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Review on carbon emissions of commercial buildings

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Abstract

The building sector accounts for one-third of energy-related carbon emissions. For commercial buildings, their energy use has been widely studied but research on their carbon emissions has not been common. To provide a state-of-the-art portrait of carbon emissions of commercial buildings, a study was conducted. Through an extensive review of official datasets, government statistics, authoritative website information and 101 journal articles that are germane to the study, it was found that the global carbon emission has continued to rise although many places have introduced incentive or subsidy schemes for carbon mitigation. Carbon emission has become a major evaluation aspect of the renowned building environmental rating methods such as BREEAM and Green Star, but it remains merely an evaluation criterion under the energy analysis category of both LEED and BEAM Plus. Whereas the first international standard (ISO 16745) on carbon emission calculation and carbon metrics for existing buildings was not referenced in any of the studies reviewed, following this standard to pursue carbon studies in future can enable comparisons of study results on the same basis. Rather than simulation studies, more empirical research using operational data of existing buildings should be carried out in order to obtain real and definite findings. Despite the wide range of efforts made, the growth of carbon emission remains a live issue. How this issue could be resolved should be the focus of future research in this area.

Highlights

- Official statistics, authoritative information and journal papers were reviewed
- The global carbon emission keeps rising despite various mitigation efforts
- A common standard should be used to assess carbon emissions of buildings
- More empirical studies using operational data of existing buildings are needed
- Future research should focus on how to cut carbon emissions of existing buildings

Keywords: building; carbon; greenhouse gas; energy; policy; review; standard

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1. Introduction

1.1 Definitions

Carbon emission, GHG emission and carbon footprint are three terms that commonly appear in carbon studies. However, the meanings of these terms may vary from one study to another [1]. Despite the controversies on the definition of the carbon footprint of a building, the U.S. EPA refers it to the total GHGs emitted into the atmosphere in a year or a building's life-cycle period, including six main greenhouse gases: CO₂, CH₄, N₂O and fluorinated compounds [2,3]. Moreover, ISO 14064-2 defines GHG emission as the "total amount of a GHG released to the atmosphere over a specified period of time" [4]. While ISO/TS 14067 is tailored for products, it defines "carbon footprint" as "the sum of greenhouse gas emissions and removals in a product system, expressed as carbon dioxide equivalent (CO_{2-e}) and based on a life cycle assessment using the single impact category of climate change" [5].

For the building sector, carbon footprint of a building equals the total GHG emission of a building in a life-cycle period that covers carbon emission and the emission of other greenhouse gases. As the units of GHG emission and carbon footprint are both CO_{2-e}, the term "carbon emission" is often misused to represent carbon footprint or total GHG emission [1]. However, since the term "carbon emission" has become a colloquial term that denotes total GHG emission, in this paper, "carbon emission" of a building refers to the total GHG emission or GHG emission resultant from any specified scope of resource (e.g. energy) used in the operation stage of the building.

1.2 Carbon emissions from commercial buildings

The global carbon emission has continuously increased - from 24.69 billion tons in 2000 to 36.14 billion tons in 2014 [6]. According to the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Environment Programme (UNEP), the building sector consumes 40% of the total energy use and accounts for one-third of energy-related carbon emissions [7,8].

Buildings account for 39% of carbon emissions in the United States (U.S.) [2], about 59% of the total electricity consumption in European Union (EU) [9], about 20%-30% of national energy consumption in China [10,11], about 90% of the total electricity consumption and 60% of carbon emissions in Hong Kong (a densely-populated, south-eastern city of China) [12,13]. In recent years, the whole building sector in Australia generates about 20% of the total CO₂ equivalent GHG emissions [14]. In Latin America, buildings produce 25% of its total carbon emissions and 65% of its total waste [15]. As the biggest country in Latin America, Brazil has a large building sector, which accounts for 35% of Brazil's carbon emissions [16].

According to a report of the Canadian Government, GHG emissions from the commercial sector are projected to reach 48 Mt CO_{2-e} in 2020 [17,18]. Referring to the Australian Council, commercial and office buildings account for about 60% of the total energy consumption [19]. In South East Asia, the commercial sector is responsible for about 37% of the total electricity consumed in Singapore [20], while consumes 65% of the total electricity in Hong Kong [12,13].

In fact, commercial buildings are major energy consumers; for instance, the energy use intensity (EUI) of commercial buildings in Hong Kong was between 236 and 270 kWh/m²/year and the counterpart of Singapore

was 297 kWh/m²/year [21,22,23]. Compared with the EUI of residential buildings, for example 105-147 kWh/m²/year in Hong Kong [24], the EUI of commercial buildings is around two times higher. While commercial buildings consume a considerable amount of energy and hence produce significant carbon emissions, they have attracted less attention than residential buildings in energy/carbon studies [25]. Although carbon emission has become a hot topic in recent years, a holistic picture of the carbon emission of commercial buildings is not available. In view of this knowledge gap, a comprehensive review study was initiated.

The following section introduces the research method adopted for the review study and the materials covered in the review process. Then, the findings are discussed, which include the global trend of carbon emission, carbon mitigation schemes and programs, building environmental rating methods, and standards and guidelines found from the review on government statistics, official websites, etc. The key observations from a review of 101 journal articles that are germane to the topic of this study are also discussed. Built upon the findings, finally, conclusions are drawn and suggestions for future research works are given.

2. Material and Methods

Using a multi-pronged research approach, firstly, datasets of global total CO₂ emissions, global total GHG emission, and GHG emissions per capita by country, were downloaded from the European Commission's Emission Database for Global Atmospheric Research [26]. Then, the datasets downloaded, including those corresponding to the main countries/cities across the world, were charted to show the trends of carbon emissions in recent years.

Secondly, the energy use of commercial buildings, which accounts for the majority of the buildings' carbon emissions [27,28], was studied. As this study focuses on GHG emissions in CO_{2-e} terms from operational energy use of existing commercial buildings, energy use data of two large countries (the U.S. and China) and two energy-intensive places (Hong Kong and Singapore) were retrieved from the Monthly Energy Review of U.S. Energy Information Administration (EIA), China Building Energy Use Report of Tsinghua University, Hong Kong Energy End-use Data of Electrical and Mechanical Services Department (EMSD), and Singapore Energy Statistics of Energy Market Authority (EMA), respectively [29-32]. As the units of the energy use data vary between the four countries/places, a standard energy unit, ton of oil equivalent (toe), was adopted. This was done by using the online tool of the International Energy Agency to convert the energy units [33]. Because only the exact values of energy use between 2014 and 2016 were provided in the reports for China [30], the energy use levels in the preceding years were estimated based on the charts presented in the reports. Referring to the definitions in the reports, the scope of public and commercial buildings in China is similar to that of the commercial sectors in the U.S., Hong Kong and Singapore. The total energy use of commercial buildings in China was taken as the sum of the energy use (excluding heating energy) of the buildings and the heating energy for the commercial sector.

Thirdly, publications on the following facets were reviewed: i) prominent carbon and energy-related programs, schemes and standards; ii) renowned building performance rating methods; and iii) recommended strategies or measures for reducing carbon emissions. The sources from which such information was found include the official websites of nations/governments (e.g. United States Environmental Protection Agency), inter-governmental organizations (e.g. World Bank), international organizations (e.g. International Organization for Standardization)

and leading environmental organizations (e.g. the United States Green Building Council, Building Research Establishment).

