Optimisation of Operating Resources and Carbon Footprints for Attaining Sustainable Commercial Buildings

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Introduction

Hong Kong
- an Asian city with a sub-tropical climate
- crowded with high-rise commercial buildings

Commercial buildings
- 66.3% of the total electricity consumption
- contribute to carbon emissions

Target of Hong Kong Energy Saving Plan 2015:
- by year 2025 and with 2005 taken as the base year, the city’s energy intensity will be reduced by 40%
Introduction

Questions:

◦ What is the total carbon emission level of Hong Kong?

◦ What is the per capita carbon emission level of Hong Kong?
Introduction

Electricity generation

- accounts for about 68% of the total emissions

Continuous increase of carbon emissions in HK:

33.3 million tonnes in 1990

43.1 million tonnes in 2012

Reporting of GHG emissions from buildings in Hong Kong is not mandatory
Introduction

Total carbon emissions of HK generally increase since 2000 with slight dips in 2008 and 2010

(*Figures of 2012 are provisional)
Introduction

Total carbon emissions (by sector) of HK:

(Updated: 2018/08)
Introduction

Facilities in commercial buildings
• air-conditioning systems, lighting, lifts, escalators, etc.
• consume energy $\rightarrow$ carbon emissions
• if inefficient energy use $\rightarrow$ aggravate the carbon emission problem

With improvement works (e.g. retrofits) for deteriorating facilities
• efficient energy use $\rightarrow$ minimize carbon footprints
Financial resources are constrained by predetermined budgets.

Facility managers (FMs) are responsible for:
- maximizing building performance
- minimizing financial expenditure

Objectives:
- Identify the carbon footprints of commercial buildings
- Investigate the effectiveness of reducing the footprints through improving the facilities of the buildings
Introduction

- Demand of implementing building retrofits, especially those energy saving measures (ESMs), is getting widespread and urgent, 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.
Introduction

- Owners of private buildings are concerned with real benefits and costs of the ESMs.

- Owners in the public sector, are keen to know, given the budget available, how well the environment could be improved by implementing the ESMs.

- To strike an optimal balance between the often-constrained financial budget 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
Many 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.

The use of market-average data, however, tends to average out the unique performances of certain ESMs in different contexts.
Introduction

- 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 cases where the assumptions are over-simplified, the evaluation results are skeptical and thus could hardly go far in facilitating ESM-related decisions.
## Relevant Previous Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Key findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Suzuki and Oka</td>
<td>• Estimated the total carbon emission caused by the construction, operation, maintenance, and renovation of office buildings in Japan</td>
</tr>
<tr>
<td>2006</td>
<td>Georgopoulos et al.</td>
<td>• Proposed a methodological framework for examining the economic attractiveness of possible GHG emission reduction measures</td>
</tr>
<tr>
<td>2008</td>
<td>Langston et al.</td>
<td>• An adaptive reuse potential model taking into account financial and environmental parameters: -help stakeholder decision-making towards more sustainable practices</td>
</tr>
<tr>
<td>2009</td>
<td>Kofoworola and Gheewala</td>
<td>• A life cycle energy analysis (LCEA) on a typical office building in Thailand • The operation phase of commercial buildings accounted for over 80% of their life cycle energy consumption</td>
</tr>
<tr>
<td>2010</td>
<td>Kneifel</td>
<td>• Based on 576 energy simulations for 12 prototypical buildings in the US: -estimated the life-cycle energy saving, carbon emission reduction, and the cost-effectiveness of energy efficiency measures in new commercial buildings</td>
</tr>
</tbody>
</table>
## Relevant Previous Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| 2010 | Ramesh et al. | • Reviewed the LCEA results for 73 buildings across 13 countries  
• The operation phase of commercial buildings accounted for over 80% of their life cycle energy consumption |
| 2012 | Wu and Skitmore | • A case study on a newly completed commercial building |
| 2012 | Kok et al. | • Addresses the economic implications of LEED certification on commercial buildings in the US |
| 2013 | Dequaire | ▪ Multiple-case study of four school retrofits in Austria  
▪ Large retrofitted buildings, such as schools, have more than 80% reduction in heat demand when compared with the traditionally planned refurbishments  
▪ Achieved the energy efficiency level of Passivhaus standard for new buildings  
▪ The Passivhaus approach to the renovation of large buildings is reliable for improving energy efficiency of large buildings |
### Relevant Previous Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Author</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| 2013 | Cheung and Fan | • Examined how a hotel had reduced its carbon emissions using a range of sustainability design strategies for existing buildings  
• The resulting cost savings can be significant in the long run although large investments are required |
| 2013 | Swan et al. | ▪ Analysing the questionnaire data provided by 130 social housing providers in the UK  
▪ The providers were aware of the sustainable retrofit agenda, but with different levels of strategic readiness  
▪ The emerging nature of the sustainable retrofit market as the major risk for adoption  
▪ Market-making should not be pursued at the risk of the residents’ health or financial well-being  
▪ Carbon retrofits have attracted an increasing attention around the world  
▪ In-depth studies taking a longitudinal approach to investigate changes in carbon emissions resultant from retrofitting facilities in commercial buildings remain to be seen |
## Relevant Previous Studies

