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Environmental and Economic Evaluations of Building Energy Retrofits: Case Study of a Commercial Building

Linzi Zheng[1] and Joseph Lai*

Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China

Abstract

Implementing energy saving measures (ESMs) in buildings is a critical part of the global de-carbonization process. To private building owners, the cost-effectiveness of ESMs is a major concern. To public policy makers, maximizing carbon reduction within budgets is a common goal. As such, a plethora of studies have been pursued to evaluate the economic or environmental effectiveness of ESMs; however, the reliability of their results are often uncertain due to the dearth of real data. This paper reports a case study on evaluating the retrofit adopted for the air-conditioning (AC) system of a commercial building in Hong Kong. Using longitudinal energy and cost data of the AC system, the economic performance of the retrofit was evaluated by analyzing its net present value and return on investment, and an indicator known as 'carbon reduction efficiency' was introduced to assess the environmental-cum-economic performance of the retrofit. Besides the development of a scaling factor that accounts

*Corresponding author. Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong SAR, China. Tel: (852) 2766 4697; Fax: (852) 2765 7198.
Email addresses: bejlai@polyu.edu.hk (Joseph Lai), h1099026@connect.hku.hk (Linzi Zheng).

for the climatic influence on AC energy use, the effect of equipment degradation on the long-term environmental performance of the retrofit was revealed. Providing empirical evidence of economic or environmental effectiveness of ESMs, this study illustrates a rigorous, pragmatic approach to evaluating retrofit projects in real-world buildings.

Keywords: Air-conditioning; carbon; economic; energy; environment; retrofit

'Declarations of interest: none'

1. Introduction

The demand of implementing building retrofits, especially those energy saving measures (ESMs), is getting widespread and urgent [1, 2]. It is widespread because energy is needed for running a variety of building services installations such as air-conditioning (AC) and lighting that are essential to the activities of a great many people in the modern society. The urgent demand is resultant from the increasingly considerable building energy consumption, which has contributed to acute environmental problems, including the rising greenhouse gas emissions (or carbon emissions) around the world.

Despite the worldwide recognition of the importance of ESMs in environmental conservation, getting the ESMs implemented remains a lingering goal of many building owners [3]. A candid reason for this grudging behavior of the owners of private buildings is their concern on the real benefits and costs of the ESMs [4]. To the owners in the public sector, they are keen to know, given the budget available, how well the environment could be improved by implementing the ESMs [5]. To strike an optimal balance between the often-constrained financial budget [6] and the need of minimizing the environmental impacts of building energy use, it is imperative to realize the cost effectiveness of different ESMs, thereby determining their priority order for implementation in real-world buildings.

Running in parallel to the call for implementing ESMs is the inquiry into their empirical performances. The owners of both the private and public buildings have been in need of credible information that can assist them to make ESM-related decisions [7, 8, 9]. To this end, researchers have endeavored to conduct environmental or economic evaluations of various ESMs [10].

In fact, a great deal of hypothetical ESM evaluations have been promulgated, but the lack of real data is an impediment to the rigor of the evaluations. Without detailed empirical data, many researchers resorted to using market-average data simulation approaches [11, 12]. The use of market-average data, however, tends to average out the unique performances of certain ESMs in different contexts. Although using a simulation approach for evaluation purposes allows a comprehensive incorporation of possible costs and benefits of the ESMs into analysis, the downside is that it could be too complicated for application in practice. In most cases, assumptions are made in the simulations and, where the assumptions are over-simplified, the evaluation results are skeptical and thus could hardly go far in facilitating ESM-related decisions.

In view of the shortage of credible, empirical evaluation studies on ESMs, a research project was initiated to evaluate the economic and environmental performances of ESMs that had been implemented in buildings. For this purpose, Hong Kong was selected as the investigation base since it has an astonishing high-rise, high-density built environment where the energy consumption of buildings is remarkably intense and the associated carbon footprint has continued to enlarge [13]. In addition, it is well acknowledged that Hong Kong as an international, harbor city lacks indigenous energy resources; the Government has recognized implementing ESMs in buildings as a crucial issue. Under the Hong Kong Energy Saving Plan 2015, a target is that, by year 2025 and with 2005 taken as the base year, the city’s energy intensity will be reduced by 40% [1].

Shown in the next section is a review of the literature related to the research project. Then, an in-depth case study completed under the project, its research method and the characteristics of the building studied as well as the ESMs implemented in the building will be reported. After presenting the detailed economic and environmental evaluations made on the ESMs, the conclusions drawn from the case study, including particularly the implications to setting policies on energy saving of existing buildings, are given.

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2. Literature review

2.1 Environmental evaluation of ESMs

The existing attempts of analyzing environmental impacts of ESMs in buildings are mainly through studying the amount of energy saved and/or carbon emission reduced. Many researchers placed a particular emphasis on the operational energy (OE) used for maintaining the indoor environment during the building service life [14, 15, 16]. These studies essentially fall into two categories, namely, empirical research and simulation research.

Relevant empirical studies, using the data collected from interviews or case studies, were often based on qualitative data. For example, Teng et al. [17] analyzed the relative importance of ESMs to hotel buildings based on opinions of practitioners in Taiwan's hotel industry. Dequaire [18] investigated the impacts of different energy-efficient retrofits by interviewing the key personnel of four school buildings in Austria. Bernardo et al. [19] carried out a study that was "indirectly" about the quantitative evaluation of ESM in buildings. They firstly proposed a strategy for assessing energy performance and indoor climate by conducting a case study in a Portuguese building context. Based on their assessment strategy for ESMs, they anticipated that a better usage of daylighting and a reduction of fresh air flow rates could achieve an energy consumption reduction of 11.2% and 4.5% respectively.

