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Levelized cost analysis of indirect evaporative cooling in a data centre

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Given the eruption of AI technology, the cooling requirement in data centres has drawn significant attention due to the increasing demand for data processing and storage. Indirect evaporative cooling (IEC) is a cutting-edge cooling technology with huge advantages of energy economy and environmental friendliness compared with conventional mechanical vapour compression cooling systems. Herein, we perform a levelized cost analysis (LCA) to determine the economic performance and energy consumption of the traditional mechanical vapor compression (MVC) cooling system and a novel hybrid IEC + MVC cooling system in data centre applications. A data centre model is adopted and applied in various climate zones in 10 cities from 8 countries. The results showed that the hybrid IEC + MVC system presented energy savings in all the cities, especially in Riyadh, with an energy saving of 41.3 GWh for the year. Most cities showed cost saving with the hybrid system, with London and Madrid achieving cost savings of 52–53%. All the cities showed significant CO_2 reduction with the hybrid system, especially in Riyadh (23 547 tons), Jeddah (18 740 tons), and Dubai (12 432 tons). This study sheds light on the cost analysis based on levelized cost analysis (LCA) for next-generation cooling technology for data centres.

Sustainability spotlight

Given the eruption of AI technology, the cooling requirement in data centres has drawn drastic attention. Indirect evaporative cooling (IEC) is a cutting-edge cooling technology with huge advantages of energy economy and environmental friendliness compared with conventional mechanical vapour compression cooling systems. Herein, we perform the levelized cost analysis and analyse the economic performance and energy consumption of the novel hybrid IEC + MVC cooling system in data centre applications. Most cities showed cost saving with the hybrid system, with London and Madrid showed 52%–53% of cost saving. This study underpins the following SDGs: Industry, Innovation and Infrastructure (SDG 9), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13).

1. Introduction

Rapid advancements in information technology and the emergence of generative AI systems, like GPT-4, GitHub Copilot, and DALL-E2, have dramatically transformed modern society. Data centres have become an essential infrastructure for managing IT servers and meeting the escalating demands for data processing and storage capabilities. However, this technological evolution presents significant challenges, particularly regarding the substantial energy consumption required to maintain these facilities. According to the International Energy Agency (IEA) report, the global energy consumption for data centres reached 460 TWh in 2022 ($\sim$2% of global power usage), which is about 224 Mt CO_2.[1,2] This figure is projected to double by 2026.[1,2] Notably, cooling systems account for 40% of the data centre power consumption to prevent overheating and equipment damage, emphasizing the imperative for high efficiency and sustainable cooling technologies.[3,4]

The power of the current cooling systems is heavily consumed to dissipate the heat generated by the data servers. Traditional cooling systems typically rely on specialized computer room air conditioner (CRAC) units that utilize mechanical vapor compression refrigeration technology. This technology holds a dominant position in the cooling system market.[4,5] IEC technology presents a significant opportunity as an alternative to traditional vapor compression cooling systems.[6] The coefficient of performance (COP) of conventional vapor compression cooling systems typically ranges from 2 to 4.

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The energy consumption for compressor operation and reliance on refrigerants make them neither sustainable nor environmentally friendly. In contrast, IEC cooling utilizes water as the primary cooling medium, offering a sustainable and environmentally friendly option compared to conventional technologies. Additionally, IEC systems boast an impressive COP ranging from 15 to 21[6], which can significantly contribute to addressing net-zero targets (Table 1) in an energy saving manner. In addition, the effectiveness of the IEC varies significantly with climatic conditions, leading to substantial differences across diverse climate zones.[7] The feasibility of employing IEC technology in various climatic regions has been examined in several studies. Jaber[8] assessed the IEC in three cities under various climatic conditions. Balyani *et al.*[9] and Rao and Datta[10] investigated evaporative cooling performance in Iran and India under various climate zones, respectively. Sohani *et al.*[11,12] evaluated the performance of evaporative cooling in 30 cities across the world. Based on previous studies, the results indicate that the performance of systems varies dramatically with the climate. Consequently, cost analysis is desired to provide insights into the sustainable development of the IEC by integrating geodemographic dependence.

Previous studies have exploited the energy-saving potential of IEC systems in various settings, including human thermal comfort in buildings,[11,13] data centres,[4,14,15] and poultry houses.[16–19] Jaber,[8] Navon and Arkin[20] evaluated the economic feasibility and cost savings of indirect and hybrid evaporative cooling systems, respectively, highlighting significant reductions in CO_2 emissions, payback periods, and electricity consumption compared to traditional systems. Existing cost evaluations of cooling systems primarily adopted life cycle analysis. Moreover, we just summarized several literature about IEC application, with some life cycle cost analysis papers in Table S1. However, the levelized cost of cooling (LCOC) metrics are underrepresented. Levelized cost analysis is particularly useful in the energy sector for comparing the economic viability of technologies that have been applied to energy systems (*e.g.*, levelized cost of electricity) with extensive research on wind,[21,22] solar energy, and energy storage systems (*e.g.*, levelized cost of energy storage).[23] The levelized cost of cooling (LCOC) metric provides a standardized and lifecycle-based economic indicator, allowing for an equivalent evaluation of various cooling systems.

Ibrahim *et al.*[24] conducted an economic assessment of solar-assisted and conventional cooling systems for buildings in Saudi Arabia using the levelized cost annuity method. They found that the solar-assisted system had an annual energy-saving cost of ~USD 137 944 and a payback period of about five years. Liu *et al.*[25] analysed a solar-assisted combined heat and cold storage system using the levelized annual cost model, revealing a payback period of 17.13 years. Lee *et al.*[26] conducted an economic assessment that compared electric heat pumps (EHP) and gas engine heat pumps (GHP) for medium space cooling using the levelized cost annuity method. The study found that EHPs are more cost-effective from the primary energy and final consumer perspectives. There remains a significant research gap in the application of indirect evaporative cooling systems within data centres, particularly from economic, environmental, and social impact perspectives.[6,27] Moreover, variations in climate and economic conditions need to be considered, as they can lead to significant differences in outcomes across different countries.[8–12]

This study addresses the existing research gap in the field of advanced energy-saving cooling systems for data centres from both economic and environmental perspectives through the following key dimensions:

1. Employing an advanced hybrid IEC + MVC system in a realistic data centre model to explore the energy saving potential compared to the conventional MVC cooling system.

2. This research explores the economic feasibility of the employed hybrid IEC + MVC cooling system by adopting a levelized cost model to assess its lifetime financial performance in large-scale data centre applications and compares its cost performance with that of the conventional MVC system under the same operating conditions. Moreover, the reduction potential in carbon dioxide emissions associated with the electricity consumption required to operate the cooling systems is evaluated.

3. Expanded research in various climate zones with 10 cities from 8 countries by applying realistic hourly climate data for one whole year to explore the possibility and performance of hybrid and conventional systems.