<table>
<thead>
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</table>
- Studied their suitability in meeting the UK’s climate change reduction target: **80% reduction** in carbon emission by **2050 over the 1990 levels**  
- If the building stock is refurbished at **nearly 2.5%** of its floor space per year, **more than half** of the energy used by the stock could be **reduced** |
| Ferreira et al. | 2014 | - A multifamily retrofit building located in Matosinhos of Portugal  
- Identify **the most cost-effective** solution for achieving **net-zero** energy targets  
- **Different combinations** of retrofit packages, including replacement of damaged tiles, installing building-integrated technical systems for domestic hot water, providing heating and cooling for restoring building functionality, were considered  
- **No major difficulties** for the transition between ‘cost optimality’ and ‘nearly zero-energy buildings’ |
### Relevant Previous Studies

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</table>
| Sun & Lau    | 2015 | - Made use of the retrofitting project at the Chow Yei Ching Building of the University of Hong Kong to study the process of retrofits and energy audit for an existing building  
  - The building is a multipurpose, 13-storey building comprising offices, lecturer rooms and laboratories  
  - Aimed at achieving 30% energy savings, the energy service company proposed a range of facility improvement measures, including: chilled water plant upgrading and optimization, building management system upgrading and with energy monitor and controlling, lighting retrofits, window film, solar panel, etc.  
  - Computer simulations evaluate how much energy can be saved by adopting the retrofits  
  - After the retrofits, the study team would conduct 1-year testing to verify the simulated energy savings |
Relevant Previous Studies

<table>
<thead>
<tr>
<th>Author</th>
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<th>Key points</th>
</tr>
</thead>
</table>
| Oree et al.  | 2016 | - Case study of the 10-storey Emmanuel Anquetil building in Mauritius  
- **Without** structural development in its **35 years** of operation, the building was considered representative as a **worst-case scenario** in energy efficient building design  
- The potential of retrofitting the building was reviewed through energy audit, simulation software and Integrated Environmental Solutions – Virtual Environment  
- Validations by comparing the **actual** result with the **simulated** one  
- Using double glazing, applying inner insulation and using energy efficient luminaires, replacing all T8 light tubes with T5 tubes achieved the most energy saving  
  - **5.52% decrease** in the **actual** building scenario  
  - A **shorter** payback period |
Adopted a socio-technical building performance evaluation approach to assess the actual performances before and after the implementation of two discrete deep low energy retrofits in the UK

The post-retrofit, which was a Victorian house, could achieve nearly 75% carbon reduction

The counterpart of the modern house was reduced by 57%

Occupants’ satisfaction and comfort were greatly improved in both cases

the significant difference between the modelled and actual carbon emissions of the retrofits underlined the need to calibrate energy models with real energy and environmental performance data
## Relevant Previous Studies

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<tbody>
<tr>
<td>Baniassadi <em>et al.</em></td>
<td>2018</td>
<td>Emphasize on the <em>operational energy (OE)</em> used for maintaining the indoor environment during the building service life</td>
</tr>
<tr>
<td>Kim <em>et al.</em></td>
<td>2017</td>
<td>Analyzed the relative importance of ESMs to hotel buildings based on opinions of practitioners in Taiwan’s hotel industry</td>
</tr>
</tbody>
</table>
| Mao *et al.*    | 2017 | - Carried out a study that was “indirectly” about the *quantitative evaluation of ESM* in buildings.
  - 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 |
Both the **cost** incurred (y) and **environmental impact** (z) are **dependent** on the **quantity of resources** (x)
If part of the cost lies in implementing some environmental improvement measures, the extra cost would be offset against the reduction in carbon footprint.