In the midst of conducting environmental evaluation of ESMs, a common hurdle is the lack of real data. To circumvent this hurdle, an alternative is to use simulation models. For instance, Gupta and Gregg [20] simulated the carbon footprints before and after two discrete deep energy-efficient retrofits in a Victorian house and a modern house in the UK. With the combined use of a simulation software and the computation of a "virtual environment" applied to a 35-year-old building in Mauritius, Oree et al. [21] found that the best potential of ESMs for the building was 5.52% reduction in the consumption of OE. Sun and Hong [22] adopted a computer simulation method to estimate the energy savings of occupant behavior measures in buildings. Similarly, using an energy simulation and optimization tool, Kim et al. [15] established an optimal occupant behavior that can simultaneously reduce energy consumption and improve indoor environmental quality. Asadi et al. [23] employed a simulation-based scheme to optimize the retrofit cost, energy savings and thermal comfort of a residential building. Using whole-building simulations, Baniassadi and Sailor [14] identified significant impacts of underlying climate in a particular region on performances of ESMs in buildings.

2.2 Lifecycle environmental impacts of ESMs

In addition to the studies focusing on the OE of buildings, research concerning impacts of ESMs on the embodied energy sequestered in building materials and components, from production to final demolition [24], also existed. These studies generally pertain to the lifecycle assessment of the energy used by buildings. Perhaps due to the manifold connections and the complexity therein [25], researchers frequently resorted to the theoretical modelling approach and the use of assumed figures in their assessments. For instance, Kneifel [26] tried to estimate the lifecycle energy savings, carbon emission reduction, and the energy efficiencies of commercial buildings in the US. The data used for the estimation were based on assumptions and the aggregate average of 12 buildings. For a similar estimation purpose, Pal et al. [27] proposed a lifecycle simulation-based approach to demonstrating the minimized lifecycle carbon footprints and costs achievable by adopting seven ESMs in the building design stage.

Another approach commonly used for lifecycle ESM evaluation is the assessment of energy returned on energy invested (EROEI) [7, 25, 28]. Being a well-known concept in energy economics, EROEI expresses the ratio of the amount of exergy delivered from a certain energy resource to the amount of exergy used to obtain that resource [29]. The work of Kuusk et al.

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[7], for example, applied the EROEI concept to evaluate ESMs in the building context based on a combined use of case data and assumed figures.

2.3 Economic evaluation of ESMs

Notwithstanding the potentials of ESMs as shown in the studies above, an "energy-efficiency gap" [3] seems to be persistent, according to the often-heard assertion that the practical ESM implementation is below a desired level [7]. As it is important to identify issues surrounding investors' real options about ESM implementation in buildings [12], many researchers have endeavored to measure the financial gains of implementing ESMs in buildings [3, 12].

To facilitate the determination of the return on investment (ROI) of ESMs in buildings, Pearce et al. [3] adopted a mathematical modelling method to develop a graphical tool depicting the payback and device lifetime. Using assumed figures about the associated economic benefits and costs, Nikolaidis et al. [30] calculated the net present value (NPV) of implementing ESMs in a Greek house. They showed that lighting retrofit, roof insulation, and use of automatic temperature control system are the most financially significant amongst all the examined ESMs within a uniform evaluation period. Based on the data from documented case studies and assumed values of ROI variables, Chang et al. [31] developed a discrete-event simulation model to investigate the varying costs of different maintenance strategies after implementing energy-efficient building retrofits.

Interested in examining any conflicts between the goals of cost optimality and nearly zero-energy buildings, Ferreira et al. [32] used the data of energy needs in residential buildings computation in order to determine the most cost-effective packages of ESMs for achieving the net-zero energy target in Portuguese multifamily buildings. Also in the context of the Portuguese building sector, Tadeu et al. [12] used a multi-objective optimization approach and grouped market data of the associated cost and benefit to identify the minimum cost and energy needs of various combinations of energy efficiency measures.

2.4 Challenges of ESM evaluation

The existing studies on ESM evaluations have provided useful methodological and theoretical insights. However, there remain various great challenges to the evaluations, primarily due to the limited evidence of the real costs and benefits involved in ESM implementations [3]. Regarding the appraisal of additional costs for implementing ESMs in buildings, from the perspective of investors, decisions on an investment hinge on the upfront (or initial) cost and continuous (or recurrent) cost of the concerned alternative [33]. For an ESM, the recurrent cost primarily consists of the costs for its operation and maintenance (O&M), the actual variations of which are critical to an accurate cost and benefit analysis (CBA) of the ESM. Previous studies on this area, in many cases, mainly aimed to provide support to the upside of ESMs, particularly their positive impacts on the environment. Attention paid to their downside (e.g. cost burden), on the other hand, was comparatively less.

Another challenge to ESM evaluation is attributed to the data needed for CBA analyses. Monetary data, which may reflect the financial performance of an organization, are often regarded as too sensitive for disclosure to outsiders [34]. Consequently, researchers tended to use assumed and/or market-average data to carry out CBA analyses to support ESM implementation. In doing so, the researchers also admitted that it was difficult to collect reliable data on aspects such as changes in the associated O&M cost of the ESMs studied and evidence of their benefits [35].

Facing these challenges, what is in need is a rigorous, pragmatic approach that can be used to evaluate the ESMs already implemented in buildings. The approach would be desirable if it is inclusive enough to cover the lifecycle benefits and costs of the ESMs. Of equal importance, the approach needs to be practicable considering the large amount of data required and the complexity of O&M practices in real-world buildings. Such an approach, developed using the real data of the ESMs completed in a commercial building, is demonstrated below.