2. Methods

The methodology begins with a data centre case study, which is then extended to simulate two cooling systems across selected cities using a bottom-up cost analysis approach. The overall research methodology is illustrated in Fig. 1a under the trend of considerable global energy consumption in data centres, as depicted in Fig. 1b. Details of the data centre case study and the selected cities are provided in Subsections 2.1 and 2.3, respectively. Subsection 2.2 offers an in-depth description of the hybrid cooling systems. Furthermore, the operational settings of the data centre,

Table 1 The comparison of MVC and IEC[6]

Features	Mechanical vapour compression	Indirect evaporative cooling
Market	Major market share	Growing adoption
COP	Low (2–4)	High (15–21)
Energy	Energy intensive	Energy economic
Environmental friendliness	Use refrigerants	Use water
Maintenance requirement	Regular (compressor)	Minimal (heat exchangers)

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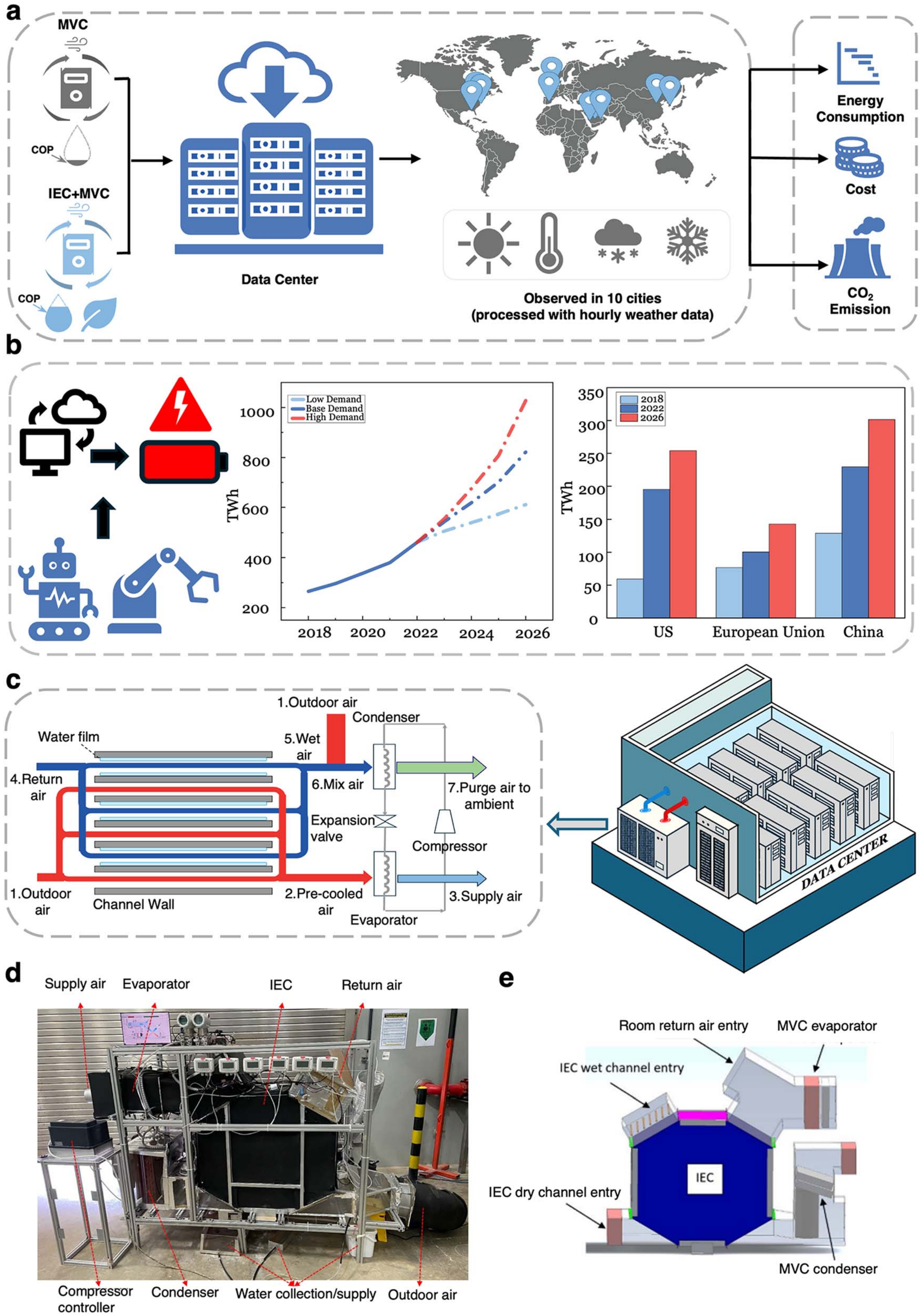

Fig. 1 (a) Research path. (b) Estimated global data centres electricity consumption from 2018 to 2026.[1] (c) Schematic of hybrid IEC + MVC system in a data centre.[13,28–30] (d) and (e) Hybrid MVC + IEC pilot at KAUST.[31]

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along with the individual contributions of the indirect evaporative cooling (IEC) and mechanical vapour compression (MVC) components, are outlined in Subsections 2.4 and 2.5. The methodology for levelized cost analysis is discussed in Subsection 2.6.

2.1 Data centre

To assess the cost of the MVC and IEC + MVC system applications in the data centre, Table S2 illustrates the configuration details of the designated data centre. The data centre is a nine-story building that encompasses an area of 2250 square meters on each floor. There are 720 server racks per floor, with a heat generation rate of 4 kW per rack. The thermal output timetable for server computers is presented in Table S3.[32,33]

2.2 Hybrid IEC + MVC system

Chen *et al.*[13,28,29] developed IEC and MVC systems to improve energy efficiency (Fig. 1c–e). The IEC part is structured of dry and wet channels, where the hot and humid ambient air is channelled into the dry path, while the returned room air (RA) flows through the wet channels. At the same time, water is doused at the starting points of the wet channels. Given that the RA is not yet saturated, the introduced water evaporates, extracting heat from the wet channels and thereby cooling the outdoor air (OA) in the dry channels. After pre-cooling, the out door air (CA) flows through the evaporator of MVC, where it is further conditioned to the desired state before supplied to the room.[13,28,29] Then, the moisture produced in the evaporator can be further utilized as a water source for the wet channels. The air discharged from the wet channels of the IEC cycle is reused in the MVC, where it is combined with outdoor air to be used as the condenser heat sink.[13,31]

2.3 Climate classification and observed cities

To evaluate the levelized cost of two cooling systems in different cities, the data centre was assumed to be situated in various places under diverse climatic conditions. The Köppen–Geiger climate classification system has been adopted,[12,34] which is recognized as the most utilized system for classifying climates. The classification system divides the world climate into five groups: A (tropical or equatorial zone), B (arid or dry zone), C (warm/mild temperate zone), D (continental/cold zone), and E (polar zone). Each zone is extended and categorized by temperature and humidity features; the details of the Köppen–Geiger climate classification system are presented in Table S4. The representative cities were chosen based on the study of Sohani *et al.*[11,12] The cities with the features of applicability of the IEC are selected. Riyadh, London, Windsor, Madrid, Atlanta, another 3 other cities (Beijing, New York, and Seoul), and Dubai are considered with the feature of high data centre density because they are the capital or hold a leading position in the country. Jeddah is included to test the difference with Riyadh. The observed city temperature and humidity with climate classification are summarized in Table S5. The annual weather condition details are shown in Fig. S1.

Table 2 Thermal guidelines for data centres by ASHRAE 2021 (ref. 35)

	Equipment environment specifications for air cooling equipment under operation	
Equipment classes	Dry-bulb temp. (°C)	Relative humidity (%)
Recommended A1–A4	18–27	50–70%

2.4 Data centre criteria

Temperature and humidity are controlled for servers working under the recommended conditions of the ASHRAE standard (Table 2). Based on the recommended dry-bulb temperature and relative humidity, the maximum humidity ratio of the data centre is (dry-bulb temperature: 27 °C; relative humidity: 70%). The dry bulb temperature in the data centre is managed by cooling systems from 25 °C to 27 °C.

2.5 IEC + MVC operation condition of the hybrid system

To optimize the efficiency of cooling systems, Chen *et al.*[28,29] proposed a hybrid cooling system for residential usage. In this study, we propose a hybrid system combining an indirect evaporative cooler (IEC) and mechanical vapour compression (MVC) for data centre applications. The observed hourly weather data for 10 cities in the same year (2022) are collected from the Visual crossing database.[36] Python is adopted for data selection and analysis. The operation condition is set as follows: when the humidity ratio is greater than 15.7 g kg^{-1}, only the MVC unit is working; if the humidity ratio is less than or equal to 15.7 g kg^{-1}, and the temperature is above 25 °C, only the IEC part operates. The energy consumption of hybrid IEC + MVC is compared with MVC in each month, and the energy savings for each city are calculated. As the situation varies in different countries due to the weather and economic situations, cost analysis is conducted in 10 cities for 8 countries.