Fourthly, literature germane to the topic of this study was reviewed. To strive for a contemporary review, journal articles published between 2000 and 2018 were covered. This literature review process was conducted following the four-step procedure of the PRISMA (preferred reporting items for systematic reviews and meta-analyses) protocol - a method widely adopted for systematic review and meta-analysis [34]. The four steps taken, as Fig 1 depicts, are: i) identify the relevant articles through database searching; ii) screen the articles based on established criteria; iii) check the eligibility of the articles; and iv) include the eligible articles in the review and analysis. Given that this study aims to give an elaborate review on carbon emissions of existing commercial buildings, keywords "carbon emissions" and "commercial buildings" were used to search articles in three renowned databases: ScienceDirect, Taylor & Francis, and Springer. As studies on carbon emissions of existing commercial buildings were found to be limited, "office buildings" (being a common type of commercial buildings) were also used in the search process. Due to the limited number of studies on carbon emissions from existing buildings, the literature search was expanded to include life cycle emissions from commercial buildings. This step resulted in identifying a total of 425 articles. After removing the duplicated articles that appeared in two or three of the databases, 298 articles remained and then the titles and abstracts of these articles were screened manually for their relevance to the topic being studied. By this step, 210 articles were shortlisted and 185 of them were given access to their full texts. Through the final step where the 185 full-text articles were perused, 101 most-related papers were included for in-depth review and analysis.

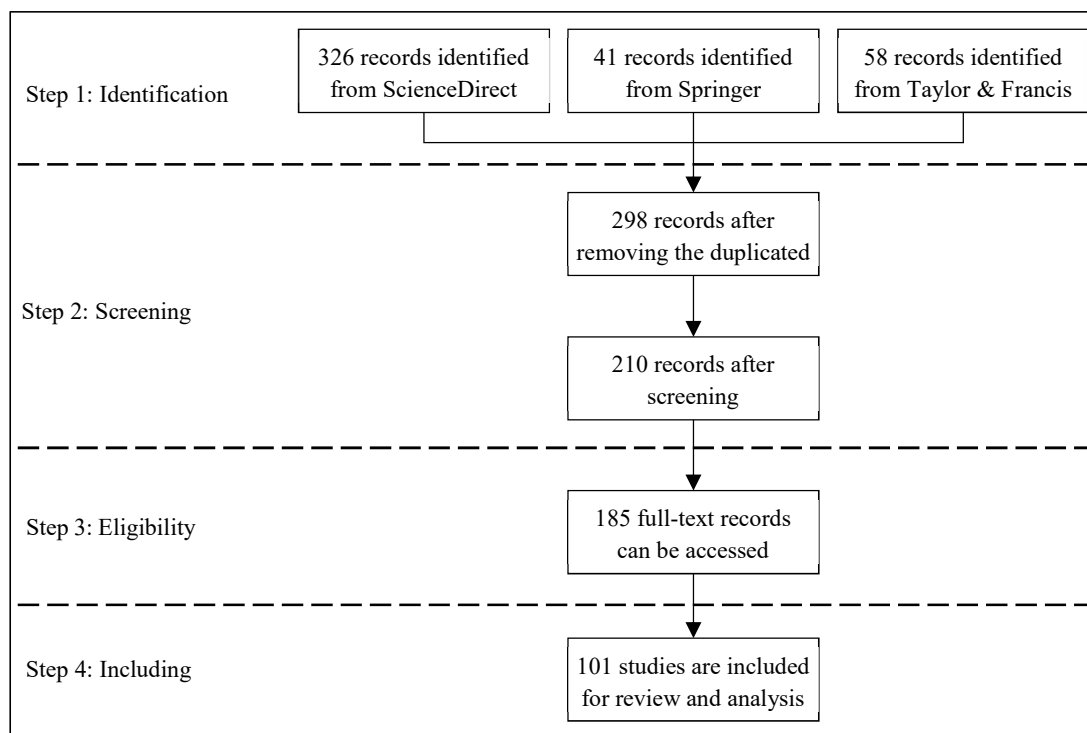


Fig 1. PRISMA flowchart for literature review

Almost half of the 101 articles were collected from ScienceDirect and another 40% were from Springer. The articles spread over 42 journals, with 8 main journals each containing 4 articles or more. Journal of Building

Simulation hits the top by covering 16 articles; other major journals are: *Journal of Energy and Buildings*, *Journal of Building and Environment*, *Journal of Energy Efficiency*, etc. (Table 1).

Table 1. Articles reviewed and their journals

Journals	Article counts
<i>Journal of Building Simulation</i>	16
<i>Journal of Energy and Buildings</i>	11
<i>Journal of Building and Environment</i>	8
<i>Journal of Energy Efficiency</i>	8
<i>Journal of Applied Energy</i>	5
<i>Procedia Engineering</i>	5
<i>Journal of Energy</i>	4
<i>Journal of Building Research & Information</i>	4
<i>Journal of Frontiers in Energy</i>	3
<i>Journal of Advances in Building Energy Research</i>	2
<i>International Journal of Life Cycle Management</i>	2
<i>Journal of Cleaner Production</i>	2
<i>Journal of Central South University</i>	2
Other 29 journals (each contains 1 article)	29

3. Findings and Discussion

3.1 Global trend of carbon emission

The trends of both global GHG emission and CO₂ emission, as Fig 2 shows, generally rose over the years. In 2008-2009, subsequent to the global financial crisis of 2007-2008, there were mild dips in the emissions. Afterwards, both the global GHG emission and CO₂ emission resumed their upward trend. While available data of global GHG emission were only up to 2012, the level of CO₂ emission plateaued in 2013 (Fig 2). This may be because, although the emissions of the developing countries have kept on rising, the developed countries have taken carbon reduction actions in response to the climate change agreements. Note that when global GHG emission data pertaining to the period beyond 2012 are made available in future, a more complete comparison could be made between the two trends in Fig 2.

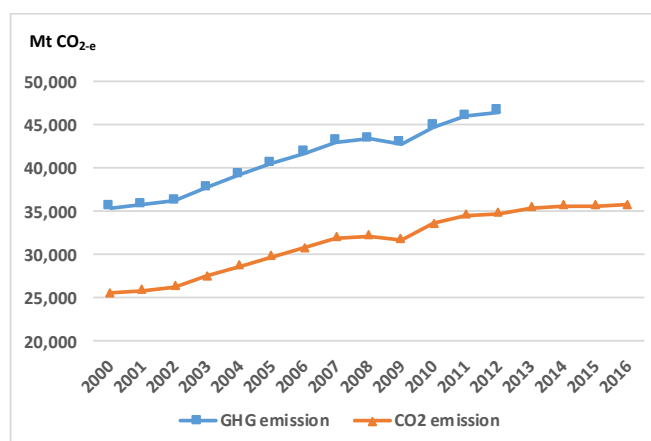


Fig 2 The trends of Global GHG emission and CO₂ emission

(Data source: European Commission’s Emission Database for Global Atmospheric Research [26])

The trends of GHG emission per capita shown in Fig 3, besides that pertaining to the whole world, are those of the main places including the European Union (covering 28 member countries), major countries (Australia, Canada, China, India, Japan, Russia, Singapore, and the U.S.), and Hong Kong – a subtropical metropolis similar to Singapore in aspects such as population and climate. It was found that the developed countries (e.g. Canada, Japan, the U.S.) are more carbon-intensive than the developing countries (India and China). Countries with abundant natural resources such as Canada, which is abundant in crude oil reserves [35], and Russia, which is rich in natural gas reserves [36], tend to generate more emissions than countries with less natural resources. The highest GHG emission was found with Australia (26 to 29 tons of CO_{2-e} per capita), followed by the U.S and Canada. Common to all these three countries, their emission levels between 2000 and 2012 generally decreased. On the other hand, both the emission trends of China and India were on the rise. Around 2012, the emission levels of the European Union, China, Japan and Singapore were comparable - around 8 to 10 tons of CO_{2-e} per capita. When data after 2012 are made available, in future, further comparisons could be made between the GHG emissions of the various places.