3. Method and data

3.1 Data collection

At the initial stage of the study, an online survey was distributed to the members of four main stakeholder organizations of existing buildings in Hong Kong, namely, Hong Kong Green Building Council, Greater China Institute of Property Management, Hong Kong Institute of Facility Management, and Building Services Operation and Maintenance Executives Society. As reported by Lai [36], the survey questionnaire requested the respondents, who are facilities management (FM) professionals working on commercial buildings, to provide data about the characteristics of their buildings and any ESMs implemented, and indicate if they are interested in joining a further part of the study where the energy use and carbon emission of their building would be audited.

After the survey, the study team contacted each of the interested parties and a face-to-face interview was held during which the types and extents of the data needed for the audit were explained. Then a set of electronic templates, devised for collecting the data in two parts, was provided to the participants. The first part asks about the physical characteristics (e.g. age, number of floors, floor areas) of the buildings. Data collected by the second part include monthly energy end-uses and cost data of the building's ESMs over a period of five years.

Because the data needed are highly detailed and voluminous, the process of retrieving them from the relevant data records was time-consuming. In most of the cases, the respondents could only provide the data batch by batch. Follow-up meetings were held with the participants to collect the sensitive cost data and clarify data that were identified as outliers. Among the buildings sampled, the one with data allowing the carrying out of the most comprehensive environmental-economic evaluation was selected for the case study as reported in the following.

3.2 Environmental evaluation

In this study, the environmental performance of the ESMs implemented to the building was evaluated by measuring the resultant reduction of carbon emission. Following the guidelines issued by the Environmental Protection Department and the Electrical and Mechanical Services Department [37] based on the Greenhouse Gas Protocol (i.e. GHG Protocol [38]), the first step was to quantify three different scopes of carbon emissions associated with building energy use. With reference to the calculation procedure of Lai [39], the first part of carbon emission due to on-site fuel combustion (under scope 1 of the GHG Protocol), referred to as EM_A^D (in tonnes CO_2-equivalent), was computed by Eq. (1):

$$EM_A^D = \sum_{f=1}^{f=F} \sum_{t=1}^{t=T} A_{f,t} \times F_{(f)A} \times G_{(A)} \qquad (1)$$

where

$A_{f,t}$ = amount of fuel f consumed in the t^{th} period;

$F_{(f)A}$ = emission factor of gas A (e.g. CO_2, CH_4 or N_2O) for fuel f; and

$G_{(A)}$ = global warming potential of gas A.

The second part of carbon emission due to the consumption of purchased electricity (under scope 2 of the GHG Protocol), i.e. EM_{GHG}^E, was computed by Eq. (2):

$$EM_{GHG}^E = \sum_{t=1}^{t=T} A_{(E)t} \times F_{(E)t} \qquad (2)$$

where

$A_{(E)t}$ = amount of electricity used (kWh) in the t^{th} period; and

$F_{(E)t}$ = emission factor (kg CO_2-e/kWh) of electricity used in the t^{th} period, which varies with power company and year [40, 41].

The third part of carbon emissions (under scope 3 of the GHG Protocol), computed by Eq. (3), covers those due to electricity used for fresh water supply and processing sewage (i.e. EM_{GHG}^{SS}):

$$EM_{GHG}^{SS} = A_{(W)} \times (F_{(W)} + F_{(D)}) \quad (3)$$

where

$A_{(W)}$ = amount of water consumed (m^3);

$F_{(W)}$ = emission factor of fresh water supply (kg CO_2-e/m^3); and

$F_{(D)}$ = emission factor of processing sewage (kg CO_2-e/m^3).

Based on the amounts of carbon emissions determined from Eq. (1) to Eq. (3) above, the total carbon emissions, respectively in the periods before and after the ESMs were implemented, were calculated by Eq. (4). Using Eq. (5), the amount of carbon emission reduced by the ESMs (i.e. ΔCR_t) was determined:

$$C_x = EM_A^D + EM_{GHG}^E + EM_{GHG}^{SS} \quad (4)$$

$$\Delta CR_t = C_b - C_a \quad (5)$$

where

C_x = C_a, i.e. carbon emission after ESM implementation (kg CO_2-e), or C_b, i.e., carbon emission before ESM implementation (kg CO_2-e).

3.3 Economic evaluation

The economic evaluation of the ESMs implemented in the building was conducted with use of two key indicators, namely, return on investment (ROI) and net present value (NPV). ROI reflects the overall profitability of an investment by measuring the ratio of the total monetary benefits over the total costs. NPV is used to translate future monetary values (e.g. saving in electricity bill, O&M cost) incurred at different time into current equivalents. The NPV and ROI of a certain ESM were calculated using Eq. (6) and Eq. (7):

$$NPV_B = \sum_{t=1}^{n} \frac{B_t - M_t}{(1+i)^t} \tag{6}$$

$$ROI = \frac{NPV_B - NPV_I}{NPV_I} \tag{7}$$

where

NPV_B = net present value of monetary benefit gained from an ESM after cost;

NPV_I = net present value of investment on the ESM;

t = unit time interval within the evaluation period;

B_t = monetary benefit gained between time intervals t and $t-1$;

M_t = O&M cost increase (positive value) or decrease (negative value) resultant from implementation of the ESM;

i = discount rate of money;

n = number of time intervals within the ESM's functional lifespan

For an investment made on an ESM before the base time at which the economic evaluation refers to, its net present value (i.e. NPV_I) was determined using Eq. (8). Note that because different types of equipment have different functional lifespans, the length of time during which an ESM can contribute to energy saving, subject to which the NPV calculation was carried out, varies from one type of ESM to another. In general, the energy efficiency of equipment drops over time; for example, the wear and tear of the mechanical parts of a water pump reduces the pump's efficiency. Such decay in energy saving is referred to as "degradation" of equipment [42]. Thus, a degradation factor (δ) is introduced to describe the annual rate according to which the EMS would lose its energy saving capacity. Note that the calculation of δ generally depends on the type and situation of an ESM implemented. Regarding how the degradation factor of an ESM is determined, more details will be given in section 5.2.2.