Optimum overall cost depends on the cost efficiency and environmental effectiveness of the measures.
Survey

Initial online survey
• distributed to FM practitioners of existing commercial buildings
• gathered data:
  • characteristics of the buildings
  • types of improvement works implemented

Also asked the respondents to participate in a further part of the study
  ◦ Detailed audit and analysis of their buildings’ carbon emissions
Survey

1st batch of survey data

Average work experience of respondents: 18 years

90% of respondents in the private sector

Types of buildings:

- 20% office
- 40% office + retail
- 23.3% retail
- 16.7% others (office and/or retail + other building types)
Survey

Mean age of the buildings: **18.4 years**

Newest building occupied for **1 year**

Oldest building occupied for **33 years**
Survey

Proportions of buildings with *improvement works implemented* within the 5 years preceding the survey:

- HVAC: 90%
- Lighting: 100%
- Electrical installation: 60%
- Lift and escalator: 40%
- Plumbing and drainage: 80%
Top 10 lighting improvement works:

1. Modify circuit of non-maintained type emergency lights (energised only when normal power fails)
2. Add photo sensor control
3. Use self-luminous “Tritium” EXIT signs to replace conventional signs with lighting
4. Replace malfunction switch/sensor
5. Replace with energy efficient lighting/control when lighting is near end of operational life
6. Modify switching arrangement such that lighting groups can be better controlled
7. Add programmable lighting control to suit end-user need
8. Combined use of electronic ballast with automatic control
9. Replace conventional electro-magnetic ballast with electronic ballast
10. Add timer control
Carbon Audit

- The study team contacted those interested in joining the carbon audit after the survey

- A meeting for explaining to each participant the data needed for the audit

- A set of electronic data templates was provided to the participants

- Collected data for a reporting period of five years
Carbon Audit

Quantifications of carbon emissions for three scopes:

- **Scope 1 - direct emissions/removals** (due to stationary sources combustion, mobile sources combustion, fugitive emissions, and assimilation of carbon dioxide into biomass)
- **Scope 2 - energy indirect emissions** (due to consumption of purchased electricity, consumption of town gas)
- **Scope 3 - other indirect emissions** (due to methane gas generation at landfill resulting from disposal of paper waste, consumption of fresh water, treatment of waste water, and business travel by employees)

Information about improvement works for HVAC, lighting, lifts, escalators, and plumbing and drainage installations was collected
Carbon Audit

The first part of the templates - data about the physical and operational characteristics of the buildings:

- age
- total number of floors
- construction floor area
- internal floor area
- number of staff
- power supply for the air-conditioning system
- improvement works implemented
- in-house staff,
- outsourced manpower
- O&M works
- fuel and energy consumptions
The remaining parts of the templates solicit monthly data:

- **Diesel oil consumption** (e.g. for emergency power generation)
- Amount of fuels consumed by **mobile combustion sources** (e.g. transport service for guests)
- Local and overseas **travelling records** for management office staff
- **Inventory levels of refrigerants** and amounts of refrigerants added and removed
- Quantity and height of **trees** planted or removed
- **Electricity consumptions** and metered readings of electricity used
- **Town gas consumptions** and metered readings of town gas used
- **Inventory levels of paper** and amounts of paper used and collected for **recycling**
- **Water consumptions** and metered readings of fresh water used
Calculation of Carbon Emission

The amount of carbon emission due to combustion of fuel at the building (Scope 1 direct emission) obtained using Eq. (1):

\[
E_A^C = \sum_{f=1}^{F} \sum_{t=1}^{T} A_{f,t} \times F_{(f)A} \times G_{(A)}
\]  

(1)

Where

\( E_A^C \) = gas A emission due to fuel combustion (tonnes CO\textsubscript{2}-equivalent); gas A can be CO\textsubscript{2}, CH\textsubscript{4} or N\textsubscript{2}O

\( A_{f,t} \) = amount of fuel f consumed (litre) in the t\textsuperscript{th} period

\( F_{(f)A} \) = emission factor of gas A for fuel f

\( G_{(A)} \) = global warming potential of gas A
Calculation of Carbon Emission

Emissions due to consumption of electricity purchased from the power company (i.e. energy indirect emissions in Scope 2) calculated using Eq. (2):

\[
E_{GHG}^E = \sum_{t=1}^{T} A(E)_t \times F(E)_t
\]

(2)

Where

\(A(E)_t\) = amount of electricity used (kWh) in the \(t^{th}\) period

\(E_{GHG}^E\) = carbon emission (kg CO\(_2\)-e) due to the use of purchased electricity

\(F(E)_t\) = emission factor (kg CO\(_2\)-e/kWh) of electricity used in the \(t^{th}\) period, which varies with power company and year
Calculation of Carbon Emission