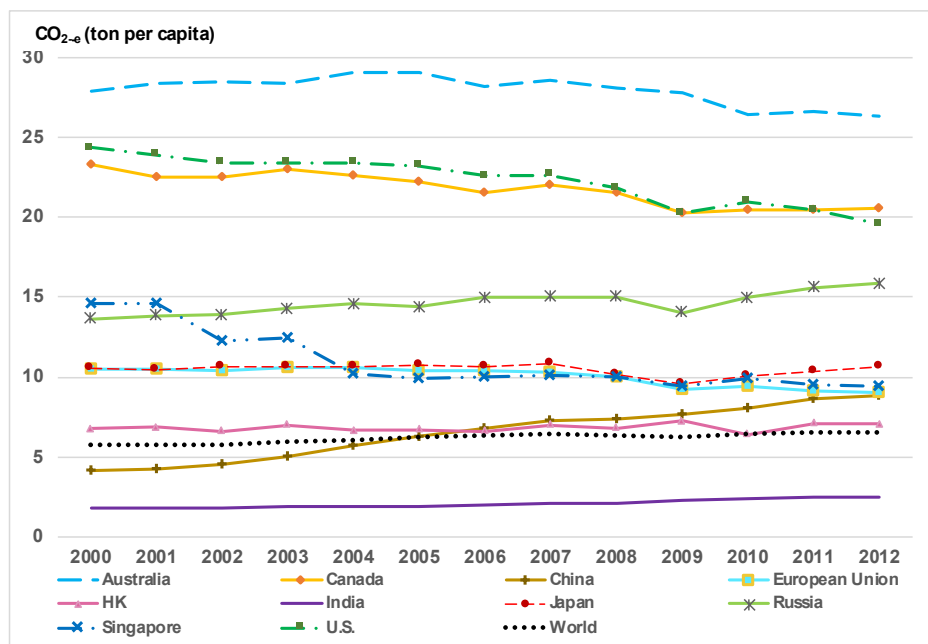


Fig 3 GHG emissions of the world and various places

(Data source: European Commission’s Emission Database for Global Atmospheric Research [26])

In the process of information and literature search for this study, specific statistics of carbon emissions of commercial buildings could not be found. Nevertheless, energy use statistics are available. As a large portion of carbon emission was due to energy used for buildings, especially commercial buildings [27], an inspection was made on the amounts of energy use of commercial buildings of two major countries - China and the U.S. The energy use of commercial buildings in the U.S., which accounts for the majority of all the energy consumed in the commercial sector, was around 450 Mtoe (Fig 4(a)). While for China, an obvious, upward trend was observed (Fig 4(b)). In 2016, the energy use of commercial buildings in China approached 384 Mtoe, which almost triples the level in 2001. Note, however, that because China and the U.S. have different climatic conditions, building

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stock characteristics and usage patterns etc., Fig 4(a) and Fig 4(b) are not meant to be used for direct comparison between China and the U.S. Instead, they show the trends of the two countries.

As regards Hong Kong and Singapore, both their energy used for commercial buildings increased over the years. In 2016, the energy use level of Hong Kong was close to 3,000 ktoe (Fig 5(a)), which is around double the level of Singapore (Fig 5(b)). Nevertheless, as illustrated in Fig 3 above, Hong Kong is less intensive than Singapore in terms of GHG emission per capita by 2012. While the climatic conditions of Hong Kong and Singapore are not as distinct as those between China and the U.S., the difference in building stock characteristics and usage pattern etc. between Hong Kong and Singapore are factors leading to their different energy use levels.

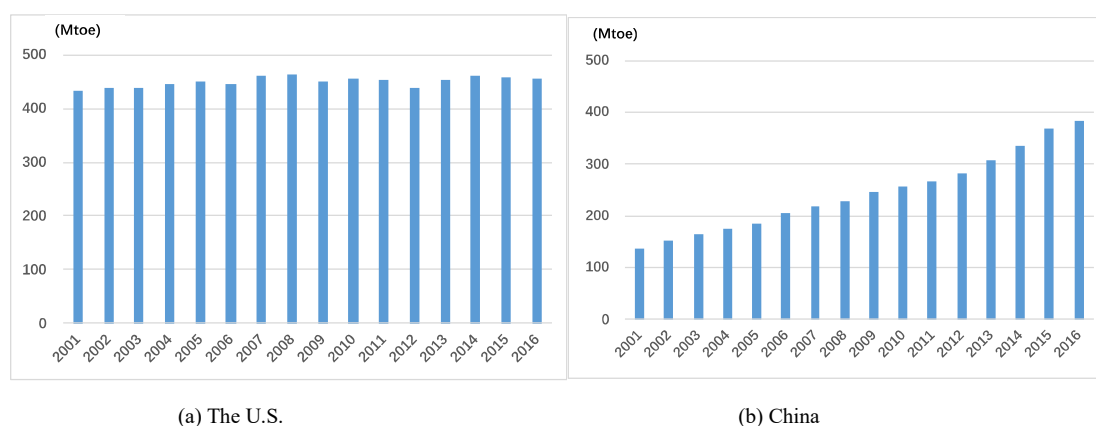


Fig 4 Energy use of commercial buildings in the U.S. and China

(Data source: Monthly Energy Review of U.S. Energy Information Administration (EIA), and China Building Energy Use Report of Tsinghua University [21,22])

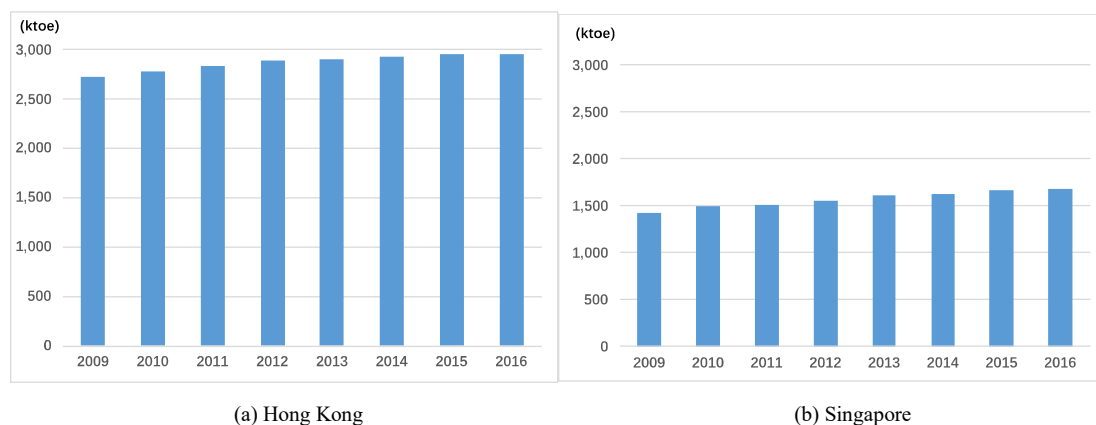


Fig 5 Energy use of commercial buildings in Hong Kong and Singapore

(Data source: Hong Kong Energy End-use Data of Electrical and Mechanical Services Department (EMSD), and Singapore Energy Statistics of Energy Market Authority (EMA) [23,24])

3.2 Carbon mitigation schemes and programs

For the purpose of lessening global warming and climate change, countries around the world signed the Paris Agreement in 2015, aiming to reduce CO₂ emission and other GHG emissions [37]. Meanwhile, individual countries have launched their emission trading systems, building environmental rating schemes, carbon reduction

strategies and green building programs in addition to reporting systems on carbon emissions [38]. Following is a review on the notable carbon mitigation schemes/programs in Europe, America, Australia and Asia.

3.2.1 Europe

Emission trading is an important economic tool for reducing carbon emissions. The European Union Emissions Trading System (EU ETS), a commonly adopted carbon trading scheme that works on the ‘cap-and-trade’ principle, was developed in 2005 [39]. Known as the world’s first international emission trading system, the EU ETS accounts for 75% of international carbon trading and is applicable to buildings, including commercial buildings [40,41]. Compared to 1990 levels, EU targets to reduce GHG emissions to 20% by 2020 and at least 40% by 2030 [42]. As the world’s biggest and most mature carbon trading scheme, the EU ETS has served as a model for many other countries such as China, India and Brazil [43,44].

Apart from the EU ETS, other international emission trading schemes (e.g. Green Investment Scheme (GIS)) were also created for international carbon trading [45]. Countries in middle and eastern Europe such as Russia, Hungary and Poland have surplus of Assigned Amount Units (AAUs) of carbon emissions under Article 17 of the Kyoto Protocol, while countries like Spain and Netherlands are projected to be short of AAUs [45-47]. As a result, the GIS was proposed and, since 2008, countries like Hungary and Poland have been able to sell their AAUs [48].