2.6 Levelized cost analysis

This research applies the levelized cost method to calculate the annuity levelized cost of cooling energy (LCOC). This method considers the cost drivers from the payments of the investment stage over the operating process to life end recycle to derive the levelized annual total cost ($LACOC_{tot}$). The cost represents equivalent annual payments, discounted to their present value, encompassing all cash flows associated with the cooling systems. Five components need to be considered: $CAPC_L$ is the capital cost, MC_L is the maintenance cost, ELC_L is the electricity cost, CC_L is the CO_2 emission cost, and SI_L is the salvage income. The $LACOC_{tot}$ can be assessed using the following equation:[25]

$$LACOC_{tot} = CAPC_L + MC_L + ELC_L + CC_L - SI_L, \quad (1)$$

where CRF denotes the capital recovery factor, which is defined as follows:[24,25]

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \quad (2)$$

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where n denotes the lifetime of the cooling system and i represents the annual discount or the interest rate on average.

The levelized annual capital cost ($CAPC_L$) involves two components: the purchase cost (Z_K) and installation cost (C_{IN}). The purchase cost (Z_K) of the mechanical vapour compression system includes the cost of each component, which is the cooling tower, chiller, condenser water pump, CRAH, and chilled water pump. For the IEC + MVC system, the capital cost includes components of the MVC system and IEC components, which are heat and mass exchanger, filters, air handling units (AHUs), fans, and pumps. The capital cost can be calculated using the following equation:[24]

$$\mathrm{CAPC_L} = \mathrm{CRF}\left(C_{\mathrm{IN}} + \sum_K Z_K\right). \tag{3}$$

The levelized annual maintenance cost (MC_L) is the cost that occurs during the operation of the cooling system. The MC_L is determined by multiplying maintenance during the first year by the levelization factor (LF).[24,37]

$$\mathrm{MC_L} = \mathrm{MC_0LF} = \mathrm{MC_0}\frac{h_{\mathrm{MC}}(1 - {h_{\mathrm{MC}}}^n)}{1 - h_{\mathrm{MC}}}\mathrm{CRF}, \tag{4}$$

$$h_{\mathrm{MC}} = \frac{1 + r_{\mathrm{n,OM}}}{1 + i}, \tag{5}$$

$$r_{\mathrm{n}} = (1 + r_{\mathrm{r}})(1 + r_{\mathrm{i}}) - 1, \tag{6}$$

where the MC_0 denotes the maintenance cost of the first year for each system and $r_{n,OM}$ denotes the annual nominal rate of growth for maintenance cost. Moreover, r_n denotes the annual nominal escalation rate, which reflects the overall yearly rate variation of maintenance and replacement costs. There are two factors: the real escalation rate (r_r) and the inflation rate (r_i); both have an impact on r_n.[24,25,37] Escalation rates indicate fluctuations in the prices of services or products within a certain part of the economy. Inflation rate is one of the factors that affects the escalation rate; moreover, the escalation rate is influenced by market demand, technology changes, environmental or policy effects, *etc.*[38] As the data lack real escalation rates for each country, this study considers only the inflation rate as the factor that influences prices, and the real escalation rate (r_r) is adjusted to 0.

The levelized annual electricity cost (ELC_L) can be calculated using the following eqn (7):[25,37]

$$\mathrm{ELC_L} = \mathrm{ELC_0}\frac{h_{\mathrm{Elc}}(1 - {h_{\mathrm{Elc}}}^n)}{1 - h_{\mathrm{Elc}}}\mathrm{CRF}, \tag{7}$$

where ELC_0 denotes the electricity cost of the first year during the operation, which can be calculated based on the first year energy consumption E (kWh) of cooling systems, multiplied by the unit price of electricity P_E:[24,25]

$$\mathrm{ELC_0} = E \times P_{\mathrm{E}}, \tag{8}$$

$$h_{\mathrm{Elc}} = \frac{1 + r_{\mathrm{n,elc}}}{1 + i}, \tag{9}$$

where $r_{n,elc}$ is similar to eqn (5) and denotes the nominal escalation rate for electricity, affected by the real escalation rate of electricity and the inflation rate:[24,25]

$$r_{\mathrm{n,elc}} = (1 + r_{\mathrm{r,Elc}})(1 + r_{\mathrm{i}}) - 1. \tag{10}$$

The calculation of the real escalation rate of electricity is based on a method provided by the U.S. Bureau of Labor Statistics, which applies the CPI of industry electricity prices.[39]

The levelized annual CO_2 emissions cost (CC_L) is an important factor in the decision-making of selecting the proper technology. Considering the socio-environmental perspective and pollution control, it is important to consider the cost of CO_2 emissions in the cost analysis. The equation is presented as follows:[25]

$$\mathrm{CC_L} = \mathrm{CC_{L0}}\frac{h_{\mathrm{CO_2}}(1 - {h_{\mathrm{CO_2}}}^n)}{1 - h_{\mathrm{CO_2}}}\mathrm{CRF}, \tag{11}$$

where CC_{L0} is the cost of carbon dioxide emissions of the cooling system in the first year, which is calculated using the energy consumption of the cooling system multiplied by the carbon dioxide equivalent (CDE) index. The CDE index is a metric that computes the volume of CO_2 discharged during the process of producing a kilowatt-hour (kWh) of electricity.

There are many options for carbon pricing across the world; however, the most common types adopted are emission trading systems (ETSs) and carbon taxes. The carbon pricing is based on the average price of 2022. For the unit cost of carbon dioxide emissions in a specific country (P_{CO_2}), the equation can be expressed as follows:[25]

$$\mathrm{CC_{L0}} = \mathrm{CDE} \times E \times P_{\mathrm{CO_2}}, \tag{12}$$

where r_{n,CO_2} is similar to eqn (9) and (10) and h_{CO_2} can be expressed as follows:[25]

$$h_{\mathrm{CO_2}} = \frac{1 + r_{\mathrm{n,CO_2}}}{1 + i}, \tag{13}$$

$$r_{\mathrm{n,CO_2}} = (1 + r_{\mathrm{r,CO_2}})(1 + r_{\mathrm{i}}) - 1. \tag{14}$$

As of 2022, the Kingdom of Saudi Arabia and the United Arab Emirates have not implemented any carbon pricing mechanisms within their regulatory framework, nor have they instituted a carbon taxation system or a cap-trade emission trading scheme.

In this work, we propose to consider salvage income (SI_L) in the levelized annuity method to improve accuracy. The salvage income was substituted into the economic assessment, defined using the following equation:[7,8]

$$\mathrm{SI_L} = \left(C_{\mathrm{IN}} + \sum_K Z_K\right) \times S \times \mathrm{CRF}, \tag{15}$$

where S is the salvage value ratio.

The cost analysis parameters and data for the selected cities are presented in supplemental materials (Table S6). To improve accuracy, the average discount rate of the year is adopted.

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Moreover, the inflation rate and the real escalation rate are considered the 5 year average rate, as the electricity price changed a lot in 2022 due to the energy crisis and wars. The lifetime of cooling systems is set at 15 years. In this research, all currencies are converted into USD, and the average exchange rate in 2022 is adopted.[40]

3. Results and discussion

3.1 Performance of the hybrid IEC + MVC system

The hybrid IEC + MVC system was first implemented in the Riyadh data centre, with the MVC system applied as a benchmark. Fig. 2a shows the energy consumption of both systems. Riyadh's annual temperature and humidity are depicted in Fig. S1, highlighting a typical high temperature year-round with an average of 37 °C and low humidity (6.6 g kg^{-1}) in summer. The IEC unit contribution is 100%, achieving 84% energy savings. Monthly saving is shown in Fig. 2b, with 6.1G Wh in July and 6.2 GWh in August, totalling 41.3 GWh annually. Additionally, the hybrid system significantly reduced CO_2 emissions, as shown in Fig. 2c, with a total reduction of 23 500 tons annually, including 3500 tons per month in July and August. The results suggest the significant environmental benefits of the hybrid system, especially in high-demand periods. Chen *et al.*[13] applied the hybrid system in Riyadh for human comfort on a representative day of July and found that the IEC component contributed approximately 60% of the total cooling load, achieving a 50% energy saving compared to a conventional system. The differences in the IEC unit contribution and energy savings within the IEC + MVC system between the two studies are attributed to variations in application, operational settings, and climate conditions. These works reveal that the hybrid IEC + MVC cooling method provides a more sustainable alternative to traditional systems.