Using Eq. (9), the monetary benefit gained from an EMS at a certain time interval was calculated.

$$NPV_I = \sum_{t=1}^{n*} I(1+i)^t \quad (8)$$

$$B_t = B_1(\delta_t) \quad (9)$$

where

n^* = number of time intervals between the investment was made and the evaluation base time

B_1 = monetary benefit gained from the ESM in the first time interval;

δ_t= degradation factor at time interval t

3.4 Environmental-cum-economic evaluation

To evaluate the cost effectiveness of ESMs, a metric known as carbon reduction efficiency (*CRE*) was introduced in this study. Calculated by Eq. (10), CRE is an indicator (unit: kg/$) that gauges how much the carbon footprint of a building can be reduced per unit present value of cost incurred for implementing a certain ESM:

$$CRE = \frac{\sum_{t=1}^{n} \Delta CR_t}{NPV_I + NPV_M} \quad (10)$$

where

NPV_M = net present value of the change in O&M cost in using the ESM

A workflow showing the relationships between the various parts of environmental and economic evaluations is shown in Fig. 1.

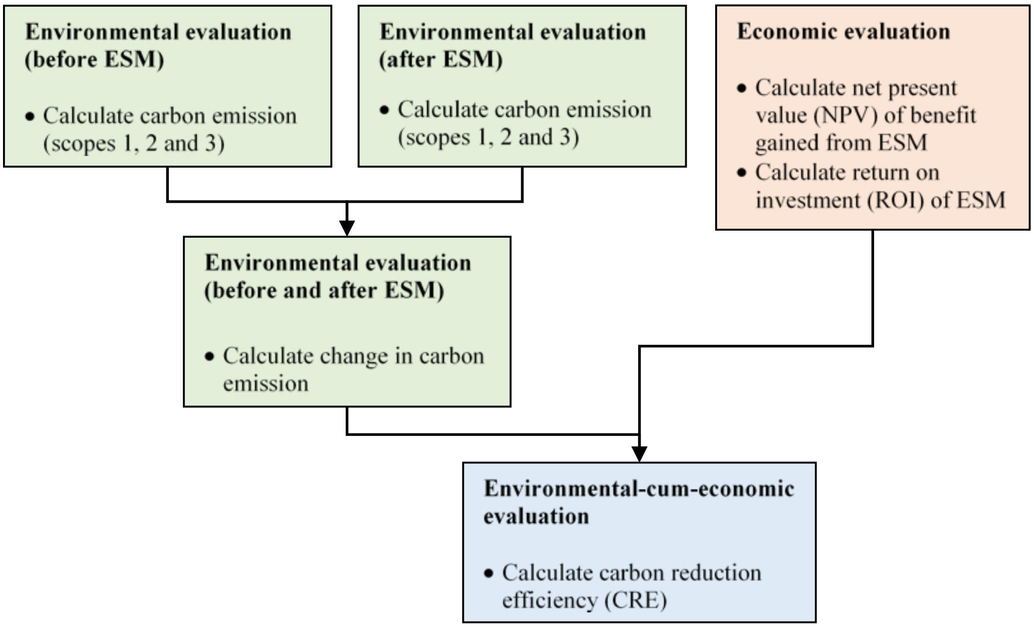

Fig. 1 Workflow of the environmental and economic evaluations

4. The case building

4.1 Characteristics

The building is a 21-storey curtain-walled commercial building located in the downtown area of Hong Kong. It has been occupied since 1991 and has a total internal floor area of about 21,039 m^2: office area (15 floors, 13,051 m^2), retail area (3 floors, 3,606 m^2) and 4,382 m^2 of common areas. The common areas include lobbies, staircases, back of house, and communal places (e.g. corridors) outside the office and retail premises.

A central chiller plant, comprising four chillers each of 320 TR (1 TR = 3.517 kW) cooling capacity, is located at the roof of the building. It provides air-conditioning (AC) for the office area, retail area, lobbies and corridors. The AC terminals installed in the office and retail premises are fan-coil units, whose temperature set-points are adjustable by the tenants to suit their needs.

Electricity is the major type of energy used for the operation of the case building. In addition to the central chiller plant and the lighting system serving the common areas, communal facilities such as lifts, potable and flushing water pumps, fire services equipment, etc. contribute to the landlord’s electricity consumption. In 2010, the total electricity bill of the landlord was $420,743 (all monetary figures in this paper are expressed in US dollars; US$1 = HK$7.8). In addition, diesel oil is the liquid fuel used by the emergency power generator in cases of electricity supply outage or regular test-run of the generator.

4.2 Carbon emissions

Carbon emissions of the building between 2011 and 2015, which were computed using Eq. (1) to Eq. (4), are summarized in Table 1. The major emission source was the use of electricity purchased from the power company for running the communal electrical installations, and the corresponding amounts of carbon emission range from 1,250.7 tonnes (99.4%) to 2,140.7 tonnes (99.8%). In contrast, the carbon emissions due to the consumption of electricity for water supply and processing sewage were minimal. The counterpart due to the use of diesel oil for emergency power generation were even negligible. No emissions due to emergency power generation were recorded in 2013 and 2015 because, according to the data

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provider, the corresponding amounts of diesel oil consumed were purchased for storage in 2012 and 2014 respectively.

Emission (kg CO_2-e)	2011	2012	2013	2014	2015
Emergency power generation (scope 1)	283	189	-	565	-
Electricity (scope 2)	2,002,801	1,979,281	2,140,745	2,047,683	1,250,726
Electricity for water supply and processing sewage (scope 3)	4,739	4,874	4,622	3,751	7,783
Total:	2,007,823	1,984,344	2,145,367	2,051,999	1,258,509

Table 1 Summary of carbon emissions

Between 2011 and 2014, the variations of the dominant carbon emissions (under scope 2 of the GHG Protocol) were not obvious. In 2015, nevertheless, the amount of scope 2 carbon emission dropped drastically, to only 1,250.7 tonnes. Built upon this observation, a series of further investigations were made, as reported in the following.