Besides voluntary schemes (e.g. Logistics Emission Reduction Scheme (LERS)) initiated by industries to reduce carbon emissions [49,50], there are mandatory schemes (e.g. Carbon Reduction Commitment (CRC) Energy Efficiency Scheme) operated by the governments in the U.K. The CRC Energy Efficiency Scheme, introduced in 2010, covers private and public organizations (e.g. supermarkets and banks) and public buildings such as council buildings, hospitals and schools [49,51]. Organizations that fall into the criteria of the Scheme must buy allowances for the amount of carbon they emit. Such allowances can be traded, for example, at around £17 to £18 per tons CO₂ during 2018 and 2019 [49], where CO₂ emissions are calculated by multiplying relevant conversion factors (kg CO₂/kWh) for natural gas and electricity [52].

3.2.2 America

Enacted by the U.S. Congress, the Clean Air Act Amendments were signed in 1990 considering the emission from all types of buildings [53,54]. Founded in 2009, the Regional Greenhouse Gas Initiative (RGGI) is the first mandatory market-based program in the U.S. to cap and reduce carbon emissions [55]. The RGGI specifies the reduction of carbon emission in the building sector [56,57]. In particular, Senate Bill No. 350 - Clean Energy and Pollution Reduction Act of 2015 was introduced to strengthen energy efficiency for buildings [58]. In California, the Cap-and-Trade Program of the California Air Resources Board aims to mitigate GHG emissions that were mandated to be reported since 2018 [59].

Initiated in February 2007, the Western Climate Initiative is a non-profit organization that coordinates and supports GHG emissions trading among American states and Canadian provinces [60,61]. Recently, the federal government of Canada has implemented the Greenhouse Gas Pollution Pricing Act. Originally applicable to industrial facilities that emit 50 kt CO_{2-e} every year, the Act will cover smaller facilities in 2020. Facilities with emissions exceeding the allowable limits can choose to buy surplus credits or pay emission charges to the government [62].

In Ontario, a cap-and-trade program has been designed for the carbon market in order to support the GHG emissions trading business [63]. Back in 2008, the province of British Columbia took lead in Canada to impose carbon taxes: since April 1, 2018, the carbon tax rate has been increased to \$35 per ton of CO₂-e [64]. Currently, several programs such as the Green Infrastructure programs and the Clean Growth Program are granted by the Canadian Government to support energy reduction [65]. The Green Infrastructure programs, for example, comprise multiple sub-programs: Energy Efficient Buildings Research, Development and Demonstration; Emerging Renewable Power; Smart Grids; etc. [66]. The Energy Efficient Buildings Research, Development and Demonstration program, with contribution between \$50,000 and \$5 million per project, aims to increase energy efficiency of homes and buildings. Around one fourth of the total funding (\$182 million) supports the development and implementation of building codes for existing buildings and new zero-carbon buildings [67].

3.2.3 Australia

In 2003, the government of New South Wales launched its Greenhouse Gas Reduction Scheme (GGAS) [68]. In 2008, the Carbon Pollution Reduction Scheme (CPRS; a cap-and-trade emissions trading scheme for anthropogenic greenhouse gases) was proposed by the Australian Parliament, but the legislation for the CPRS had not been passed [69]. Since 2010, owners and managers of commercial office buildings in Melbourne have been encouraged and supported by the 1200 Buildings Program to implement retrofits, thereby improving the energy efficiency of their buildings [70]. In the meantime, the Australian Government launched the National Carbon Offset Standard (NCOS) and the Carbon Neutral Program in 2010. In 2017, the Ministry of the Environment officially expanded the NCOS (a standard designed for measuring, reporting and reducing carbon emissions) to cover buildings [71,72]. In particular, carbon neutral certifications for buildings can be gained via the National Australian Built Environment Rating System (NABERS) and the Green Star – a system that assesses the sustainable design, construction and operation of buildings, fitouts and communities [73]. Other environmental programs, funds, policies and tools of the Australian Government include: Clean Energy Innovation Fund, Renewable Energy Target, 20 Million Trees, Solar Communities Program, Carbon Farming Futures, National Climate Resilience and Adaptive Strategy, and so on [74].

3.2.4 Asia

In Japan, the Green Building Program was introduced by the Tokyo Metropolitan in 2002 for encouraging large building owners to adopt energy saving techniques and environmental friendly designs [75-77]. Launched in 2010, the Tokyo Cap-and-Trade Program of Japan aims at reducing energy consumption of office, commercial, public and industrial buildings [78,79].

As the biggest carbon emission country in the world, China witnessed the reduction of carbon emission per GDP in 2014 by 33.8%, compared to the level of 2005 [80]. Meanwhile, the Emission Trading Scheme (ETS) has been promoted by the National Development and Reform Commission (NDRC) of China to support carbon reduction [81]. For the building sector, in particular, multiple policies have been implemented; for instance, the Green Building Action Plan, which was proposed by NDRC and the Ministry of Housing and Urban-Rural Development (MOHURD), was passed by the State Council to promote energy-saving retrofit on public buildings, shopping malls, office buildings, etc. [82].

In Hong Kong, the “Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings”, which was first published in 2008 and then revised in 2010, aims to facilitate building managers and

users of commercial and residential buildings to measure their GHG emission performance [83]. While following the Guidelines is entirely voluntary, the Environmental, Social and Governance Reporting Guide (ESG Guide) requires companies listed on the Stock Exchange of Hong Kong (SEHK), starting from 2015, to disclose their environmental and social information annually in accordance with the Companies Ordinance (Cap 622). Explicitly, the environmental subjects cover emissions, consumptions and environmental impacts [84]. In 2012, the Building Energy Efficiency Ordinance (BEEO) (Cap 610) was enacted, requiring owners of commercial buildings to conduct, for every ten years, an energy audit for their central building services installation based on the Energy Audit Code [85]. Since 1 January 2018, buildings that are compliant with the BEEO and certified by BEAM Plus or other recognized building rating systems can register with the Energy Efficiency Registration Scheme for Buildings [86].

3.3 Building environmental rating methods

Worldwide there are more than 40 building environmental rating methods [87], including Building Research Establishment Environmental Assessment Method (BREEAM) of the U.K., Leadership in Energy and Environmental Design (LEED) of the U.S., BEAM Plus (Building Environmental Assessment Method) of Hong Kong, Green Star of Australia, BCA Green Mark of Singapore, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) of Japan, etc. Among them, the following popular methods – one each from different continents across the world – were reviewed and compared: BREEAM (Europe), LEED (America) and Green Star (Australia) and BEAM Plus (Asia).

BREEAM, the first sustainable building assessment method that was developed by the Building Research Establishment (BRE), has been applied in 77 countries [88]. Applicable to residential and commercial buildings, BREEAM covers ten assessment aspects: management, health and wellbeing, energy, transport, water, materials, waste, land use and ecology, pollution, and innovation (additional) [88]. Part 2 of the Technical Manual for the BREEAM In-Use International scheme, which is on building management for non-domestic existing buildings [89], is relevant when it comes to carbon emissions of commercial buildings.

Developed by the U.S. Green Building Council, LEED is known as the most widely-used building rating system in the world. Building rating evaluators used for the newest version of LEED (LEED v4) include location and transportation, sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and regional priority [80]. Credits are allocated to each evaluator and total credits are calculated for determining building ratings. LEED contains several rating systems, which are for buildings at different stages (i.e. design, construction, operation and maintenance). For existing buildings, which are the focus of the current review, LEED Building Operations + Maintenance (LEED O+M) is applicable [90].

Launched by the Green Building Council of Australia in 2003, Green Star is a voluntary rating system that assesses the sustainable design, construction and operation of buildings, fitouts and communities. Similar to BREEAM, Green Star covers various assessment aspects except the waste aspect, which is a sub-indicator under materials and other categories [91]. As far as carbon emission of existing commercial buildings is concerned, Green Star – Performance, which is one of the four sub-schemes of Green Star, assesses the performance of building operation and maintenance.