3.2 Life cycle cost and levelized cost analysis results

Life cycle cost analysis is adopted as a benchmark of cost analysis metrics to compare with levelized cost analysis (Fig. 2e). The method, which is developed by Sohani *et al.*,[7] considers the same cost factors: levelized annual total cost of cooling system, involved capital cost, maintenance cost, electricity cost, and carbon dioxide cost. Fig. 2d illustrates the cumulative present worth of the life cycle cost and levelized annual total cost for both the MVC system and the hybrid IEC + MVC system over their entire lifetime (year 0 to year 15). To compare the costs of the two cooling systems, by adopting the life cycle analysis technique, it was observed that before year 6, the MVC system had a lower cost, demonstrating economic benefits over the hybrid IEC + MVC system. However, after year 6, the hybrid system exhibited lower costs. The cumulative present value of costs indicates that over the entire 15 year system life cycle, the IEC + MVC system ultimately showed lower total costs.

A comparison of the levelized annual cost of cooling energy (LACOC) indicates that the IEC + MVC system presents economic advantages over the MVC system. Specifically, the levelized annual total cost ($LACOC_{tot}$) of the IEC + MVC system is \$3.1 million, which is significantly less than \$4.51 million for the MVC system. Furthermore, the levelized cost of cooling energy (LCOC) of the hybrid system is \$18 USD per MWh, which is notably lower than \$39.2 USD per MWh for the MVC system. The above results with both economic metrics reveal the economic efficiency of the hybrid system.

Existing studies refer to cost analysis in cooling systems and widely apply the life cycle cost analysis metric. Based on the above results, it can be observed that the levelized annual cost of cooling (LACOC) metric can be used as a refinement and a complementary metric for existing studies in the cost analysis of cooling systems. Moreover, the levelized cost showed the equivalent annual payment and levelized unit cost, which is more intuitive and can compare various technologies fairly when systems have different scales and lifetimes. Additionally, decision-makers of engineering projects commonly need to consider an annual budget plan; the levelized annual cost metric is a more suitable option.

3.3 Performance of the hybrid IEC + MVC system in various cities under differentiated climatic conditions

The Köppen–Geiger climate classification system is employed in this study. Selected cities located in Zones B, C, and D were considered. For each climate zone, a representative city was selected to illustrate the performance of the hybrid IEC + MVC system, along with the corresponding energy savings, IEC part contribution and reductions in CO_2 emission for the whole year, as shown in Fig. 3. Jeddah was chosen as the representative city for Zone B (low rainfall OR MAP <10 × $P_{threshold}$)[34] classified as an arid climate zone to present the system's performance under hot temperature and low rainfall climate with high annual temperatures (16–48 °C, Fig. S1). However, with the influence of humid wind from the Red Sea, the average humidity ratio ranges from 9.1–18 g kg^{-1}. Fig. 3a shows energy consumption that deals with all the year-round cooling requirements in Jeddah. Fig. 3b depicts that the IEC part contributes 59.2% and 32.9 GWh of energy savings for the hybrid system.

London was selected to represent Zone C (T_{hot} > 10 and 0 < T_{cold} < 18),[34] which corresponds to the temperate climate, providing insights into system performance under mild temperatures, without dry seasons (precipitation is relatively evenly distributed throughout the year). Fig. 3d illustrates the energy consumption of primary cooling requirement in warm summer (T_{aver} > 19.5). Fig. 3e shows that the IEC unit provides 100% of the cooling load in London from May to September, saving 1.3 GWh and 1 GWh in July and August, respectively. London's summer low humidity (average 8.7 g kg^{-1}) allows for full IEC part contribution in cooling requirement.

Seoul was chosen to represent Zone D (T_{hot} > 10 and $T_{cold} \leq 0$),[34] which falls under the cold climate category, allowing for the assessment of the system operated in cold temperature but with a hot summer ($T_{hot} \geq 22$).[34] The hybrid system in Seoul achieves 20.6% for the whole year, saving 1 GWh and 1.2 GWh of energy in June and September, respectively. With a hot summer (T_{aver} > 25) but high humidity (average 15.3 g kg^{-1}), Seoul saves 3.7%

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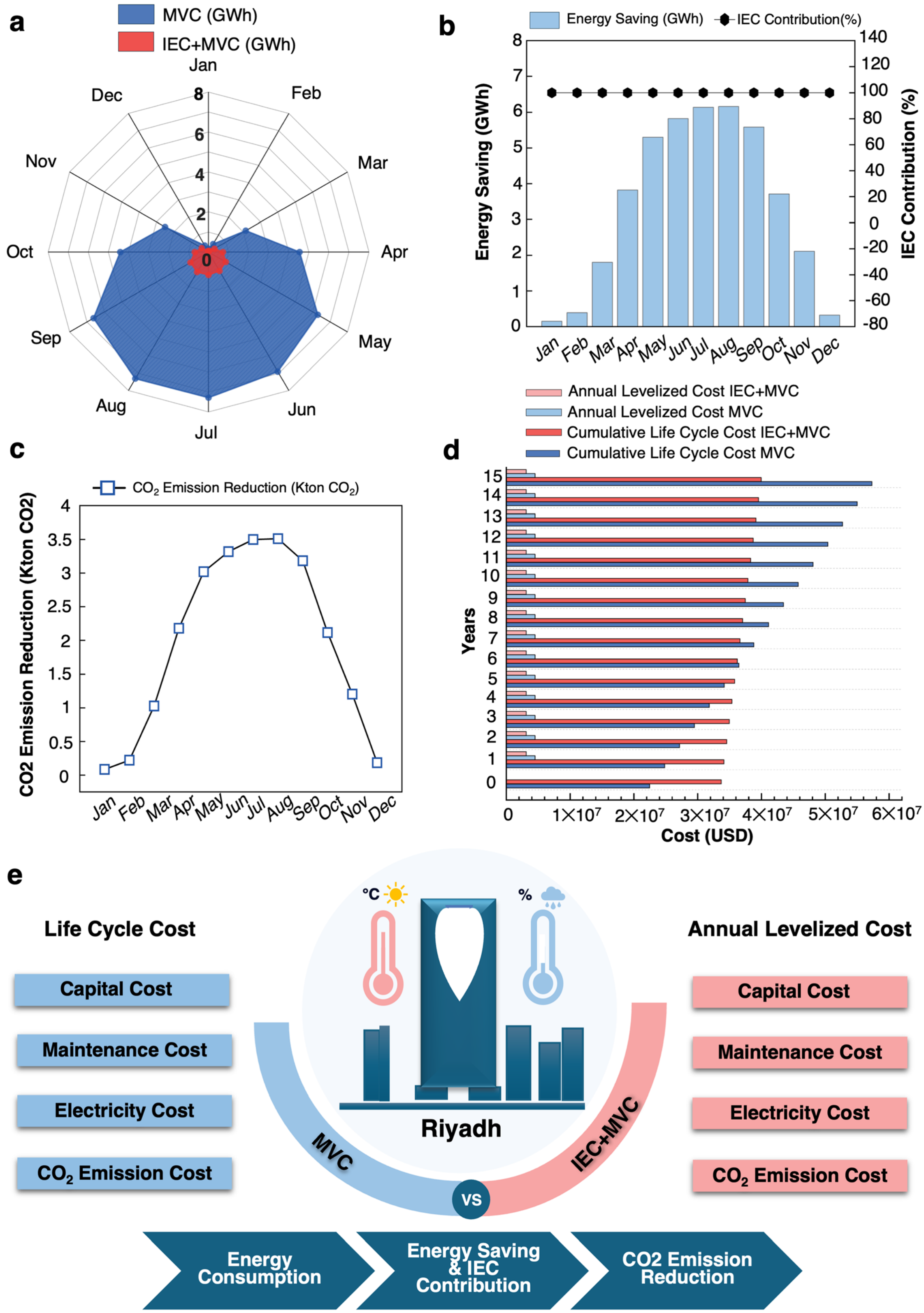

Fig. 2 (a) Comparison of energy consumption for the MVC and IEC + MVC systems in Riyadh. (b) Energy saving of the IEC + MVC system compared to the MVC system and IEC contribution in Riyadh. (c) CO_2 emission reduction of the IEC + MVC system compared to the MVC system in Riyadh. (d) Cost of the MVC system and IEC + MVC system in Riyadh. (e) Concept of cost analysis of MVC and IEC + MVC.