Other indirect emissions (Scope 3) including those due to paper waste disposed at landfills and electricity used for fresh water supplies and sewage processing computed using Eq. (3) and Eq. (4)

\[ E_{GHG}^P = (P_s + P_i - P_c - P_e) \times F_{(P)} \]

Where

- \( E_{GHG}^P \) = carbon emission (kg CO\(_2\)-e) due to paper waste disposed at landfills
- \( F_{(P)} \) = emission factor of paper used (estimated at 4.8 kg CO\(_2\)-e/kg)
- \( P_s \) = paper inventory at the beginning of the reporting period (kg)
- \( P_i \) = paper added to the inventory during the reporting period (kg)
- \( P_c \) = paper collected for recycling purpose (kg)
- \( P_e \) = paper inventory at the end of the reporting period (kg)

As there were no inventory records of paper, the inventory levels at the beginning and at the end of the reporting period were assumed to be the same, i.e. \( P_s = P_e \)
Calculation of Carbon Emission

The amounts of carbon emissions due to consumption of fresh water and treatment of waste water obtained using Eq. (4)

\[ E_{SS}^{GHG} = A_{(W)} \times (F_{(W)} + F_{(D)}) \]  

(4)

\( F_{(W)} \) or \( F_{(D)} \) were determined in two steps:

1. Figures on power consumption for water supply and sewage treatment were retrieved from reports of Water Supplies Department and Drainage Services Department

2. The unit power consumption figures were multiplied by the territory-wide default value of purchased electricity (0.7kg/kWh)
Calculation of Carbon Emission

\[ E_{GHG}^{SS} = A_{(W)} \times (F_{(W)} + F_{(D)}) \]  \hspace{1cm} (4)

where

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

\( E_{GHG}^{SS} \) = carbon emission due to electricity used for processing fresh water and sewage by the Water Supplies Department (WSD) and Drainage Services Department (DSD)

\( F_{(W)} \) = emission factor of \textit{processing fresh water} \((\text{kg CO}_2\text{-e}/m^3)\)

\( F_{(D)} \) = emission factor of \textit{processing sewage} \((\text{kg CO}_2\text{-e}/m^3)\)

With no records of business travels, the corresponding amounts of carbon emissions could not be determined.
# Buildings studied

32 buildings studied. Summary of relevant landlord data of 30 buildings:

<table>
<thead>
<tr>
<th></th>
<th>Water consumption / IFA (m³/m²/year)</th>
<th>Electricity consumption / IFA (kWh/m²/year)</th>
<th>Carbon emission / IFA (kg CO₂-e/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>0.0016</td>
<td>10.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Max.</td>
<td>1.4444</td>
<td>286.7</td>
<td>155.3</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3201</td>
<td>106.6</td>
<td>62.1</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.4000</td>
<td>69.3</td>
<td>38.2</td>
</tr>
</tbody>
</table>
Case study

Key characteristics of the building

<table>
<thead>
<tr>
<th>Age of building:</th>
<th>25 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of floors:</td>
<td>21</td>
</tr>
<tr>
<td>(including basement floors)</td>
<td></td>
</tr>
<tr>
<td>Internal floor area:</td>
<td>~ 21,000 m²</td>
</tr>
<tr>
<td>Provisions for air-conditioning in tenant areas:</td>
<td>Chilled water supply to fan coil units was provided by landlord; electricity supply for fan coil units was provided by tenants.</td>
</tr>
</tbody>
</table>
## Sources and Amounts of Carbon Emissions

### Summary of carbon emissions of the building

<table>
<thead>
<tr>
<th>Emission (kg CO₂-e)</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency power generation (on-site)</td>
<td>283</td>
<td>189</td>
<td>-</td>
<td>565</td>
<td>-</td>
</tr>
<tr>
<td>Electricity (purchased)</td>
<td>2,002,801</td>
<td>1,979,281</td>
<td>2,140,745</td>
<td>2,047,683</td>
<td>1,250,726</td>
</tr>
<tr>
<td>Paper consumption</td>
<td>65,731</td>
<td>45,458</td>
<td>48,494</td>
<td>59,228</td>
<td>71,694</td>
</tr>
<tr>
<td>Paper for recycling*</td>
<td>-517,680</td>
<td>-463,728</td>
<td>-293,520</td>
<td>-207,936</td>
<td>-186,336</td>
</tr>
<tr>
<td>Electricity used for water supply and processing sewage</td>
<td>4,739</td>
<td>4,874</td>
<td>4,622</td>
<td>3,751</td>
<td>7,783</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>2,073,554</strong></td>
<td><strong>2,029,802</strong></td>
<td><strong>2,193,760</strong></td>
<td><strong>2,111,227</strong></td>
<td><strong>1,330,203</strong></td>
</tr>
</tbody>
</table>

*Note: The amount of paper collected for recycling, which is more than that of paper purchased, was omitted in determining the total amount of carbon emission. Negative value represents removal of carbon emission.
Sources and Amounts of Carbon Emissions

- **No emissions** due to the use of emergency power generator (i.e. consumption of diesel oil for regular tests or occasional emergency power supplies) in 2013 and 2015 because no diesel oil was purchased for replenishment during those periods.