Certified by the Hong Kong Green Building Council (HKGBC), BEAM Plus is a voluntary green building assessment scheme. Comprising a series of assessment tools for new buildings, existing buildings, interiors and neighborhood, BEAM Plus offers a set of performance criteria for a wide range of sustainability issues relating to the planning, design, construction, commissioning, management, operation and maintenance of a building [92]. Of particular relevance to the current study is the assessment tool for existing buildings [93]. Compared with BCA Green Mark, of which Singapore shares similarities with Hong Kong in aspects such as climate, etc., BEAM Plus is suitable for assessing high-rise, high-density buildings [92].

The above assessment methods have sub-divided rating tools for different types of buildings (e.g. residential, commercial, public buildings) and for buildings at different stages (design and construction, interior fit-outs, operation and maintenance). Referring to the scoring schemes applicable to existing commercial buildings (BREEAM In-Use International (Part 2), LEED (O+M), Green Star - Performance and BEAM Plus – Existing Buildings), including their assessment aspects and the weightings allocated to individual aspects [89,90,91,94], a comparison table was prepared (Table 2). It shows that the four schemes are similar in that they all cover the following aspects: sustainable sites (land use and ecology), water, energy, materials, and indoor environmental quality (health and wellbeing). Common to these four rating tools, energy is the dominant aspect, carrying the highest weighting (22% to 38%) in assessing building environmental performance. In recognition of the importance of building management, especially operation and maintenance [93], a weighting (24%) which is the same as that of the energy aspect is assigned to the management aspect of BEAM Plus. In BREEAM In-Use International (Part 2), LEED (O+M) and BEAM Plus – Existing Buildings, carbon audit is subsumed under the energy aspect instead of being a standalone aspect. Only Green Star has a category dedicated for carbon emission.

Table 2. Assessment aspects and weightings

Assessment aspect	BREEAM	LEED	Green Star	BEAM Plus
Sustainable sites/ Land use and ecology*	12.5%*	10%	6%*	10%
Water	5.5%	12%	12%	14%
Energy	31.5%	38%	22%	24%
Materials	7.5%	8%	14%	14%
Indoor environmental quality/ Health and wellbeing#	15%#	17%	17%	14%
Location/Transportation	N.A.	15%	10%	N.A.
Emission	N.A.	N.A.	5%	N.A.
Pollution	13%	N.A.	N.A.	N.A.
Management	15%	N.A.	14%	24%
Additional: Innovations (and others)	10%	10%	10%	+

Notes: *The scope of “Land use and ecology” (in BREEAM and Green Star) is similar to that of “sustainable sites” (in LEED and BEAM Plus). #The scope of “Indoor environmental quality” (in LEED, Green Star and BEAM Plus) is similar to that of “health and wellbeing” (in BREEAM). +Applicable (but the amount of weighting is not specified).

Besides energy, water is a resource whose utilization in existing commercial buildings would affect the amount of carbon emissions. Water efficiency or water use, under the four schemes, concerns issues such as water consumption reduction, leak detection, water recycling, etc.

Fuels used for transportation are among the factors contributing to carbon emissions. Transportation, under the assessment of Green Star, concerns car parking capacity, low emission transportation, public transport accessibility, etc., while LEED covers alternative transportations. In both BEAM Plus Existing Buildings and BREEAM In-Use International (Part 2), transportation is not covered.

3.4 Standards and guidelines

In total, 40 international or national standards/guidelines were cited in the 101 papers reviewed. A summary of these standards/guidelines, including their title, in which paper(s) they were cited and the number of such paper(s), is shown in Table 3.

Table 3. Standards/guidelines cited in the papers reviewed

	Code/Serial No.	Title	Cited in	Counts	
International	1	ISO 50001	Energy management systems	[95]	1
	2	ISO 14044	Environmental management-Life cycle assessment-Requirements and guidelines	[96,97]	2
	3	ISO 14040	Environmental management-Life cycle assessment- Principles and framework	[98-101]	4
	4	ISO 14041	Environmental management-Life cycle assessment- Goal and scope definition and inventory analysis	[101]	1
	5	ISO 21931-1:2010	Sustainability in building construction (Part 1: Buildings)	[96]	1
	6	EN 15251:2008	Indoor environmental input parameters for design and assessment of energy performance of buildings	[102]	1
	7	EN 15978:2011	Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method	[96]	1
	8	CEN/TC 350	Sustainability of construction works	[103]	1
	9	PREN 15603 2007	Energy Performance Of Buildings - Overarching Standard	[104]	1
	National/State	1	BS 8900:2006	Guidance for managing sustainable development	[97]
2		-	Australian National Carbon Offset Standard	[97,105]	2
3		-	California's building energy efficiency standards Title 24	[106-109]	4
4		GB 50189-2015	National Standard for Energy Efficiency Design of Public Buildings	[110-118]	9
5		GB 50365-2005	National Standard for Energy Efficiency Design of Public Buildings	[119]	1
6		DBJ 15-51—2007	(Guangdong) Design Standard for Energy Efficiency of Public Buildings	[120]	1
7		GBES	The Ministry of Construction of China--Green Buildings Evaluation Standard	[121]	1
8		Executive Order EO 12902	Energy efficiency and water conservation at Federal facilities, USA	[122]	1
9		Sveby standard	Standardize and verify energy performance in buildings (Sveby) standard	[123]	1
10		AS/NZS 3598	Energy Audit series (Commercial Building)	[95]	1
Professional	1	CIBSE Guide F	Energy Efficiency	[124]	1
	2	CIBSE Guide A	Environmental Design	[125]	1
	3	COMNET	Commercial Buildings Energy Modeling Guidelines and Procedures	[106]	1
	4	ASHRAE Guideline 14	Measurement of Energy, Demand and Water Savings	[108,118]	2
	5	ASHRAE Guideline 140	Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs	[108]	1
	6	ASHRAE 90.1	Energy Standard for Buildings Except Low-Rise Residential Buildings	[106,108, 125-131]	9
	7	ASHRAE AEDG	Advanced Energy Design Guides	[127]	1
Others	Other 14 Standards		[97,99,104,114,116,119,120,126,128,130,132-140];		29
	Papers with no standards/guidelines cited: [24,27,141-192]				54

Most of the standards/guidelines are published by well-known standardization bodies, e.g. the International Organization for Standardization (ISO), and the European Committee for Standardization (CEN). In the U.K., its own national standard (British Standard (BS)) is adopted. In China, the national standard used is called Guobiao (GB). In the U.S., there are standards for individual states (e.g. California's building energy efficiency standards).

Standards related to energy management, life cycle assessment, thermal comfort, etc. (e.g. ISO 14000 family of standards) were widely cited. In this family of standards, ISO 14001 and ISO 14004 are related to the environmental management aspect [193]. The ISO 14040 series, for example ISO 14041 and ISO 14044, focus on life cycle assessment [194,195]. Yet ISO/T 14067, which sets out requirements and guidelines for the quantification and communication of carbon footprints of products [5], was not cited in any of the 101 papers. Besides, the standards of the ISO 50000 series are on the energy aspect. For example, ISO 50001 and ISO 50003 deal with energy management, and ISO 50002 concerns energy audit [196,197]. The ISO 14000 or ISO 15000 standards, however, do not specify requirements on carbon emission of buildings.

In March 2006, ISO 21931-1 was released. Focusing on environmental impact assessment of buildings, the standard provides a method for assessing the life-cycle environmental impact of buildings. The standard was updated in 2010, but carbon emission is not particularly mentioned [198].

Entitled "Sustainability in building construction -- General principles", ISO 15392 was issued in 2008, intended for application to construction works. It sets out objectives of sustainability in buildings and other construction works by considering economic, environmental and social aspects [199]. Nevertheless, carbon emission was not specified in ISO 15392.