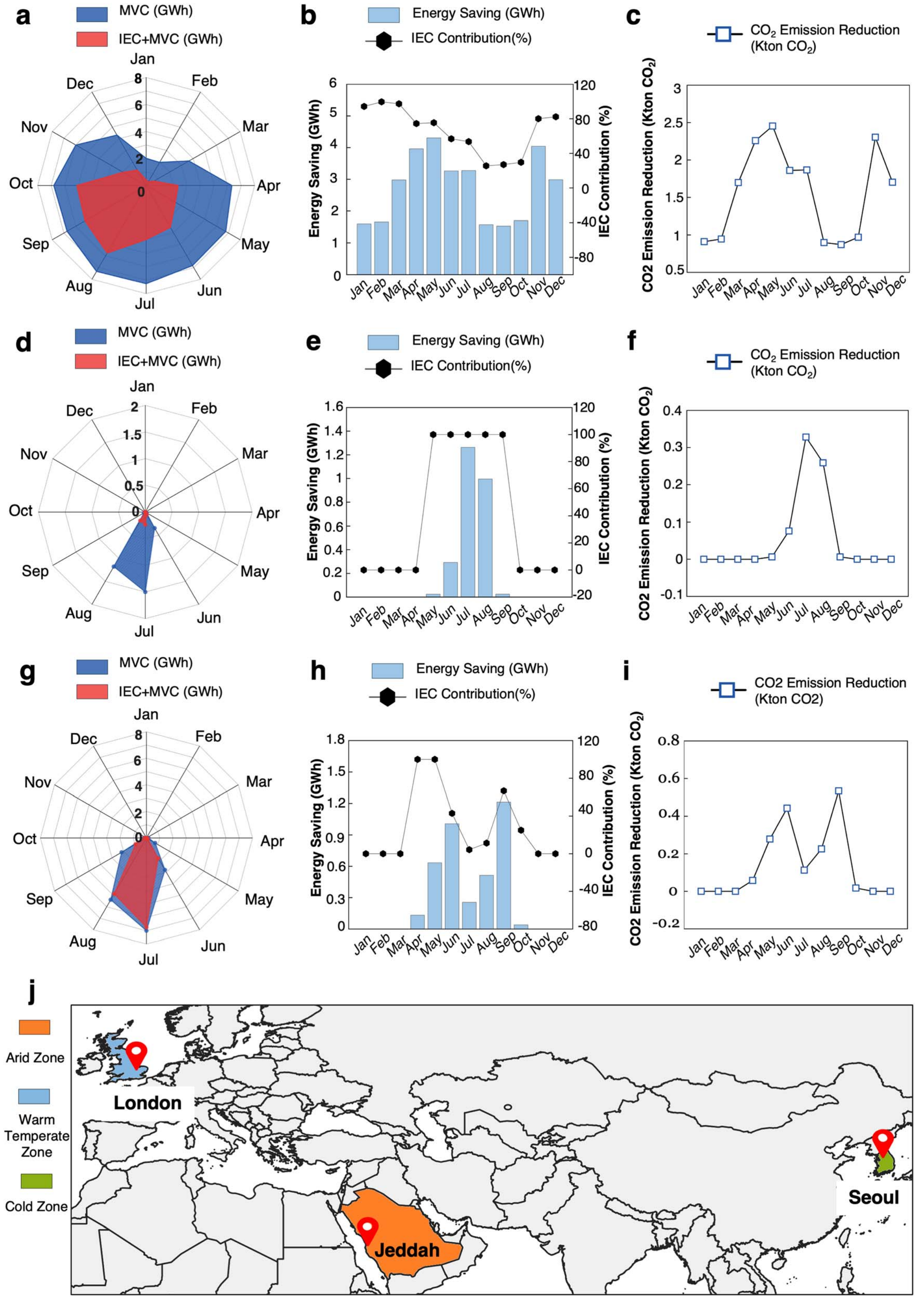

Fig. 3 (a) Jeddah comparison of energy consumption. (b) Jeddah energy saving. (c) Jeddah CO_2 emission reduction in the arid zone. (d) London comparison of energy consumption. (e) London energy saving. (f) London CO_2 emission reduction in the warm temperate zone. (g) Seoul comparison of energy consumption. (h) Seoul energy saving. (i) Seoul CO_2 emission reduction in the cold zone. (j) Köppen–Geiger climate zone distribution map of three locations.[34,41,42]

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and 9.5% of energy in July and August, respectively (Fig. 3h). Fig. 3c, f and i illustrate the monthly CO_2 emission reduction in the 3 cities. The geographical locations of Jeddah, London and Seoul are depicted in Fig. 3j. The remaining observed cities are shown in Fig. S2, S3 and 2.

The hybrid system presents annual energy saving with IEC part contributions for all cities, as depicted in Fig. 4a. IEC part contributes 100% to satisfy cooling requirements and save energy in Riyadh (41.3 GWh), Madrid (14.1 GWh) and London (2.6 GWh). The hybrid IEC + MVC system demonstrates strong performance in Riyadh, which represents cities located in the arid zone with hot temperatures (T_{aver} > 31 from Mar to Nov, T_{summer} > 34), along with low humidity from Mar to Nov (average 5.7 g kg^{-1}). Moreover, the hybrid system performs well in both Madrid and London, which are representative cities located in the temperate zone characterized by hot ($T_{\text{hot}} \geq 22$)[34] or warm summers (not hot summer and $T_{\text{mon10}} \geq 4$).[34] Madrid experiences a dry summer climate, whereas London, despite its overall without a dry season (precipitation is relatively evenly distributed throughout the year) climate profile, maintains relatively low humidity (average 8.7 g kg^{-1}) during the warm summer (T_{aver} > 19.5) period when cooling demand arises. Conversely, the hybrid system demonstrates weak performance in Seoul, which is located in the cold zone (T_{hot} > 10 and $T_{\text{cold}} \leq 0$),[34] representative cities with high humidity from Jul to Sep (average 15.3 g kg^{-1}) despite cooling requirements for hot summer (T_{aver} > 25.2); however, it still presents 24.4% IEC contribution and 20.6% energy saving (3.8 GWh) compared to the conventional system.

The CO_2 emission reduction for the hybrid system, as shown in Fig. 4b, highlights a significant CO_2 reduction across all observed cities. Cities located in Zone B (low rainfall or mean annual precipitation <10 × $P_{\text{threshold}}$)[34] classified as an arid climate zone, with the feature of desert (W) and hot temperature (h) (T_{aver} > 31 from Mar to Nov, T_{summer} > 34), presented the highest CO_2 reductions. Riyadh achieves an 84% reduction (23.55k tons) in humidity from Mar to Nov (average 5.7 g kg^{-1}), Jeddah achieves a 50% reduction (18.74k tons) in humidity from Mar to Nov (average 14.8 g kg^{-1}), and Dubai achieves a 51.20% reduction (12.43 k tons) in humidity from Mar to Nov (average 14.4 g kg^{-1}).