- The majority of the emissions were due to the use of **electricity purchased** from the power company.
  - Between 1,250.7 tonnes CO₂-e (94.0%) and 2,140.7 tonnes CO₂-e (97.6%)
Sources and Amounts of Carbon Emissions

- **Small** amounts of carbon emissions due to the use of other resources (paper and electricity for water supply and processing sewage)

- **Negative** amounts of carbon emissions due to paper for cycling because the volume of paper (for general purposes and goods packaging) collected for recycling exceeded the volume of paper purchased
Sources and Amounts of Carbon Emissions

• 2011-2014: no substantial changes in the emissions (between 2029.8 and 2111.2 tonnes CO\textsubscript{2}-e per year)

• 2013: peak emission (2193.8 tonnes CO\textsubscript{2}-e)

• 2014-15: emission drastically dropped to 1,330.2 tonnes CO\textsubscript{2}-e (about 60% of the peak)

Figure 1. Total yearly carbon emissions of the building
Sources and Amounts of Carbon Emissions

Improvement works:

• Installation of an automatic tube cleaning system for chillers
• Adoption of fresh water cooling
• Use of a centralized control monitoring system (CCMS)

• Replacement of the existing lamps with energy efficient lamps
Improvement Works and Carbon Reductions

• After the air-conditioning improvement works
  • electricity consumption decreased from 118,364 kWh to 75,443 kWh (36%)
  • carbon emission dropped to 40,739 kg (46%)

• % changes in electricity consumption and carbon emission are different
  (since annual emission factor of electricity varies with the contents of fuels used by the power company over the 5-year period)
# Improvement Works and Carbon Reductions

**Improvement works for the air-conditioning system**

<table>
<thead>
<tr>
<th>Improvement works</th>
<th>Start</th>
<th>Finish</th>
<th>Meter involved</th>
</tr>
</thead>
</table>
| 1. Install **automatic tube cleaning system for chillers** | 02/02/2015  | 04/11/2015   | Meter 2: Central HVAC Power (for Chiller Nos. 3 & 4)  
                              Meter 3: Central HVAC Power (for Chiller Nos. 1 & 2) |
| 2. Adopt **fresh water cooling**                          | 02/02/2015  | 04/11/2015   | Meters 2 and 3                                      |
| 3. Use of a **CCMS**                                      | 02/02/2015  | 04/11/2015   | Meters 2 and 3                                      |

<table>
<thead>
<tr>
<th>Electricity consumption (kWh)</th>
<th>Carbon emission (kg CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Before improvement</strong></td>
<td>118,364</td>
</tr>
<tr>
<td><strong>After improvement</strong></td>
<td>75,443</td>
</tr>
<tr>
<td><strong>Change</strong></td>
<td>-42,921 (-36%)</td>
</tr>
</tbody>
</table>
Improvement Works and Carbon Reductions

- Reduction in electricity consumption: **21%**
- **28%** carbon reduction

*Improvement work for the lighting system*

<table>
<thead>
<tr>
<th>Improvement work</th>
<th>Start</th>
<th>Finish</th>
<th>Meter involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Replace the existing lamps with energy efficient lamps that provide similar illumination levels.</td>
<td>1/1/2011</td>
<td>31/12/2015</td>
<td>Meter 1: Public Area (General)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Electricity consumption (kWh)</th>
<th>Carbon emission (kg CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before improvement</td>
<td>55,335</td>
<td>32,648</td>
</tr>
<tr>
<td>After improvement</td>
<td>43,621</td>
<td>23,555</td>
</tr>
<tr>
<td>Change</td>
<td>-11,714 (-21%)</td>
<td>-9,093 (-28%)</td>
</tr>
</tbody>
</table>
Questions:

◦ How much carbon emission can be reduced by investing in environmental improvement work?

◦ Is there a figure in kg/\$?
Case Study

*Environmental evaluation*

- The environmental performance of the energy saving measures (ESMs) implemented to the building was evaluated by measuring the resultant reduction of carbon emission.