4.3 ESM projects

In order to reduce energy use and hence mitigate carbon emission, starting from 2011 onwards, the FM team of the building decided to implement some ESMs.

Owing to the hot and humid subtropical climate of Hong Kong, the AC systems of most commercial buildings run for a long period every year, consuming a substantial amount of energy. A few decades ago, since Hong Kong experienced the problem of water scarcity, the use of fresh water as heat rejection medium normally were not allowed for chiller plants in the city. The water scarcity problem was then eased by importing water from the Dongjiang River in the neighbouring Guangdong province of China. Thereafter, in 2001, the Hong Kong

Government introduced the "Fresh Water Cooling Towers Scheme" to promote energy-efficient water-cooled AC systems [1]. In line with the encouragement under the Scheme, the FM team considered that retrofitting the original air-cooled AC system of the building would be beneficial. Towards this goal, a fresh water cooling system was installed for the chiller plant and, in this connection, a central control and monitoring system (CCMS) was added. An automatic cleaning system, which prevents the heat exchanger tubes of the chillers from fouling and hence ensuring their heat exchange efficiency, was also installed for the chiller plant. For gauging the energy consumptions of the retrofitted installations, dedicated sub-meters (named as Meter 2 and Meter 3) were installed. The ESMs for the chiller plant were started on 2 February 2015 and completed on 4 November 2015. Their initial costs are shown in Table 2.

ESM	Cost ($)
Use a fresh water cooling system for the chiller plant	2,101,076
Install automatic tube cleaning system for chillers	95,769
Install a CCMS for the chiller plant	184,615

Table 2 Initial costs of the ESM projects

5. Evaluations and results

5.1 Benefits and costs of the AC retrofit

Based on the monthly electricity consumption readings of Meters 2 and 3 and the emission factors of power generation provided by the CLP Power Hong Kong Limited [40, 41], the electricity consumptions and the calculated carbon emissions pertaining to the AC system between 2011 and 2015 were determined, as depicted in Fig. 2.

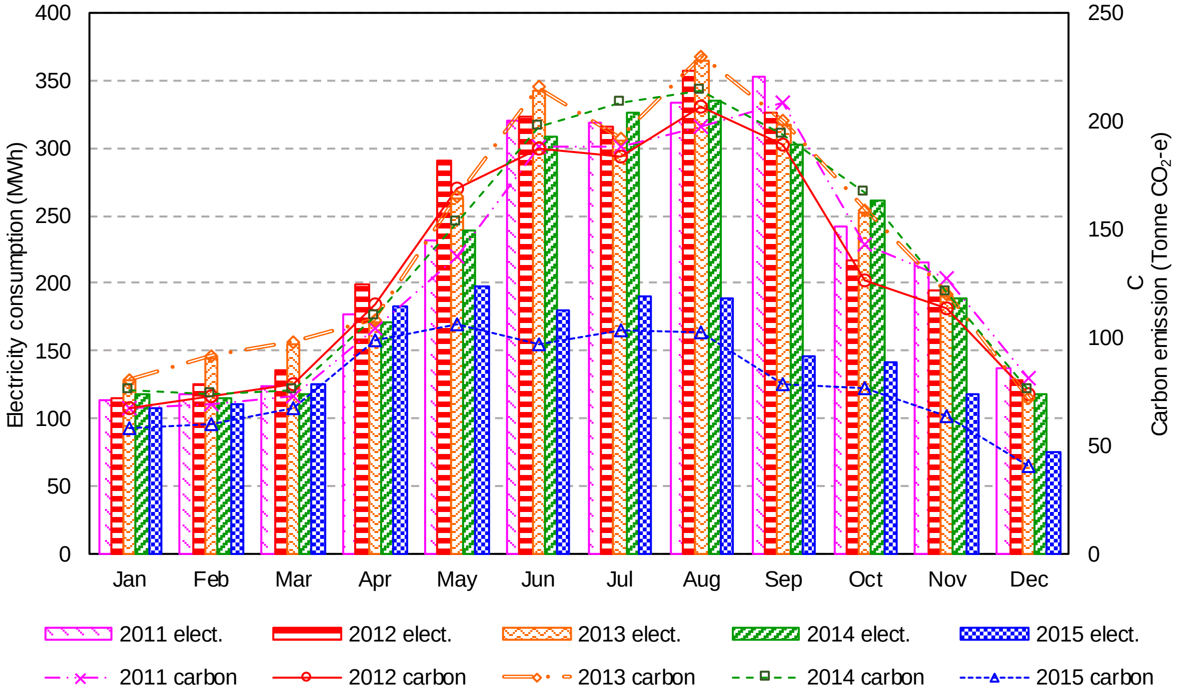

Fig. 2. Monthly electricity consumptions and carbon emissions of the AC system

Throughout the five-year period, in general, the peak electricity consumptions and carbon emissions occurred in the summer season (June to September), while the lowest consumption and emission levels appeared during winter, notably in December. From 2011 to 2014, the electricity consumptions remained at a relatively high level. At the beginning of 2015, when the implementation of the ESM commenced, part of the existing AC system was shut down to facilitate the retrofit work. As a result, both the electricity consumption and carbon emission of the system started to decrease. By comparison, the total electricity consumption of 2015 was 32.3% lower than that of 2014. In terms of carbon emission, the reduction was 42.9%.