London is located in Zone C (T_{hot} > 10 and 0 < T_{cold} < 18),[34] without a dry season (f: precipitation is relatively evenly distributed throughout the year) and warm summer (b). With cooling requirements in warm summer (T_{aver} > 19.5) and low humidity (average 8.7 g kg^{-1}), the hybrid system reduces CO_2 emissions by 675 tons. Seoul, located in cold Zone D (T_{hot} > 10 and $T_{\text{cold}} \leq 0$),[34] with a hot summer (T_{aver} > 25) but high humidity (average 15.3 g kg^{-1}) achieves a 21% reduction (1.7k tons).

The hybrid system has a strong performance in energy saving and CO_2 reduction across all selected cities, particularly strong in hot (T_{aver} > 31 from Mar to Nov, T_{summer} > 34) and dry (average 5.7 g kg^{-1}) climate, such as those found in Zone B and temperate regions with hot (T_{aver} > 25) or warm summer (T_{aver} > 19.5), typical of Zone C. Conversely, cities with a cold climate (Zone D) or higher humidity, even during hot summer, presented less IEC component contribution and energy saving percentage. This limitation arises from the limited capacity of the IEC component to manage high humidity. These findings are consistent with Chen *et al.*'s research,[13] which indicated that the IEC unit operates more efficiently under a hot, arid climate, with effectiveness diminishing in humid regions.

The meaning of $P_{\text{threshold}}$ is clarified by the Köppen–Geiger climate classification system. The perception threshold ($P_{\text{threshold}}$) varies according to the seasonal distribution of rainfall: if more than 70% of the mean annual precipitation occurs in winter, $P_{\text{threshold}} = 2 \times$ mean annual temperature; if more than 70% of the mean annual precipitation occurs in summer, then $P_{\text{threshold}} = 2 \times$ mean annual temperature + 28; and otherwise $P_{\text{threshold}} = 2 \times \text{MAT} + 14$.[34] Moreover, T_{hot} is the temperature of the hottest month, T_{cold} is the temperature of the coldest month, and T_{mon10} is the number of months when the temperature is above 10.[34]

3.4 Cost discussion for the hybrid IEC + MVC system in various cities under differentiated climatic conditions

Fig. 4c depicts the concept of the levelized cost of cooling (LCOC) in this study. Both the levelized annual cost and the unit levelized cost of cooling (levelized cost per MWh) are considered. The cost analysis results of 10 cities are shown in Fig. 4d–f. Fig. 4d presents the annual cost of the two systems and the cost-saving percentage of the hybrid system compared to the benchmark. The observed cities located in Zones B and C showed cost savings with the hybrid system. However, the observed cities located in Zone D are Seoul, Windsor and Beijing, where the costs were 7.1%, 6.1% and 3.2% higher than those of the conventional cooling system, respectively.

Moreover, the highest cost savings with the hybrid IEC + MVC system appeared in Madrid (53.2%) and London (52.4%), which are located in Zone C. These two cities have higher electricity prices and greater IEC contributions. Due to the significant energy savings from the hybrid system in both cities, these energy savings contribute to substantial cost reductions. This underscores the urgent need to improve efficiency and reduce energy consumption in these countries.

Although cities in Zone B (Riyadh, Jeddah, and Dubai) achieved the most energy savings, their energy costs are competitive, and there is no carbon cost in Saudi Arabia and Dubai. The cost savings in Riyadh, Jeddah and Dubai are 32.8%, 18.3% and 22.2%, respectively. In Seoul, Beijing and Windsor (located in Zone D), the electricity price and carbon price are considerably lower than in London and Madrid. Notably, the electricity price in Windsor is one-third of that in London. Although the IEC + MVC system achieved energy saving in the three cities, specifically achieving 68.5% energy saving in Windsor, the cost savings in electricity and carbon costs are insufficient to offset the high capital cost of the hybrid system from a lifetime levelized cost perspective. Thus, the hybrid IEC + MVC system results in higher overall costs in the three cities.

Even though Fig. 4b shows significant CO_2 reductions in Riyadh, Jeddah, and Dubai, substantial cost savings for CO_2 reduction are observed in almost all cities except these three (Fig. 4e). Madrid shows the highest cost savings for CO_2

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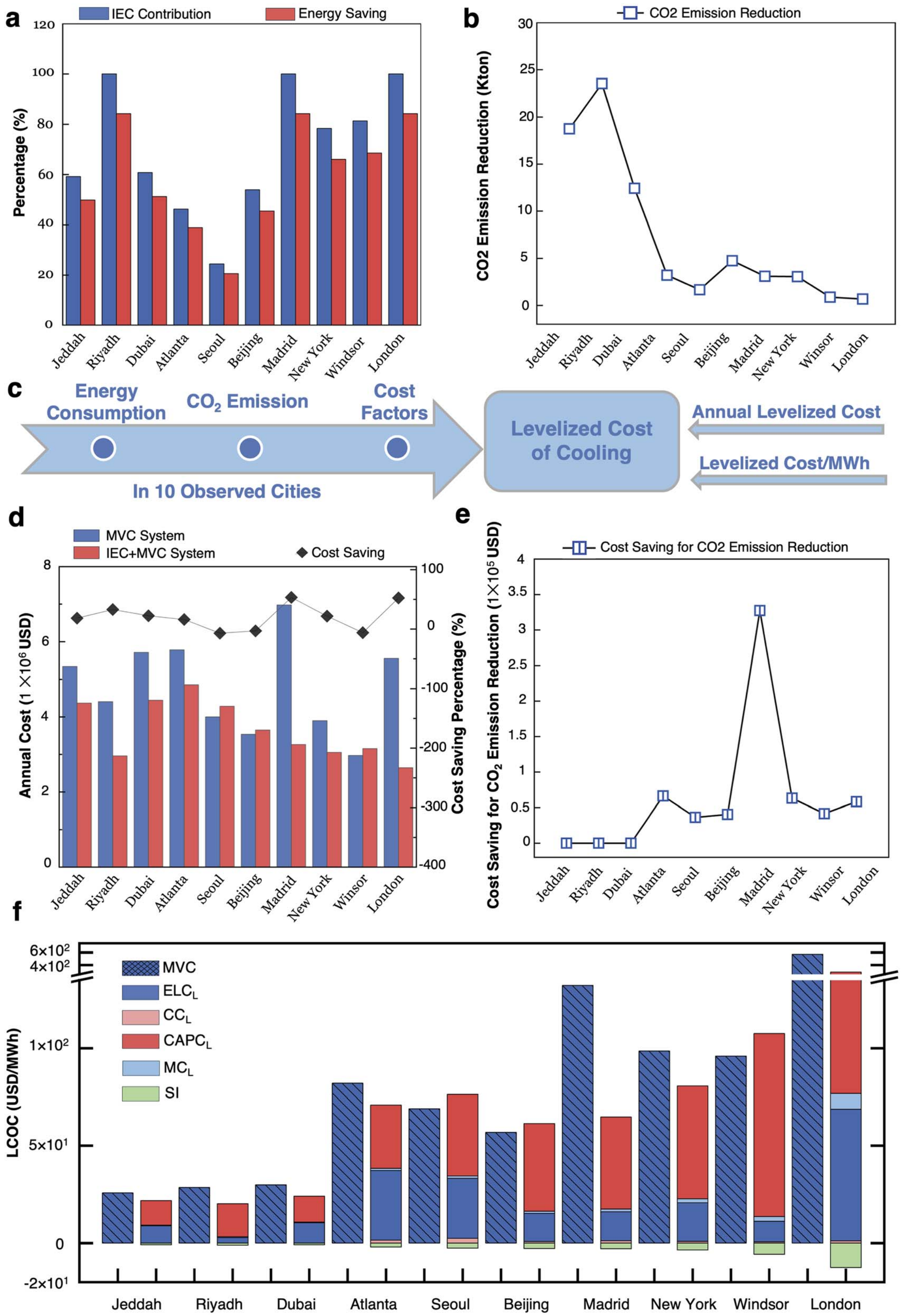

Fig. 4 (a) Annual energy saving and IEC contribution percentage in different cities. (b) CO_2 emission reduction for each city. (c) Concept of the levelized cost of cooling. (d) Annual levelized cost and cost saving percentage of cooling systems for each city. (e) Cost saving for CO_2 emission reduction for each city. (f) Comparison of LCOE (USD per MWh) for MVC and IEC + MVC systems in 10 observed cities, with distribution of cost for the hybrid IEC + MVC system.

