定，这也是保证碳排放预测准确性的重要因素。

在片区／街区尺度上，运营能耗模拟工具主要用于预测能源需求。它们通常和微气候／热舒适的评估相结合，部分工具也能进行能源系统分析和可再生能源评估。针对规划设计初期阶段的评估工具还包含其他可持续分析模块（如日光照明等），赋予设计师更加综合的视角。而隐含碳和碳汇估算工具的评估维度相对单一，主要侧重建筑和景观两方面，较少评估交通、基础设施等方面。

其中，运营能耗模拟类工具主要参考建筑形态、属性和气候信息等数据，隐含碳和碳汇估算类工具主要参考建筑、景观、基础设施的用地类型、材料、结构等数据（表3）。

1）气候数据和建筑形态属性数据是开源数据，来源于气象统计网站、open street maps和城市官方的数据库[33]，这些数据一般由用户输入，对于数据和现状不符的情况，设计师也会搜集卫星图等多方数据进行验证和调整，提高数据的准确性。侧重能源系统优化和供需分析的工具（如CEA[34]、CitySim[35]、CESAR[26]等）可参考建筑的供能系统类型和使用者的行为活动数据来获取更加精确的能耗现状，并预测未来的能源需求。这些数据可由open street maps提取，但通常只覆盖部分街区，部分工具使用人口普查数据作为补充数据源[26]。

2）隐含碳和碳汇估算工具所参考的用地类型、用地面积、材料、场地管理等数据没有直接的来源，需要综合多学科知识，并结合既有研究和实践经验来获取。同时，数据库需要随着新知识和经验的出现而不断更新，以适应多样化的项目需求。例如，Carbon Conscience分别建立了建筑和景观数据集[36]——建筑数据集参考现有的建筑全生命周期评估工具，而景观数据集来源于相关的学术研究论文——在缺乏直接参考数据的情况下，借鉴一手的学术研究中的数据资料，有效提升了隐含碳和碳汇估算的精准度。

表 2：碳评估工具的维度总结

城市尺度工具

工具名称	建筑	工业制造	商业	交通运输	电力	供热制冷	污水处理	固体垃圾回收处理	农林牧渔	仓储	通信
LEAP	√	√	√	√							
EnergyPLAN		√	√		√	√					
CURB	√		√		√		√	√			
VIA Tools	√	√	√		√	√	√	√	√		
ALasSken	√	√	√				√	√	√		√
LUCEs	√	√	√	√					√	√	
CarbonVCA	√	√		√							

片区／街区尺度工具

工具名称	运营能源需求	微气候／热舒适	能源系统设计	可再生能源	日光照明	建筑隐含碳	景观碳排碳汇	基础设施隐含碳
Ladybug Tools	√	√		√				
umi	√				√	√		
CEA	√		√	√				
CitySim	√	√	√	√				
Autodesk Forma	√	√			√			
CESAR	√	√				√		
UrbanSOLve	√							
One-Click LCA						√		
Tally						√		
Pathfinder							√	
Carbon Conscience						√	√	
Urban Decarb						√	√	√

4 讨论

4.1 评估工具的应用局限性

评估工具发展迅速且评估维度多样，但在具体规划决策和设计实践中的应用仍较为有限。目前，相较于片区／街区尺度，城市尺度碳评估工具在实践中的应用更加成熟，而工具的主要应用场景是能源规划和气候规划决策，而在规划设计初期阶段的实践中应用非常有限。因此，本文搜集并比较了未运用评估工具的低碳实践案例，以发现现有评估工具的不足。

由于各个国家和城市的差异显著，很难制定通用的碳排放评估标准和策略，通常需要根据实际情况设定相应的碳排放评估框架和标准[37]，也使得城市尺度上的评估工具在政府规划决策中的作用受限。因此，国

表 3：片区／街区尺度评估工具的参考数据总结

类别	使用数据 工具名称	气候数据	建筑形态	建筑物属性	建筑供能系统类型	使用者行为	建筑材料和结构	用地类型、面积和材料
运营能耗模拟	Ladybug Tools	√	√					
	umi	√	√	√			√	
	CEA	√	√	√	√	√		
	CitySim	√	√	√	√	√		
	Autodesk Forma	√	√	√			√	
	CESAR	√	√	√	√	√	√	
	UrbanSOLove	√	√	√				
隐含碳和碳汇估算	One-Click LCA						√	
	Tally						√	
	Pathfinder							√
	Carbon Conscience						√	√
	Urban Decarb						√	√

内外城市纷纷依据实际情况构建了低碳建设评估框架和实施方法。例如，天津市作为中国首批低碳试点城市之一，提出了基于减碳和固碳两方面的城市规划低碳评估指标体系[38]，并结合现有国土空间规划框架探索了减碳技术路线[39]。马来西亚也提出其低碳城市框架与评估系统，弥补了政府政策与市场上众多绿色城市评级工具之间的差距，以指导城市实施碳减排措施[40]。然而，无法获取案例城市的准确数据也导致了部分国家和城市开发的工具只适用于局部地区，无法广泛应用。

片区／街区尺度上，碳排放通常与微气候／热舒适、日光潜力等指标的评估相结合，这类多维度评估工具（如Ladybug Tools[33]）在规划设计初期阶段中已经得到较好的运用。另外，隐含碳和碳汇估算评估工具在建筑材料和结构设计方面的应用已日臻成熟，而在综合性城市规划设计方面的应用刚刚兴起，正逐步应用到实践项目中（如Carbon Conscience[29]）。