The cost of the AC retrofit consists of the expenditure on installation of the ESMs for the AC system and the increase in the O&M cost for the retrofitted system. As shown in Table 2, the expenditure comprises the costs for installing the fresh water cooling system, installing the automatic tube cleaning system and adding the CCMS. These two types of cost could have been avoided if the AC system were not retrofitted. But even if no retrofit had been implemented to the system, according to the FM team, an expenditure of $1,260,645 was still needed to replace the old chiller plant with a new air-cooled chiller plant. As such, the actual, additional cost for using a new water-cooled chiller plant should be $840,431 (i.e. $2,101,076 - $1,260,645). Hence the total investment on the AC retrofit project, which is the sum of this additional cost and the costs for installing the automatic tube cleaning system and the CCMS, is $1,120,815.

Based on the data collected, in addition, the retrofitted AC system incurred an additional O&M cost of $27,225 per annum. This cost penalty arises from the consumption of water for the new water-cooled system and services such as regular cleaning of the cooling towers, water treatment for minimizing risks from Legionella, and sampling and testing of the quality of condenser water.

5.2 Economic evaluation of the AC retrofit

As summarized in Table 2, the ESMs for the AC system were implemented in 2015. For the purpose of the analysis here, the time at which the investment was made for the ESMs was taken as end of 2015. The retrofitted AC system has a lifespan of 20 years [43], which means that the system is functional for saving energy between 2016 and 2035. At the end of its lifespan, the residual value of the system is zero.

Although the study team managed to collect a large volume of data covering a long period of time (2011 to 2015), data of the subsequent period were not available when the data collection work was carried out in 2016. In order to conduct a complete empirical evaluation of the system's performance, ideally, data covering the whole lifecycle of the AC system need to be collected (see Eq. 6 to Eq. 9). But this is impracticable because the lifespan of the system is as long as 20 years. As an alternative, the latest available data covering the initial period after completion of the retrofit project were used as the basis upon which the performance of the AC system, which is subject to climatic influence (see Fig. 1), was projected. The following explains the calculation steps taken for this purpose.

5.2.1 Scaling factor

The first step was to compute the electricity consumptions for the period from 2015 to 2035 as if the AC retrofit had not been implemented, i.e. the "reference year electricity consumption (E_t^R, $t \geq 2015$)". In doing so, a year-on-year scaling factor (SF_t), which accounts for the effect of climatic variations, was determined by averaging the year-on-year changes in the electricity consumptions over the preceding three years (see Eq. 11). By inputting this scaling factor and the electricity consumption of the previous year into Eq. 12, the electricity consumption of the current year was computed. By repeating this computation process, the electricity consumptions of the ensuing years (up to 2035) were determined.

$$SF_t = \frac{\sum_{t-4}^{t-1} \frac{E_{t-3}^R - E_{t-4}^R}{E_{t-4}^R}}{3} \quad (11)$$

$$E_t^R = (1 + SF_t) E_{t-1}^R \quad (12)$$

The second step was to compute the monthly electricity consumptions of 2015, i.e. E_{2015}^N, as if the retrofitted AC system had been put into use to save energy since the very beginning of the year. Note that, as Table 2 shows, the AC retrofit project was completed in November 2015. Only the electricity consumption of the subsequent month (December 2015) can manifest the energy saving capability of the ESMs. To account for the seasonal variations in AC demand, a scaling factor of the base year 2015 (i.e. SF_{2015}^m) was determined by averaging the year-on-year changes in the monthly electricity consumptions (i.e. E_t^m) over the preceding three years (see Eq. 13). Processing such scaling factors and the monthly electricity consumptions by Eq. 14, the monthly electricity consumptions of the base year and the remaining years (up to 2035) were determined.

$$SF_{2015}^{m} = \frac{1}{3}\sum_{t=2015-1}^{t=2015-3}\frac{E_t^{m+1}-E_t^{m}}{E_t^{m}} \quad (13)$$

$$E_t^{m} = (1 + SF_t^{m})E_{t-1}^{m} \quad (14)$$

5.2.2 Degradation factor

After the retrofit was completed in 2015, the energy saving in the first year (ES_1), i.e. that can be realized in 2016, was calculated using Eq. 15. Likewise, the energy savings in the following years ES_2,…, ES_{20} (between 2017 and 2035) were determined.

$$ES_1 = E_{2016}^{R} - E_{2016}^{N} \quad (15)$$

In an ideal situation, after the AC system was retrofitted, the same amount of energy can could be saved every year. But in reality, as mentioned in section 3.3, the energy saving of an ESM degrades over time. Ideally, the degradation factor of an ESM can be traced by logging and analyzing the real energy performance data of the system. However, this necessitates significant resources and, as pointed out earlier, performance data of the system in its remaining 20-year lifespan were yet to be available. To overcome such constraints, a widely used approach is to make reference to publications on the energy performance of AC systems.

Referring to the publication of Hoffman et al. [44], the degradation factors for an oversized evaporative condenser, for example, are 0.98, 0.96, 0.93, 0.91, 0.89, 0.87, 0.84, 0.82 respectively for the period between the 2nd year and the 9th year. The degradation factors remain at 0.8 for the remaining period (from the 10^{th} to the 20^{th} year). According to LINCUS [45], a typical AC system on average degrades by 1.1% per year. With these two reference sources taken into account, the following four degradation scenarios were established for consideration in the analysis:

- Scenario 1: when the degradation rate δ_1 is zero;
- Scenario 2: when the compound degradation rate δ_2 is 1.1%;
- Scenario 3: when the average degradation rate δ_3 is 1.1%; and
- Scenario 4: when the degradation rate δ_4 is the same as that of Hoffman et al. [44].

Under the above four scenarios, the annual electricity consumptions (E_t^N) and the corresponding annual energy savings (ES_t) for the period between 2017 and 2035 were determined using Eq.16 to Eq.19.