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reduction due to significant energy savings and the highest CO_2 pollution costs in Spain among the eight countries. Cities in Zone B have the lowest LCOC of hybrid IEC + MVC systems, with 19.2 USD per MWh, 21 USD per MWh, and 23.2 USD per MWh in Riyadh, Jeddah and Dubai, respectively. Cities in Zone C generally have a higher levelized cost of cooling (LCOC) compared to Zones D and B. However, in Zone D, Seoul, Beijing and Windsor have higher costs for the hybrid system compared to the conventional system (Fig. 4f).

The distribution of cost components in the levelized cost of cooling (LCOC) changes with the transition from MVC to the hybrid IEC + MVC system. With the hybrid IEC + MVC system, capital costs become the largest component; the energy cost percentage decreased significantly in all the observed cities. Notably, the percentage decreased by 47% in London, Riyadh and Madrid. Additionally, the carbon cost percentage is reduced with the hybrid system.

3.5 Salvage income

Salvage income, the residual value of components and materials at the end of their lifecycle, can be recovered and reintegrated into the production cycle. This reduces waste and offsets initial capital expenditures, lowering overall costs. The inclusion of salvage income has reduced the levelized cost of cooling (LCOC) across all cities, with cost savings ranging from 2.8% to 5.2%. The minimum cost saving was observed in Atlanta at 2.8%. In Riyadh and Windsor, the hybrid system's LCOC exhibited cost savings exceeding 5%, decreasing from 20.2 USD per MWh and 107.5 USD per MWh to 19.1 USD per MWh and 101.9 USD per MWh, respectively. Moreover, the ability to reclaim value from used equipment aligns with sustainable practices, enhances economic efficiency, and supports the transition to a more sustainable circular economy.

3.6 Sensitivity analysis

The parameters outlined in Table 3 were systematically adjusted within a symmetrical range to evaluate model sensitivity. The variables were explained (Fig. 5a). Riyadh, London and Beijing are chosen as representative cities for Zones B, C and D, respectively.

The results of the sensitivity analysis of London, Beijing and Riyadh are shown in Fig. 5b–d, with average LCOC of \$272.2 per MWh, \$58.6 per MWh, and \$19.2 per MWh, respectively. Adjusting the system lifetime had the most significant impact, changing LCOC by up to \$76 per MWh in London, \$15.9 per MWh in Beijing, and \$7 per MWh in Riyadh. The system lifetime presented an asymmetric response in LCOC due to its non-linear features. A five-year reduction in system lifetime increased LCOC by \$76 per MWh in London (Fig. 5b), while adding five years increased it by \$10 per MWh.

Table 3 Variables and the range are adjusted in the sensitivity analysis

Variable	Central assumption	Sensitivity range
$CAPC_L$	Variable	±10%
MC_L	Variable	±10%
ELC_L	Variable	±10%
CC_L	Variable	±10%
SI_L	Variable	±5%
Lifetime (n)	15 years	±5 years

In Beijing (Fig. 5c), a five-year reduction in system lifetime increased LCOC by \$15.9 per MWh, while adding five years decreased it by \$7.21 per MWh in LCOC. In Riyadh (Fig. 5d), a five-year reduction increased LCOC by \$6.7 per MWh, and adding five years decreased it by \$3.2 per MWh. $CAPC_L$ significantly impacts LCOC, with changes of \$20.79 per MWh in London, \$4.5 per MWh in Beijing and \$1.7 per MWh in Riyadh. ELC_L has a moderate impact, with a variation of \$6.8 per MWh in London, \$1.4 per MWh in Beijing, and \$0.3 per MWh in Riyadh. MC_L, CC_L, and SI_L showed relatively small impacts. Notably, the inclusion of the parameter "salvage income" (SI_L) in this study has a greater impact on the LCOC than the parameter "maintenance cost" (MC_L). This further underscores the importance of the salvage income (SI_L) parameter and its value in enhancing the accuracy of LCOE cost assessments. Therefore, incorporating this parameter into future levelized cooling cost assessment studies is essential.

3.7 Comparison with previous studies

Direct comparisons with previous studies are challenging because no previous study has investigated the same hybrid IEC + MVC system in a data centre under identical conditions. Previous studies have revealed considerable variations in cooling system design, system operation lifetime, cooling loads, operation conditions, and application scenarios. Therefore, we compare relevant studies from two perspectives: a cost model comparison and a performance comparison.

3.7.1 Cost model perspective. Few studies focus on cost analysis comparing the MVC system or the IEC + MVC system in data centre applications over a spatial domain. To validate the reliability of the levelized cost model in this study, existing life cycle cost analysis research is normalized to an annual levelized basis, which enables a direct economic comparison in the absence of prior MVC-specific data. Specifically, Cho *et al.*[32] conducted a life cost analysis of the MVC system for a data centre in Seoul, which has a similar system and application scenario to the present work. However, the previous study demonstrated the cost as a total life cycle cost over a 60 year lifetime (*i.e.*, 4 cycles × 15 years) with a discount rate of 0.68%. To ensure comparability, this value in the study was converted into an equivalent levelized annual cost by applying the capital recovery factor (CRF), a recognized technique in engineering economics for converting present-value costs into equivalent annual costs.

Based on this conversion, the levelized annual cost (LACOC) of the conventional MVC system reported in the existing research was USD 5,299,820.

In comparison, the levelized annual cost (LACOC) of the conventional MVC system in a data centre in Seoul assessed in this study is USD 4 096 674 when using the same parameters as those employed by Cho *et al.*[32] Moreover, this study involved salvage income, yielding a final levelized annual cost (LACOC) of USD 3 999 463.