Based on ISO standards, several European Standards on building environmental performance assessment, construction sustainability, building energy performance, ventilation for non-residential buildings, etc. were developed (e.g. EN 15251:2008, EN 13779:2007). EN 15978:2011, in particular, specifies requirements on sustainability of construction works.

Among the tabulated national/state standards, the one that recorded the highest number of citations from the papers reviewed is National Standard for Energy Efficiency Design of Public Buildings (GB 50189-2015), followed by California's building energy efficiency standards Title 24. The remaining national/state standards, such as National Standard for Energy Efficiency Design of Public Buildings (GB 50365-2005), Guidance for Managing Sustainable Development (BS 8900:2006), are mostly on energy and sustainability. The Australian National Carbon Offset Standard, in particular, stipulates specifications on carbon emission.

Guidelines published by the Chartered Institution of Building Services Engineers (CIBSE) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are the main professional documents cited in the papers reviewed. ASHRAE 90.1 is an energy standard for buildings that provides minimum requirements for energy-efficient design and construction of new buildings [203]. As a benchmark for commercial building energy codes for more than 35 years [204], it was cited in 9 of the papers that are related to building energy simulation. The other ASHRAE guidelines - No. 14 and No. 140 - are for building energy management and building energy analysis, respectively. The latter provides guidance mainly for computer simulations [205,206].

Besides the above-mentioned standards/guidelines, 14 others were cited in 29 of the papers reviewed. For the remaining 54 papers indicated in Table 3, no particular standards or guidelines were referenced.

As buildings contribute to one-third of the global carbon emission and operational energy consumption in buildings accounts for 70%-80% of the total energy use throughout the whole life cycle of buildings [200], ISO 16745 was introduced as the first international standard for measuring carbon footprint of buildings. Following the principles enumerated in ISO 15392, ISO 16745 sets out methods for the calculation, reporting and communication of a set of carbon metrics for GHG emissions arising from the measured energy use during the operation of an existing building, the measured user-related energy use, and other relevant GHG emissions and removals [200-202]. This standard, introduced in 2017, was not mentioned in any of the reviewed studies (between 2000 and 2018). This finding was not unexpected as there is always a time lag between the release of a standard and any study conducted based on that standard.

3.5 Places of matters and investigation focuses of the studies reviewed

The matters investigated in the 101 reviewed studies span 24 countries/places, with 10 of them in Europe (e.g. Germany, Sweden, Spain, etc.). It can be seen from Fig 6 that the U.S., China, the U.K., Australia, Canada and Europe collectively accounted for the largest proportion. These places, meanwhile, are the major contributors of carbon emission in the world. In particular, the U.S. and China together accounted for half of the distribution. Although India and Russia are also major contributors of carbon emission, they were not the common places where the studies were conducted. Five of the reviewed studies, each of which investigated some commercial buildings in different parts of the world instead of a particular place, were grouped as “Mixed” in Fig. 6. 10 other studies, grouped as “Others”, were focused on some places not belonging to any of the preceding groups.

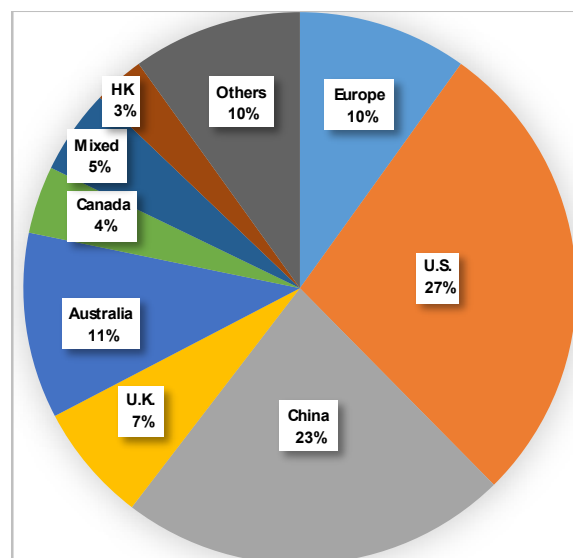


Fig 6 Places of matters investigated

The investigation focuses of the studies can be categorized into 9 groups. The frequency of the papers in each of these groups is shown in Fig 7. In some studies, the objective was to estimate the effect of building energy conservation technologies or carbon mitigation strategies while carbon audit or economic analysis was also used

for comparison and illustration purposes (e.g. [129], [154]). The hottest research focus belongs to technologies/strategies group (a total count of 42), followed by energy audit (29) and carbon audit (22). The other investigation focuses, in descending order of popularity, are as follows: 15 papers on the economic aspect (e.g. cost-beneficial analysis or economic evaluation of the energy cost of buildings), 13 papers on life cycle assessment (e.g. assessment of carbon emissions throughout a building lifecycle), 12 papers reporting on studies that analyzed the factors affecting building energy performance or carbon emission, 8 papers on policies related to carbon emission, and 7 papers that concerns approaches to energy audit or carbon audit. Other investigation focuses (e.g. social aspect) that appeared only once or twice were grouped as “others”.

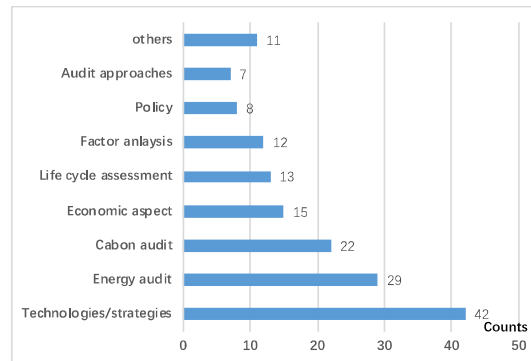


Fig 7 Investigation focuses of the studies reviewed

3.6 Building and resources types investigated by the studies reviewed

The focus of this review is on commercial buildings. Yet different researchers, depending on their practice or the common naming system in their respective places, may refer to commercial buildings as “office buildings”, “commercial office buildings”, or “retail buildings” etc. Moreover, some studies investigated both commercial and some other types of building (e.g. residential building), with an objective of comparing the energy use or carbon emission of different types of buildings. Among the 101 papers reviewed (Table 4), most of the buildings studied were office buildings (43 nos.) or commercial buildings (41 nos.). There were 6 buildings that are commercial office buildings. Coincidentally, there were 3 commercial and residential buildings, 3 commercial and institutional/public buildings, and also 3 retail buildings. In some studies, buildings called as “urban buildings”, which share similar functions of office buildings, were covered. These cases, belonging to the “others” group, were also reviewed.

Table 4. Building types of the studies reviewed

Building types	Counts
Office buildings	43
Commercial buildings	41
Commercial office buildings	6
Commercial and residential buildings	3
Commercial and institutional/public buildings	3
Retail buildings	3
Others	2

Total	101
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Most of the papers involved energy audit or carbon audit, for which consumptions of resources such as electricity, natural gas, etc. were quantified (Table 5). In determining the corresponding amount of carbon emission, the prevalent method was to multiply the amount of resources consumed by the respective carbon emission factors. Of all the papers reviewed, a major group (37%) considered only the consumption of electricity in determining the amount of carbon emission. In the other studies, some also quantified the amount of carbon emission due to the consumption of natural gas (22%) or natural gas plus fossil fuels (18%). Only one study considered fossil fuels only; three other studies considered consumptions of water plus electricity, gas, etc. However, 15 of the reviewed papers did not mention the types of resources covered when determining the amount of carbon emission. This part of the review shows that different studies may cover different scopes of carbon emissions. When comparing carbon emissions from different studies, therefore, it is essential to ensure that their comparison basis is the same.