Scenario 1: $E_t^N = E_t^R - ES_t^1 = E_t^R - ES_1$ (16)

Scenario 2: $E_t^N = E_t^R - ES_t^2 = E_t^R - ES_1 * (1 - 1.1\%)^{t-2016}$ (17)

Scenario 3: $E_t^N = E_t^R - ES_t^3 = E_t^R - ES_1 * [1 - (t - 2016) * 1.1\%]$ (18)

Scenario 4: $E_t^N = E_t^R - ES_t^4 = E_t^R - X_{t-2016} ES_1,$ (19)

where $X_1 = 0.98;\ X_2 = 0.96;\ ...X_{19} = 0.8;\ X_{20} = 0.8$

Then, the annual economic savings (B_t) in year t ($t > 2015$) were calculated using Eq.20:

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$$B_t = E_t^R * UC_1 - E_t^N * UC_2, \quad (20)$$

where UC_1 and UC_2 denote the unit electricity charges of the respective periods, which were determined via the online tariff calculator (https://www.clp.com.hk/en/customer-service/tariff) of the CLP Power Hong Kong Limited .

5.2.3 Discount factor

In analyzing the costs and benefits of the retrofit, an essential factor that needs to be considered is the discount rate (i) for future values. Typically, a discount rate of 5% (i.e. 0.05) is used in economics studies; for example, when doing analyses for making an investment decision, performing forecasts on income or expenditure, and so on. In reality, especially in this era where the economic market has been volatile, the interest rates have stayed at an exceptionally low level. According to the Hong Kong Monetary Authority, the discount window base rates between January 2015 and July 2017 varied from 0.005 to 0.015. In addition to these two values, two intermediate discount rates (0.0075 and 0.0125) and the above-mentioned typical discount rate (0.05) were considered when conducting sensitivity analyses on the costs and benefits of the retrofit.

5.2.4 Return on investment and net present value

Considering the four possible degradation factors and the four possible discount rates mentioned above, a total of twenty scenarios were taken for the economic evaluations under the study. Using Eq.6 and Eq.7, the net present value of economic savings from the AC retrofit project (NPV_{AC}) and the corresponding return on investment (ROI_{AC}) were computed. The results for all the scenarios are summarized in Table 3.

Besides concurring with the anticipation that the net present values decrease with increase in discount rate, the computed results show that the net present values drop when the degradation factors increase. The ROI values are all positive, from 2.5% to as high as 86.8%. The tabulated results also lead to two observations. First, an inequality regarding the negative impacts of the degradation factors on the ROI values exists: degradation 1 < degradation 2 < degradation 3 < degradation 4. Second, the ROI values, akin to the net present values, exhibit a negative relationship with the discount rates.

	$\boldsymbol{\delta}$ _1		$\boldsymbol{\delta}$ _2		$\boldsymbol{\delta}$ _3		$\boldsymbol{\delta}$_4	
	NPV_{AC} ($)	ROI_{AC} (%)	NPV_{AC} ($)	ROI_{AC} (%)	NPV_{AC} ($)	ROI_{AC} (%)	NPV_{AC} ($)	ROI_{AC} (%)
i _1 0.005	2188777	95.3	1928324	72.0	1910966	70.5	1787581	59.5
i _2 0.007	2133514	90.4	1881809	67.9	1865112	66.4	1744731	55.7
i _3 0.012	2028763	81.0	1793530	60.0	1778071	58.6	1663433	48.4
i _4 0.015	1979117	76.6	1751637	56.3	1736757	55.0	1624865	45.0
i _5 0.050	1436583	28.2	1291076	15.2	1282202	14.4	1201390	7.2

Table 3 ROI and NPV of the AC retrofit

5.3 Environmental-cum-economic evaluation

As introduced earlier, the carbon reduction efficiency (CRE) is the indicator used for a collective evaluation of both the environmental and economic performances of retrofit projects. Integrating Eq.10 with Eq.15 to Eq.19, the CRE can be rewritten as:

$$CRE = \frac{\sum_{t=1}^{n} F_{(E)t} ES_t}{NPV_I + NPV_M} \qquad (21)$$

The carbon emission factors of electricity ($F_{(E)t}$), according to the figures published by the power company [40, 41], vary from year to year. From 2011 to 2015, the emission factors are: 0.54, 0.59, 0.58, 0.63 and 0.64. Considering these five emission factors and the above four possible degradation factors, in total 20 scenarios were worked out for the carbon reduction efficiency of the AC retrofit. Using Eq.15 to Eq.19 and Eq.21, the amounts of carbon reduction (CR_{AC}) and the carbon reduction efficiency (CRE_{AC}) of the AC retrofit were computed, with the results summarized in Table 4.

Similar to the preceding results of NPV and ROI (Table 3), the amounts of carbon reduction decrease when the discount rates increase (Table 4), due to the drop in efficiency of the retrofitted AC system. The amounts of carbon reduction, on the other hand, increase when the emission factors increase; note that $F_{(E)\_}5 > F_{(E)\_}4 > F_{(E)\_}2 > F_{(E)\_}3 > F_{(E)\_}1$.