- Follow the guidelines issued by the *Environmental Protection Department (EPD)* and the *Electrical and Mechanical Services Department (EMSD)* based on the Greenhouse Gas Protocol (i.e. GHG Protocol)
Case Study

*Environmental evaluation*

The first step was to quantify three different scopes of carbon emissions associated with building energy use. 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):

$$EM_A^D = \sum_{f=1}^{F} \sum_{t=1}^{T} A_{f,t} \times F_{(f)A} \times G(A)$$  \hspace{1cm} (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$_2$O) for fuel $f$; and

$G(A)$ = global warming potential of gas $A$. 
Environmental evaluation

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

$$EM^E_{GHG} = \sum_{t=1}^{T} A(E)_t \times F(E)_t$$  \hspace{1cm} (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.
Environmental evaluation

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. $EM_{SS}^{GHG}$):

$$EM_{GHG}^{SS} = A(W) \times (F(W) + F(D))$$

(3)

where

$A(W)$ = amount of water consumed (m³);

$F(W)$ = emission factor of fresh water supply (kg CO₂-e/m³); and

$F(D)$ = emission factor of processing sewage (kg CO₂-e/m³).
Environmental evaluation

Based on the amounts of carbon emissions determined from the preceding 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. $\Delta CR_t$) was determined:

$$C_x = EM_A^D + EM_{GHG}^E + EM_{GHG}^{SS}$$  \hspace{1cm} (4)

$$\Delta CR_t = C_b - C_a$$  \hspace{1cm} (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).
Economic evaluation

The economic evaluation of the ESMs implemented in the building was conducted with use of two key indicators: 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.

\[
NPV_B = \sum_{t=1}^{n} \frac{B_t - M_t}{(1+i)^t} \quad (6) \hspace{2cm} ROI = \frac{NPV_B - NPV_I}{NPV_I} \quad (7)
\]

- \(NPV_B\) = 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
Case Study

\textbf{Economic evaluation}

For an investment made on an ESM before the base time at which the economic evaluation refers to, its net present value (i.e. $NPV_j$) was determined using Eq. (8).

In general, the energy efficiency of equipment drops over time. Thus, a degradation factor ($\delta_t$) is introduced to describe the annual rate according to which the EMS would lose its energy saving capacity. Using Eq. (9), the monetary benefit gained from an EMS at a certain time interval was calculated.

\begin{align*}
NPV_I &= \sum_{t=1}^{n^*} I(1 + i)^t \\
B_t &= B_1(\delta_t)
\end{align*}

$n^*$ = 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;
$\delta_t$ = degradation factor at time interval $t$
Economic evaluation

To evaluate the cost effectiveness of ESMs, a metric known as carbon reduction efficiency (CRE) was introduced. 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:

\[
CRE = \frac{\sum_{t=1}^{n} \Delta CR_t}{NPV_I + NPV_M}
\]  

(10)

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

\(NPV_I\) = net present value of investment on the ESM;

\(\Delta CR_t\) = the amount of carbon emission reduced by the ESMs
Workflow of the environmental and economic evaluations

Environmental evaluation (before ESM)
- Calculate carbon emission (scopes 1, 2 and 3)

Environmental evaluation (after ESM)
- Calculate carbon emission (scopes 1, 2 and 3)

Environmental evaluation (before and after ESM)
- Calculate change in carbon emission

Environmental-cum-economic evaluation
- Calculate carbon reduction efficiency (CRE)

Economic evaluation
- Calculate net present value (NPV) of benefit gained from ESM
- Calculate return on investment (ROI) of ESM
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 provider, the corresponding amounts of diesel oil consumed were purchased for storage in 2012 and 2014 respectively.
In 2015, 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.
Case Study

**ESM projects:**

The FM team of the building decided to implement some ESMs retrofitting the original air-cooled AC system of the building:

i) a fresh water cooling system was installed for the chiller plant

ii) a central control and monitoring system (CCMS) was added.

iii) 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.

iv) 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 Feb 2015 and completed on 4 Nov 2015.
## Case Study

Table 2. Initial costs of the ESM projects

<table>
<thead>
<tr>
<th>ESM</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use a fresh water cooling system for the chiller plant</td>
<td>2,101,076</td>
</tr>
<tr>
<td>Install automatic tube cleaning system for chillers</td>
<td>95,769</td>
</tr>
<tr>
<td>Install a CCMS for the chiller plant</td>
<td>184,615</td>
</tr>
</tbody>
</table>

To cater for international audience, the monetary figures are expressed in US dollars; US$1 ≈ HK$7.8
Case Study

**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, the electricity consumptions and the calculated carbon emissions pertaining to the AC system between 2011 and 2015 were determined, as depicted in Fig. 2.