针对片区／街区尺度上的评估工具，有以下几点局限值得讨论。

第一，大部分规划设计实践仍未将碳排放作为关键因素，而只将其作为方案完成后的评估选项之一。

第二，大多数工具只聚焦单一方面的碳排放（如只考虑运营碳或建筑的隐含碳），而城市规划设计需要综合考量城市系统内建筑、景观和交通等多方面的碳排碳汇。同时，组合使用多种工具会导致数据之间关联的缺失，难以发现要素之间的关联趋势。无锡市蠡湖新城规划项目改进现有评估模型，构建了新的碳中和评估体系，可同时评估碳排放和碳汇[41]；而济南市西部新区规划案例评估了规划方案的路网可达性、交通碳排放潜力等[42]。当前评估工具中正缺乏此类侧重空间规划设计的多维度碳排放评估。

第三，现有的工具主要关注碳排放量的量化评估，欠缺相应的设计优化建议、低碳策略和实施方法等。在实际项目中，重点在于可以指导落地的技术路线。例如，上海市斜土社区等7个社区通过传统的现状调查、碳排摸底和数据分析，制定了低碳更新策略和实施路径[43]。

最后，片区／街区尺度工具普遍缺乏全流程意识，以及项目管理和运营过程中的碳排放监控核查。目前，有部分城市对此进行探索。上海市数字江海产业园构建了全过程总控机制，通过搭建智慧减碳的数字孪生平台，可从建筑用能、交通出行和碳汇等五个维度收集和反馈管理碳排放数据，形成了统合规划、建设、管理、运营关键环节的城市街区减碳技术框架[44]。

综上，无论是城市和片区／街区尺度评估工具，都应提升工具的综合性和灵活性，使其适用于更加多样的场景，更准确、高效地辅助规划设计实践。

4.2 评估工具发展趋势

根据上述梳理分析，本文认为数字化低碳城市规划设计评估工具的未来发展趋势可总结为以下几点。

首先，多学科的交叉融合有增强工具实用性，针对碳排放问题提供一体化设计的最优化方案。在城市和片区／街区两个尺度上，未来可深入探索集成建筑、规划、景观、交通、结构、机电、可持续等多学科知识的综合性的数字化评估工具开发。

第二，数据库构建是提高评估工具应用广度和精度的关键。对于城市尺度工具而言，随着多源数据的开放获取，可进一步建立包含不同国家和城市评估标准和策略的数据库，进而提高工具的应用灵活性和竞争力，同时也减少重复开发带来的资源和时间浪费。尽管片区／街区尺度的能源、材料数据在全球范围内具有一定的通用性，但建立完善且不断更新的数据库仍存在挑战。同时，已有相关研究在两个尺度上运用跨尺度数据进行精细化评估——如基于微观地块的土地利用数据运用城市尺度工具进行自下而上的数字化碳评估[45]；基于人口普查等城市尺度数据，结合片区／街区尺度工具与GIS对不同区域进行因地制宜碳评估[26][34]——为碳评估提供了新的视角。

第三，多标准的低碳评估研究还有待深入。运用多标准的评估方法——如考虑循环经济、碳追踪的复杂性，以及碳汇受气候变化、植被生长周期等多重因素影响的动态性等——才能最大限度地模拟真实项目中的碳排放情况。

第四，提高评估工具的经济可行性和使用便捷性。在实际评估工具应用中，关于回报周期和成本价格的计算将有助于投资者权衡不同因素，确保所选方案既满足低碳节能，又具有经济可行性。此外，可视化的展示形式也可使投资人和设计师能够更容易理解不同设计的碳排放的情况，方便进行方案比选和决策。

第五，随着人工智能（AI）技术的发展与广泛应用，评估工具也将迎来数字未来智慧化的迭代革新。借助AI的算法，可以快速处理大量的数据，特别是极大提升能源模拟相关计算的效率；还可以利用AI进行环境预测，比如通过训练过往的气候数据预测气候变化，从而更好地帮助决策者制定和实施低碳政策。

4.3 研究局限

本研究主要通过谷歌学术筛选文献来收集评估工具。这一方法可能导致一些新兴评估工具，尤其是因AI兴起应运而生的工具，因为文献提及较少而未被纳入本研究中。此外，在梳理全球低碳城市规划设计案例时，主要依靠文献阅读、信息查找等方法，缺乏系统的方法来全面搜集评估工具应用案例，可在未来研究中进一步优化。

5 结语

本文从分类、特征、应用三个主要方面对数字化低碳城市规划设计评估工具进行了系统性梳理和比较研究，整体而言，此类工具在规划设计多个阶段的运用对低碳城市建设具有重要意义。在政策制定阶段，评估工具能够预测不同发展愿景和措施下城市的碳排放量，帮助决策者选择合理的减碳方案；在方案初期，不少评估工具可以从项目伊始的概念设计阶段就测算设计方案的碳排放，包括隐含碳和全生命周期的碳汇和运营碳；在方案中后期，不少评估工具也可快速、准确地对设计方案进行碳排放模拟运算；在建成后阶段，一些评估工具还可以持续追踪项目的运营碳，为日后项目优化设计提供建设性意见。未来，碳排放评估工具将朝着全球适用性、多学科涵盖、全生命周期计算、经济平衡和数据可视化等方面发展，与AI等智能技术的结合也将大大提升实践中碳评估的效率，使评估工具更好地支持城市规划设计实践。

致谢

本文作者非常感谢刘雨轩同学在工具检索和案例收集方面做出的贡献。

图 1. 碳评估工具发展趋势（圆圈标注的 One-Click LCA 和 Tally 工具出现较早，用于建筑的隐含碳评估）。