	$\boldsymbol{\delta}$ _1		$\boldsymbol{\delta}$ _2		$\boldsymbol{\delta}$ _3		$\boldsymbol{\delta}$_4	
	CR_{AC} (kg)	CRE_{AC} (kg/$)	CR_{AC} (kg)	CRE_{AC} (kg/$)	CR_{AC} (kg)	CRE_{AC} (kg/$)	CR_{AC} (kg)	CRE_{AC} (kg/$)
$F_{(E)\_}1$ 0.54	9823385	5.9981	8861534	5.4108	8796841	5.3713	8349877	5.0984
$F_{(E)\_}2$ 0.59	10732957	6.5535	9682046	5.9118	9611363	5.8687	9123014	5.5705
$F_{(E)\_}3$ 0.58	10551043	6.4424	9517944	5.8116	9448459	5.7692	8968386	5.4761
$F_{(E)\_}4$ 0.63	11460615	6.9978	10338456	6.3126	10262981	6.2666	9741523	5.9481
$F_{(E)\_}5$ 0.64	11642530	7.1089	10502559	6.4128	10425886	6.3660	9896150	6.0426

Table 4 CRE of the AC retrofit

Table 4 also presents the carbon reduction efficiencies of the AC retrofit in different scenarios, which were determined considering both the degradation factor of the equipment and the GHG emission factor. Ranging from 5.0984 to 7.1089 kg/$, the lowest carbon reduction efficiency was found with the fourth scenario of degradation factor and the first scenario of emission factor while the highest one occurs in the first scenario of degradation factor with the emission factor being the highest (i.e. 0.64). The results also show that the higher the emission factor, the larger is the range of variations in the carbon reduction efficiency against the degradation factors. This is a manifestation of the significant effect of emission factor on carbon reduction efficiency.

Reflecting the amount of carbon emission reduced per unit price of investment on the retrofit, carbon reduction efficiency serves as a useful indicator for decision makers. Such parties include: (i) building owners who need to decide on whether to invest on AC retrofits; (ii) designers who need to make justification for AC retrofit proposals; and (iii) facility managers who need to monitor and assess the actual carbon reductions. To energy policy makers, the indicator enables them to prioritize energy retrofits for implementation.

6. Conclusions

This study addresses a longstanding problem – the lack of a credible, pragmatic method for evaluating ESMs for buildings. By taking a typical commercial building in Hong Kong as a sample case, an in-depth study was conducted using the cost and energy data of the building. Without the standalone meters provided for monitoring the electricity use of the AC system and the detailed record data over a long period of time, the empirical, longitudinal study reported in this paper would not have been made possible.

Having shown how the environmental performance of buildings and their facilities could be evaluated by quantifying the amount of carbon emission according to the GHG Protocol and the applicable governmental guidelines, the method for evaluating the economic performance of retrofits, which involves a combined use of indicators (NPV and ROI), was elaborated. A novel indicator, carbon reduction efficiency (CRE), was introduced for use in evaluating both the environmental and economic performances of retrofits in an integrated manner.

Considering the climatic influence on building energy use, the scaling factor proposed in this study enables the forecast of energy consumption based on record data covering the initial post-retrofit period. The method of determining the scaling factor and the forecast technique are useful for similar studies in future. Whereas most of the existing ESM evaluation methods ignore the degradation effect of retrofits, the results of the study underscore the importance of taking into account the degradation factor in the pursuit of rigorous environmental and economic evaluations of energy retrofits. By following the methodology of this study, more in-depth case studies can be carried out to evaluate a broader range of ESMs, by then a database of environmental, economic, and environmental-economic efficiencies of ESMs can be established for benchmarking purposes.

In real-world buildings, the implementation of ESMs and the inquiry into their economic performances are inextricably linked. To private buildings owners, their business activities are frequently, if not wholly, sustained by their competitiveness in the market. Initiating ESMs for their buildings, therefore, must have a genuine economic foundation [6]. To public building owners, in order to maximize environmental improvement with constrained public finance, it is imperative to identify not only the environmental efficiency but also the economic efficiency of ESMs. Besides contributing to the literature of building energy retrofits, the study imposes implications on practice, research and energy policies on existing buildings, particularly the prioritization of ESMs for adoption in buildings.

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Nomenclature

Nomenclature	***Connotation***	***Unit***
$A_{(E)t}$	Amount of electricity used	kWh
$A_{(W)}$	Amount of water consumed	m^3
$A_{f,t}$	Amount of fuel	litre
B_t	Annual economic savings in year *t*	US dollar ($)
C_a	Carbon emission after ESM implementation	kg CO_2-e
C_b	Carbon emission before ESM implementation	kg CO_2-e
C_x	Total carbon emissions	kg CO_2-e
CR	Carbon reduction	kg
CRE	Carbon reduction efficiency	kg/$
ΔCR_t	Amount of carbon emission reduced	kg CO_2-e
EM_A^D	Carbon emission due to on-site fuel combustion	kg CO_2-e
EM_{GHG}^E	Carbon emission due to consumption of electricity	kg CO_2-e
EM_{GHG}^{SS}	Carbon emission due to consumption of fresh water	kg CO_2-e
ES_t	Energy saving in year *t*	kWh
E_t^R	Reference year electricity consumption	kWh
E_t^m	Monthly electricity consumption	kWh
$F_{(D)}$	Emission factor of processing sewage	kg CO_2-e/m^3
$F_{(E)t}$	Emission factor of electricity used	kg CO_2-e/kWh
$F_{(W)}$	Emission factor of fresh water supply	kg CO_2-e/m^3
$F_{(f)A}$	Emission factor of gas *A* for fuel *f*	kg CO_2-e/litre
$G_{(A)}$	Global warming potential of gas *A*	No unit
NPV	Net present value	$
ROI	Return on investment	%
SF_t	Scaling factor	No unit
UC	Unit electricity charge	$
Greek symbols	***Connotation***	***Unit***
δ	Degradation factor	No unit
i	Discount rate	No unit
Superscripts	***Connotation***	***Unit***
D	Diesel fuel	No unit
E	Electricity	No unit
SS	Fresh water supply and processing sewage	No unit
R	Reference year	No unit
m	Monthly	No unit
Subscripts	***Connotation***	***Unit***
t	Time interval	No unit
E	Electricity	No unit

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A	Gas A	No unit
f	Fuel f	No unit
W	Water	No unit

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