![Fig2. Monthly electricity consumptions and carbon emissions of the AC system](image-url)
Case Study

Benefits and costs of the AC retrofit

• 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.

• 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.

• The total electricity consumption of 2015 was 32.3% lower than that of 2014. In terms of carbon emission, the reduction was 42.9%.
Case Study

Benefits and costs of the AC retrofit

- 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.
- 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. Thus, the 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, 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.

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 (2016-2035). At the end of its lifespan, the residual value of the system is zero.
Economic evaluation of the AC retrofit

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.

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, was projected.
Case Study

**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 the 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.

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

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

**Scaling factor**

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, 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.

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

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

Hoffman et al.: the degradation factors, for example (condenser), 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 10th to the 20th year).

LINCUS: a typical AC system on average degrades by 1.1% per year.

With the above two reference sources taken into account, the following four degradation scenarios were considered in the analysis:

- Scenario 1: when the degradation rate $\delta_1$ is zero;
- Scenario 2: when the compound degradation rate $\delta_2$ is 1.1%;
- Scenario 3: when the average degradation rate $\delta_3$ is 1.1%;
- Scenario 4: when the degradation rate $\delta_4$ is the same as that of Hoffman et al.
Degradation factor

Under the 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.

Scenario 1: $E_t^N = E_t^R - ES_t^1 = E_t^R - ES_1$  \hspace{1cm} (16)

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

Scenario 3: $E_t^N = E_t^R - ES_t^3 = E_t^R - ES_1 \times [1 - (t - 2016) \times 1.1\%]$  \hspace{1cm} (18)

Scenario 4: $E_t^N = E_t^R - ES_t^4 = E_t^R - X_{t-2016}ES_1$,  \hspace{1cm} (19)

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

Then, the annual economic savings \( (B_t) \) in year \( t \) \( (t > 2015) \) were calculated:

\[
B_t = E_t^R \times UC_1 - E_t^N \times UC_2, \tag{20}
\]

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.
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 making an investment decision, performing forecasts on income or expenditure, etc. In reality, 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.
Case Study

Return on investment and net present value

Considering the four possible degradation factors and the five 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\textsubscript{AC}) and the corresponding return on investment (ROI\textsubscript{AC}) were computed. The results for all the scenarios are summarized in Table 3.

\[ NPV_B = \sum_{t=1}^{n} \frac{B_t - M_t}{(1+i)^t} \]  \hspace{1cm} (6)

\[ ROI = \frac{NPV_B - NPV_I}{NPV_I} \]  \hspace{1cm} (7)
## Case Study

Table 3. ROI and NPV of the AC retrofit

<table>
<thead>
<tr>
<th>$i$</th>
<th>Degradation factor</th>
<th>Discount rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_1$</td>
<td>0.005</td>
<td>$\delta_1$</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>0.0075</td>
<td>$\delta_2$</td>
</tr>
<tr>
<td>$\delta_3$</td>
<td>0.0125</td>
<td>$\delta_3$</td>
</tr>
<tr>
<td>$\delta_4$</td>
<td>0.0150</td>
<td>$\delta_4$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\delta_i$</th>
<th>$NPV_{AC}$ ($)$</th>
<th>$ROI_{AC}$ (%)</th>
<th>$NPV_{AC}$ ($)$</th>
<th>$ROI_{AC}$ (%)</th>
<th>$NPV_{AC}$ ($)$</th>
<th>$ROI_{AC}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_1$ 0.005</td>
<td>2188777</td>
<td>95.3</td>
<td>1928324</td>
<td>72.0</td>
<td>1910966</td>
<td>70.5</td>
</tr>
<tr>
<td>$i_2$ 0.0075</td>
<td>2133514</td>
<td>90.4</td>
<td>1881809</td>
<td>67.9</td>
<td>1865112</td>
<td>66.4</td>
</tr>
<tr>
<td>$i_3$ 0.0125</td>
<td>2028763</td>
<td>81.0</td>
<td>1793530</td>
<td>60.0</td>
<td>1778071</td>
<td>58.6</td>
</tr>
<tr>
<td>$i_4$ 0.0150</td>
<td>1979117</td>
<td>76.6</td>
<td>1751637</td>
<td>56.3</td>
<td>1736757</td>
<td>55.0</td>
</tr>
<tr>
<td>$i_5$ 0.0500</td>
<td>1436583</td>
<td>28.2</td>
<td>1291076</td>
<td>15.2</td>
<td>1282202</td>
<td>14.4</td>
</tr>
</tbody>
</table>
Return on investment and net present value