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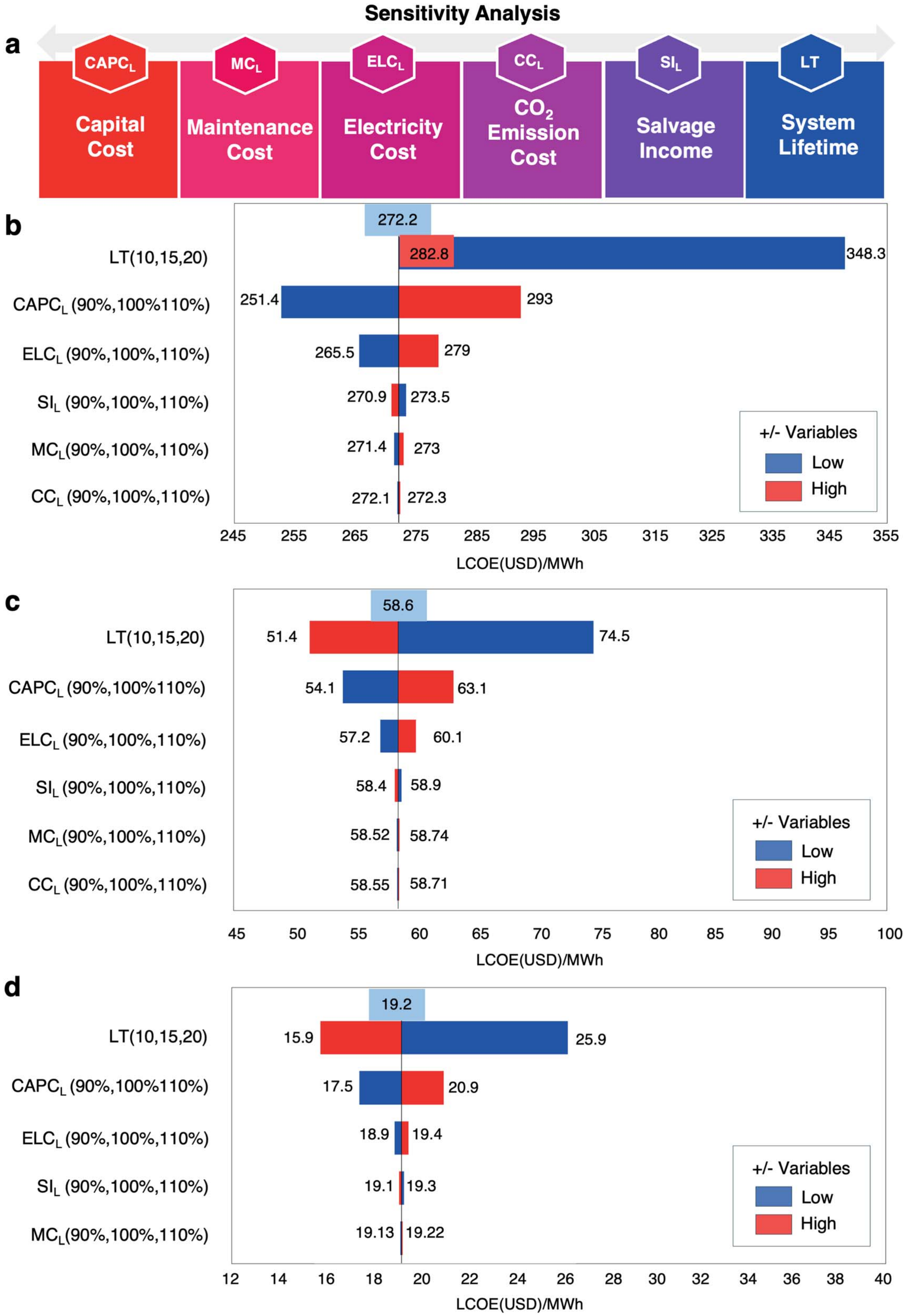

Fig. 5 (a) Illustration of sensitivity variables analysis for (b) London, (c) Beijing, and (d) Riyadh.

Despite a difference of approximately 20%, the findings of the two studies are aligned when considering the following differences in the two studies:

(1) The significant difference between the two studies is the temperature and humidity settings, influenced by updated ASHRAE standards. In Cho *et al.*'s research,[32] the indoor

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temperature and humidity are 22 °C and 50%, respectively. However, in this study, the indoor temperature and humidity are 27 °C and 70% based on ASHRAE 2021, respectively. Energy consumption is significantly reduced due to differences in temperature and humidity.

(2) Salvage income is considered in this research, contributing to the reduced costs within the same city.

(3) The different years of weather data were collected, and the weather data used in this research were collected in 2022, while Cho *et al.*[32] used data from 2017 or earlier.

3.7.2 **Performance perspective.** The primary focus of this study is to assess cost performance. However, the energy-saving potential of the hybrid IEC + MVC system was examined to ensure a comprehensive analysis. Chen *et al.*[13] conducted research with the same hybrid IEC + MVC system and compared it with a conventional MVC system under the application of a building for human comfort in Saudi Arabia. The study demonstrated energy savings of around 25% in Jeddah and 53% in Riyadh. However, the data were based on the evaluation of a single representative day in July, which has the potential to underestimate the whole year benefits of the hybrid system.

By comparison, this study conducted a full-year analysis, thereby providing the results for seasonal climate variability. Therefore, the hybrid IEC + MVC system achieved greater annual energy saving at 49% in Jeddah and 84% in Riyadh in a data centre.

The cooling demand and operation conditions for human comfort and data centre are markedly different; the direct comparison of cost results is inappropriate. To enable a meaningful comparison, a cost saving ratio as a normalized metric is employed. A previous study showed approximately 16% cost savings in Jeddah and 35% cost savings in Riyadh. The corresponding data in this study is 18% cost saving in Jeddah and 33% cost saving in Riyadh.

Strong consistency in cost savings is observed despite significant differences in operational characteristics and scale, demonstrating its superiority over the conventional MVC system in diverse application scenarios. This performance consistency validates both the generalizability of the hybrid IEC + MVC system and the reliability of the levelized annual cost model.

4. Conclusion

This study explored the feasibility of employing the IEC + MVC system for the first time in the observed 10 cities from 8 countries under various climate conditions from both techno-economic and environmental perspectives. The levelized cost annuity method is adopted to calculate the levelized annual total cost of cooling systems. This study incorporated salvage income into the levelized annual cost of cooling (LACOC) model to enhance cost estimate accuracy, which is the first time it has been considered within the levelized annual total cost model for cooling systems.

The hybrid IEC + MVC system demonstrated energy saving, particularly for cities observed in Zone B with arid and hot (T_{aver} > 31 from Mar to Nov; T_{summer} > 34) climates. Significant energy savings were recorded in Riyadh (41.3 GWh), Jeddah (32.9 GWh), and Dubai (31.1 GWh) over the entire year. With relatively strong performance in observed cities in Zone C, temperate regions with hot (T_{aver} > 25) or warm summer (T_{aver} > 19.5), such as London and Madrid. Conversely, the selected cities with cold climates (Zone D) or higher humidity, even during hot summers, presented less IEC component contribution and energy saving percentage, such as Seoul. The IEC unit operates more efficiently under a hot, arid climate; however, its effectiveness diminishes in humid regions due to its limited moisture removal capacity.

The observed cities located in Zones B and C demonstrated cost savings with the hybrid system. Cities with higher electricity prices and greater IEC contributions, such as London and Madrid, exhibited a higher percentage of cost savings, specifically above 52–53%. Sensitivity analysis was conducted for London, Beijing, and Riyadh, revealing that factors such as system lifetime, capital cost, and electricity cost significantly impact the levelized cost of cooling (LCOC). Additionally, "salvage income (SI_L)" has a greater impact on the LCOC than the parameter "maintenance cost (MC_L)". This work is expected to set a new course for future levelized cooling cost assessment studies and encompass the cost analysis for the cooling system in an accurate and dynamic fashion.

However, there are some potential barriers to implementation. As the performance of IEC is highly sensitive to ambient humidity, although the hybrid system with the support of MVC, the performance of the IEC + MVC system depends on the climate situation, thereby indicating that the performance cannot be ensured in regions with low ambient temperature and high ambient humidity. Moreover, the implementation of the hybrid system in water-scarce regions may face barriers, as the IEC part of the system requires water for evaporation to provide cooling.

This study has some limitations, as the environmental impact assessment concentrates on power consumption during operation, which does not include embodied emissions. Additionally, the evaluation of both systems has a limited geographic and climate scope.

Future work will explore the economic feasibility of more cities with hybrid cooling systems, integrating renewable energy sources for electricity supply, which is expected to further decrease the environmental impact. In addition, a comprehensive life cycle analysis over the lifespan is required of the cooling system to assess its environmental impact.

Author contributions

B. B. X., M. W. S. and Q. J. conceived the idea. Q. J. collected the data and carried out the data processing and analysis. M. A. J. helped with the computational formulae used in the analysis. Q. J. created the scientific figures included in the manuscript. The manuscript was drafted by Q. J., B. B. X., M. W. S., C. J. C. N., W. W. and L. Z. All authors reviewed and approved the manuscript. B. B. X. and M. W. S. supervised the project.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability

Additional datasets can be obtained from the corresponding authors upon reasonable request.

The data supporting the findings of this study are available within the article and its supplementary information (SI) file. Supplementary information is available. See DOI: https://doi.org/10.1039/d5su00696a.

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