Table 5. Types of resources studied in the papers reviewed

Resources	Counts	Percentage
Electricity only	37	37%
Electricity and natural gas	22	22%
Electricity, natural gas and fossil fuels (oil, coal, etc.)	18	18%
Electricity and fossil fuels (diesel, etc.)	5	5%
Fossil fuels (diesel, etc.)	1	1%
Water consumption and others (electricity, gas, etc.)	3	3%
Not specified	15	15%
Total	101	100%

3.7 Data collection methods of the studies reviewed

For the studies reported in the 101 papers reviewed, a variety of methods were used to collect data. Such methods fall into eight groups (Table 6). Belonging to the first group, there are 18 papers where the data analyzed were acquired via questionnaire survey, interview, focus group meeting or consultation. In the second group (14 papers), the data of those studies were collected by on-site survey, field audit or other audit surveys. With a comparable amount of papers (15 nos.) covered, in the third group, primary data were amassed by means of sensing, monitoring, or on-site operation/measurements.

Different from the preceding three groups, the fourth group – retrieving data from the records or bills (e.g. electricity, water) of building company/owner – was used in the studies reported in 23 papers. In fact, data retrieval was adopted in many other studies; as identified from the review, data were retrieved from yearbooks or official statistics for the studies reported in 24 papers. Retrieving data from other databases or sources was used in many simulation studies, and there are 30 papers in this group.

In contrast, using data obtained from reviews of literature or publications was not prevalent, but there are still 11 papers belonging to this group. A slightly larger amount of papers, in total 15 of them, were found to have their studies conducted based on some conceptual data/assumptions. Among this group of studies, some did not specify the method used to collect data.

Note should be taken that for studies that collected energy consumption data by referring to energy bills or building owner’s operational records, it is necessary to distinguish whether the data pertains to only the building’s common area (e.g. lobbies, corridors, etc. whose air-conditioning is provided by a centralized system) that belongs to the landlord, or both the common area and the tenant area rented for use by individual tenants. Typically, energy use of centralized systems is paid by building owners, while the tenants are responsible for the energy used by the facilities (e.g. de-centralized fan-coil units) serving the area they rented. Among the papers reviewed, merely two studies specified that their energy data refer to the energy used for common area [100,145].

Table 6. Data collection methods used for the studies reviewed

Data collection methods	Papers	Counts
Questionnaire survey/ interview/ focus group meeting/ consultation	[95,97,105,102,118,124,125,134,146,148,152,156,160,162,165,167,175,177]	18
On-site survey/ field audit/ other audit surveys	[101,123,120,122,124,134,135,142,148,154,159,165,188,192]	14
Sensing/ monitoring/ on-site operation or measurements	[22,95,102,106,119,120,128,132,134,135,158,159,166,174,180]	15
Data retrieval from company/owner records or bills	[22,25,95,98-101,122,120,122,138,141,145-147,154,165,170,175-177,181,186]	23
Data retrieval from yearbooks or official statistics of governments	[25,99,110,115,116,118,121,122,125,138,144,146,148,149,151,157,164,165,169,170,176,181,186,190]	24
Data retrieval from other databases or sources (especially for simulations)	[96,103,107,113,114,123,126,127,129-131,133,136,139,141,153,155,163,168,172,173,175,176,179,181-183,187,189,191]	30
Review of literature/publications	[98,101,111,118,143,146,147,149,152,165,178]	11
Conceptual data/assumptions or unspecific methods for simulations	[104,108,109,117,130,137,139,140,155,161,171,184,185,189,207]	15

3.8 Data analysis methods of the studies reviewed

The methods adopted by the studies in data analysis broadly fall into two groups. One group consists of simulation studies and the other covers those using analytical techniques such as statistical analysis, factor analysis, and so on (Table 7).

Besides the most popular and classic software (i.e. Energy Plus, Transient System Simulation Tool (TRNSYS) and Design Builder) adopted for building energy simulation (Table 7), software including Distributed Energy Resources Customer Adoption Model (DER-CAM), e-Quest, Integrated Environmental Solutions – Virtual Environment (IES-VE), Open Studio and Consoclim also support building energy simulations [104,208-211].

In addition, Building for Environmental and Economic Sustainability (BEES) combines both energy and economic aspects for building simulations [129,212]. IDA Indoor Climate and Energy (IDA ICE) takes into account not only building energy but also thermal indoor climate in simulations [213]. National Energy Modelling System (NEMS) was employed for energy simulation of commercial buildings [169,214]. Long-range Energy Alternatives Planning System (LEAP) enables energy policy and forecasting analysis modeling [181,215]. ESRI ArcGIS can help develop spatial maps of heating energy savings and cooling energy savings [164]. TRACE™ 700, mainly for HVAC systems, can be used to gauge energy use and life-cycle cost [146,216]. Apart from using software to carry out computer simulations, other modeling methods were also used in the studies reviewed. For example, Non-Intrusive Occupant Load Monitoring (NIOLM) was introduced for monitoring the occupancy in a

building or a room so as to estimate the energy-load [174].

Whereas regression analysis and sensitivity analysis were commonly used in the studies reviewed, basic calculation, found with 18 papers, was the most popular analytical method used to analyze data (Table 7). In this latter group of papers, many focused on energy consumption calculation. Comparatively, the method of input-output or EIO analysis, found with 5 papers, was less widely used; the use of factor analysis, found with 3 papers only, was even more uncommon. For some conference papers or review papers – in total 5 of them, no particular data analysis method was involved. Their main context is usually descriptive in nature, for example discussion on policy matters.

Table 7. Review on data analysis methods

Methods	Models	Counts	Papers
Simulation/ modeling	LEAP	1	[181]
	ESRI ArcGIS	1	[164]
	Energy Plus	14	[107-109,113,117,118,126,127,131,136,140,168,183,187]
	TRNSYS	6	[116,128,133,171,185,191]
	DER-CAM	1	[145]
	BEES	1	[129]
	IES-VE	2	[124,180]
	eQuest	2	[130,151]
	Design Builder	4	[98,113,114,142]
	Open Studio	2	[187,192]
	IDA ICE	2	[102,123]
	Consoclim	1	[104]
	TRACE™700	1	[146]
	NEMS	1	[169]
	Other modeling approaches	9	[106,121,137,141,149,161,174,190,207]
Sub-total	48		
Analytical method	Regression analysis	10	[22,116,138,148,153,155,162,182,188,191]
	Sensitivity analysis	10	[100,108,113,117,128,140,142,183,187,207]
	Input-output analysis/EIO	5	[96,99,100,115,170]
	ENSLIC tool	1	[103]
	Pearson correlation analysis	1	[134]
	factor analysis	3	[120,138,172]
	Basic calculation	18	[25,97,101,106,110,122,119,122,134,142,147,154,156-158,163,165,184]
Sub-total	48		
Not involved	Sub-total	5	[143,150,152,161,178]

3.9 Factors affecting energy consumption and carbon emission

Identification of key factors that affect building environmental performance is an essential step to reducing carbon emissions. Among the studies reviewed, Ye *et al.* [138] found that building energy consumption exhibits a close

connection with square foot area (FA) and number of energy consumption membership (ECM). Besides floor area [113,138], climate [138,188], building age [25] and building structural attributes [113,138], occupants behavior dominates building energy performance and carbon emissions. Number of storeys [25,113] and distance to city center [25,188] are proved to be less influential to building energy use [25]. Contrary to the findings from residential buildings, newer commercial buildings with higher quality tend to consume more energy but they are more resilient to hot weather [25].

Through regression analysis, Ye *et al.* [138] revealed that floor area, number of occupants, local investment have positive relationships with office energy use. Although investment could lead to improvement in energy saving technologies and hence reduction in energy demand, energy wastage or occupants desire for a more comfortable working environment (e.g. cooler or warmer environment, more elevators, brighter offices, etc.) could increase energy use and offset the savings brought by energy-saving appliances [25,138]. If building occupants or tenants face a marginal energy cost, their energy consumption can be largely reduced [25].

The analysis of Ye *et al.* [138] showed that building construction characteristics, socioeconomic environment, climate and microclimate conditions contribute to 32%, 18% and 24% respectively of the building carbon emission in China. Building characteristics such as orientation, plane shape, floor area, plane shape factor, floor height, floor number and window-to-wall ratio are dominant factors of building energy performance. In particular, reducing floor height was observed to be the most effective method for building energy reduction; increasing the plane shape factor and decreasing the floor area are also beneficial to building carbon mitigation [113]. Buildings in severely cold areas consume much more energy than those located in warmer climate zones [188].