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:

i) an inequality regarding the negative impacts of the degradation factors on the ROI values exists: degradation 1 < degradation 2 < degradation 3 < degradation 4.

ii) the ROI values, akin to the net present values, exhibit a negative relationship with the discount rates.
Environmental-cum-economic evaluation

The carbon reduction efficiency (CRE) is the indicator introduced 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:

\[ CRE = \frac{\sum_{t=1}^{n} F_{(E)t} E_{t}}{NPV_I + NPV_M} \] (21)

The carbon emission factors of electricity \(F_{(E)t}\), according to the figures published by the power company, vary from year to year. From 2011 to 2015, the emission factors are: 0.54, 0.59, 0.58, 0.63 and 0.64.

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.
Table 4. CRE of the AC retrofit

<table>
<thead>
<tr>
<th>$F(E)_1$</th>
<th>$F(E)_2$</th>
<th>$F(E)_3$</th>
<th>$F(E)_4$</th>
<th>$F(E)_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_1$</td>
<td>$\delta_2$</td>
<td>$\delta_3$</td>
<td>$\delta_4$</td>
<td></td>
</tr>
<tr>
<td>$CR_{AC}$ (kg)</td>
<td>$CRE_{AC}$ (kg/$$)</td>
<td>$CR_{AC}$ (kg)</td>
<td>$CRE_{AC}$ (kg/$$)</td>
<td>$CR_{AC}$ (kg)</td>
</tr>
<tr>
<td>9823385</td>
<td>5.9981</td>
<td>8861534</td>
<td>5.4108</td>
<td>8796841</td>
</tr>
<tr>
<td>10732957</td>
<td>6.5535</td>
<td>9682046</td>
<td>5.9118</td>
<td>9611363</td>
</tr>
<tr>
<td>10551043</td>
<td>6.4424</td>
<td>9517944</td>
<td>5.8116</td>
<td>9448459</td>
</tr>
<tr>
<td>11460615</td>
<td>6.9978</td>
<td>10338456</td>
<td>6.3126</td>
<td>10262981</td>
</tr>
<tr>
<td>11642530</td>
<td>7.1089</td>
<td>10502559</td>
<td>6.4128</td>
<td>10425886</td>
</tr>
</tbody>
</table>

$\delta$: Degradation factor

$F(E)_t$: Emission factor of electricity used
The amounts of carbon reduction increase when the emission factors increase; note that $F(E)_5 > F(E)_4 > F(E)_2 > F(E)_3 > F(E)_1$.

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.

<table>
<thead>
<tr>
<th>$F(E)$</th>
<th>$\delta_1$</th>
<th>$\delta_2$</th>
<th>$\delta_3$</th>
<th>$\delta_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$CR_{AC}$ (kg)</td>
<td>$CRE_{AC}$ (kg/$)$</td>
<td>$CR_{AC}$ (kg)</td>
<td>$CRE_{AC}$ (kg/$)$</td>
</tr>
<tr>
<td>$F(E)_1$</td>
<td>0.54</td>
<td>9823385</td>
<td>5.9981</td>
<td>8861534</td>
</tr>
<tr>
<td>$F(E)_2$</td>
<td>0.59</td>
<td>10732957</td>
<td>6.5535</td>
<td>9682046</td>
</tr>
<tr>
<td>$F(E)_3$</td>
<td>0.58</td>
<td>10551043</td>
<td>6.4424</td>
<td>9517944</td>
</tr>
<tr>
<td>$F(E)_4$</td>
<td>0.63</td>
<td>11460615</td>
<td>6.9978</td>
<td>10338456</td>
</tr>
<tr>
<td>$F(E)_5$</td>
<td>0.64</td>
<td>11642530</td>
<td><strong>7.1089</strong></td>
<td>10502559</td>
</tr>
</tbody>
</table>
Case Study

*Environmental-cum-economic evaluation*

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

(iii) **facility managers** who need to monitor and assess the actual carbon reductions

(iv) **energy policy makers (government)** who need to prioritize energy retrofits for promotion/implementation
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.
Conclusions

- 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.
Conclusions

- 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.
Conclusions

- 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.

- 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.
Conclusions

- 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.

- 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.
References and further readings


Acknowledgement:

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End of Presentation

Thank You

Q&A