While many of the studies reviewed above are from China, they cover various cities – from north to south, e.g. Guangzhou, which is next to places such as Hong Kong and then Singapore. The factors revealed from the above studies can serve as reference for these places as they have similar tropical climates. Nevertheless, the basis of the above review is confined to the studies identified from the literature search process for the current study. Future studies of this kind should review more research that investigates factors that affect the carbon emissions of commercial buildings in other locations such as the U.S.

3.10 Measures for energy conservation and carbon reduction

Recognizing the main factors that affect building environmental performance, various strategies and technologies on energy-saving design and retrofit have been introduced for buildings. As Jiang & Tovey [110] pointed out, effective energy management system, efficient heating, lighting and ventilation through retrofits of walls, roofs and windows, and improved occupants' behaviors are practical energy efficient measures for commercial buildings. The study of Zuo *et al.* [97] revealed that market demand, a clear definition, material selection, construction technologies, facility manager's knowledge, a precedent project, government support, trainings to tenants, industry training are critical for achieving building carbon reduction. Replacing common building materials (e.g. concrete) with environmental-friendly and reusable materials can largely conserve embodied carbon. An exemplary carbon-zero building and the market demand for green building are also best motivators for reducing carbon emission.

Alongside the growing support of the industry and society to the goal of green buildings, government support can help promote the achievement of building energy efficiency. Case studies in the US confirmed that access to comprehensive information about energy saving techniques/strategies and financial incentives are important to making buildings energy efficient [144]. Interviews in the UK showed that due to the relatively low energy cost, building landlords and tenants are indifferent to energy reduction [152].

Since carbon emissions from buildings are mainly due to the use of energy [1], curbing energy consumption should be the most efficient approach to carbon mitigation [181]. Besides training the occupants on energy efficiency or rewarding the tenants for energy saving [162,178], monitoring indoor CO₂ concentration to optimize ventilation was confirmed to be an effective approach to minimizing energy consumption [132]. Installation of sensors and sub-meters for energy monitoring are also useful measures [162,178].

Application of conventional energy efficiency measures such as thermal insulation and daylighting controls can reduce energy use by 20-40% for new commercial buildings located in different climate zones [129]. Energy efficient HVAC system (especially air-conditioners) and lighting system (e.g. compact fluorescent bulbs, LED lights), according to studies in India, the U.S. and Hong Kong [122,132,154], are among the most effective measures on energy reduction. For instance, a combined cooling, heat and power (CCHP) system can save carbon emission by 29% [145] and a combined heat and power (CHP) system can reduce around 20% of carbon emission [168].

Cool roof technology, according to simulation results, can reduce cooling demand in climatic zones [180]. Replacing natural gas furnace with ground source heat pump, as illustrated by experimental results, is an effective method to decrease energy consumption and GHG emission in short- and long-terms [181]. Optimized operation for moderate and small chiller plants, in some case studies, can save up to 40% and 20% of energy use [84]. Switching energy type and changing construction materials can also cut down carbon emissions from buildings [103,162].

The above measures, grouped into different categories such as occupant behavior, energy conservation or management systems, etc., are summarized in Table 8. To facilitate implementation of the measures in practice, in parallel, governments have released various guidelines. In Hong Kong, for example, the Electrical and Mechanical Services Department (EMSD) has published the Energy Saving Tips For Office, in which guidance such as installing thermometers and occupancy/motion sensors, replacing T8 and T12 fluorescent lamps with T5 fluorescent, compact fluorescent or LED, etc., are recommended [217]. Meanwhile, the EMSD has maintained a website on energy efficiency, on which practical and emerging measures as well as related retrofit projects are shown for knowledge sharing purposes [218].

Table 8. Measures for energy conservation and carbon reduction

Category	Measures (and reference sources)
Occupants behavior	Change occupants behavior [162,178]
	Train employee, building managers or tenants on energy efficiency [162,178]
Energy conservation or management system	Install occupancy sensor, load sensor, remote control, CO ₂ sensor, etc. [109,132,162]
	Improve energy efficiency of motors, on-site generation, etc. [162]

	Install sub-meters [162,178]
	Apply energy efficient auxiliary equipment [162]
	Retrofit data centers and server rooms [162]
	Implement energy benchmarking and standardization [178]
	Improve energy management through enhanced analysis and control together with implementation of adaptive energy management strategies [111]
HVAC system	Install facilities for heat recovery and adopt natural ventilation [111]
	Apply combined cooling, heating and power system [145,168]
	Use ground source heat pump (replace natural gas furnace) [181]
	Adopt efficient cooling design with precise refrigerant valves, blower speed controller, and efficient motor [181]
	Install high-efficiency chiller for space cooling [181,184]
	Apply heat and moisture recovery (e.g. energy recovery ventilators, enthalpy exchangers) [178]
	Apply variable frequency drive (VFD) control of pumps [118]
	Apply economizer cycle [173]
	Apply central solar water heating system [122]
	Apply variable air volume (VAV) system [173]
	Replace fossil fuel energy devices with heat pumps [111]
Lighting system	Apply high-intensity discharge ballast [181]
	Apply pulse-starting metal halide bulbs [181]
	Install sensors / automated lighting controls [129,173,178]
	Use compact fluorescent bulbs, LED lights, etc. [111,112,154,173,178]
Building envelope or materials	Use air sealing that can reduce cold drafts and help improve thermal comfort in buildings [109]
	Adopt cool roof technology [180]
	Change reinforced concrete to solid laminated wood [103]
	Apply high-level insulated ceiling/wall/window/ventilation [129,181]
	Change construction slabs from concrete to wood [103]
	Install white wares [103]
Others	Switch from fossil fuels to energy efficient fuels [162]
	Install automatic frequency induction system for the escalators [112]

4 Conclusion

The review reveals that the global carbon emission has continued to rise and, in recognition of this problem, most countries and energy-intensive metropolises such as Hong Kong have introduced schemes for carbon mitigation. Given that buildings, especially commercial buildings, are major contributors of carbon emission, many of the schemes have included incentives or subsidies for implementation of carbon reduction measures in commercial buildings.

Due to the lack of published data and the limited empirical studies on carbon emission or carbon emission intensity of existing commercial buildings, the charts presented above (Fig 2 to Fig 5) can only serve as some general pictures of carbon emission intensity by countries or total energy use of commercial buildings in the

respective locations. In future, if official statistics on particular aspects such as carbon emission intensity of existing commercial buildings are made available, specific analyses can be carried out correspondingly.

The comparisons between the four well-known rating methods show that while carbon audit has been covered, carbon emission is merely an evaluation criterion under the energy analysis category of both LEED and BEAM Plus rather than being a major evaluation aspect - as in BREEAM and Green Star. Whereas various standards on building energy have long been established, the first international standard (ISO 16745) on carbon emission calculation and carbon metrics for existing buildings was not available until 2017. The finding that this standard was not referenced in any of the 101 papers reviewed unveils a gap for future research on carbon emission of existing buildings. Following a common standard in pursuing carbon studies can also enable comparisons of study results on the same basis, such as same scope of carbon emission and same type of building area.

Among the studies reviewed, investigations on energy conservation technologies or strategies were common. Compared with energy audit, carbon audit was not a common investigation focus. A major group of the studies, especially the simulation studies, used data retrieved from some conventional databases, while not many studies collected data through on-site surveys or field audits on individual buildings. More studies that probe into the operational data of real-world buildings (e.g. [219,220]), therefore, should be conducted to provide more empirical findings.

Many of the past studies investigated factors that affect building energy consumption and carbon emission. Measures for energy conservation and carbon reduction, too, have been widely studied. Practical guidelines on the implementation of such measures have also been made available. Despite these efforts, the continuous growth of carbon emission remains a live issue. Future studies that can identify and remove the root cause of this issue, therefore, should top the agenda for this research area.

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