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Effects of Sorting Schemes on the Most Cost-Effective Number of Energy Conservation Measures

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Abstract – *When several energy conservation measures (ECMs) are to be implemented to earn points from a building energy rating system, it is essential to decide upon the order of their implementation. To answer the question about what sorting scheme should be employed, this study aimed to investigate the effects of different sorting schemes on the most cost-effective point and the corresponding number of ECMs to be implemented. Six sorting schemes comprising energy saving, investment, points, payback period (PB), net present value (NPV), and internal rate of return (IRR) were applied to 10 common ECMs that were to be implemented on four sample buildings. The chosen rating systems were ASHRAE's Building EQ, and the energy topic in LEED v4, BEAM Plus v1.2, and TREES v1.1. The study's findings showed that each sorting scheme led to literally the same cost-effective point. If the ECMs were sorted by energy saving or points, a significantly lower number of ECMs would be required. However, this needed a trade-off with high investment in ECMs from the beginning. Conversely, the other four sorting schemes required a gradual increase in investment in ECMs, as well as almost all, or all, ECMs needing to be implemented. Moreover, the more stringent rating systems, such as Building EQ and LEED, tended to have a higher investment cost in ECMs per unit area per %credit. The implementation of expensive ECMs was found to be more economic in larger buildings.*

Keywords – *building energy rating systems, energy conservation measures (ECMs), most cost-effective point, sorting scheme.*

1. INTRODUCTION

Global energy consumption has been increasing every year [1], with Thailand also experiencing this trend [2]. In Thailand, residential and commercial buildings contribute 24.0% and 24.4%, respectively, of the total electrical energy consumption [3].

Energy use in buildings causes direct and indirect impacts on the environment. One of the many examples is carbon emission to the atmosphere which induces the greenhouse gas effect. These problems are causing concern to many countries. Several organizations have been established to regulate or promote buildings that are more environmentally friendly and that improve occupants' well-being and productivity. The US Green Building Council (USGBC) was founded in 1993 in the United States (US). One of its objectives was to shift the concept of building design, construction, and operation to become more sustainable and environmentally friendly but still profitable. A green building system called Leadership in Energy and Environmental Design (LEED) was created. In 1998, LEED v1.0 was released. Since then, it has been continuously improved with the latest version, LEED v4, released in 2013. In 1996, the Hong Kong Green Building Council Limited (HKGBC) developed a green building standard called the Hong Kong Building Environmental Assessment Method (HK-BEAM) [4]. The standard has been constantly updated and, after a later name change, is called BEAM Plus. The latest version was launched in 2012.

In Thailand, the Thai Green Building Institute (TGBI) was established and a green building rating system, Thai's Rating of Energy and Environmental Sustainability for New Construction and Major Renovation (TREES-NC) was issued. The latest version was released in 2012. A building is assessed in accordance with several topics in eight credit categories and classified under four labels, depending on the points earned, with these comprising: Certified (30 to 37 points); Silver (38 to 45 points); Gold (46 to 60 points); and Platinum (> 61 points) [5].

In 2011, ASHRAE released a building energy rating system called Building Energy Quotient (bEQ) which is now called Building EQ. The first version was the In Operation rating system which was intended to assess the energy use of an existing building compared to the Median Energy Use Index (Median EUI) of building stock of the same type. In 2012, ASHRAE launched the As Designed rating system to apply to new buildings. A building is scored at one of seven levels depending on how much less energy the building consumes than the Median EUI, with these being: Unsatisfactory (F, > 145); Inefficient (D, 116 to 145); Average (C, 86 to 115); Efficient (B, 56 to 85); Very Efficient (A-, 26 to 55), High Performance (A, 1 to 25), and Zero Net Energy (A+, ≤ 0) [6].

The choice of rating system affects the design of a building as each rating system has different requirements and coverage. If the owner or the designer wants to cover several environmental aspects, a green building rating system such as LEED, BEAM Plus, or TREES should be selected. If energy efficiency is the main interest, then Building EQ may be a more specific

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choice. However, when one of LEED, BEAM Plus, or TREES is selected, the energy category should still be given special attention as it contains the highest points, provides obvious financial benefits, and influences expenses during the life of the building. Each standard has different requirements and available scores which lead to different assessment results. For example, a study in Hong Kong compared the application of HK-BEAM, BREEAM (a building rating system from the United Kingdom (UK)), and LEED to office buildings [4]. The results showed that the points earned from the energy category of HK-BEAM and LEED increased linearly with the number of measures applied. However, the earning of points from BREEAM was much more stringent as scoring is based on carbon reduction, not only on direct energy reduction. Results from other studies also showed that the scoring of points in LEED was fairly strict when compared with HK-BEAM and Chinese regulations [7], [8].

After assessing the building and listing the feasible energy conservation measures (ECMs), sorting needs to be done to determine which measures should be done first and which ones should be done next. Droutsa et al. considered two ranking criteria from building owners' point of view, namely, energy saving and payback period (PB), when investigating the implementation of ECMs on heating in residential buildings in Greece [9]. In their study, Champion and Gabriel proposed a two-level optimization model (knapsack problem) to select a group of ECMs that should be implemented to receive the highest saving within a given investment budget [10]. Hirunyakan and Tangwichai, Samutsopakul and Lakboon, and Chantrasawang and Ounwised conducted studies on a financially optimum green building label and proposed to implement four groups of measures in the following order: measures with no investment and with saving, measures with no investment and with no saving, measures with investment and with saving, and measures with investment and with no saving. The results showed that the Gold label was the optimum level [11]-[13]. In fact, ECMs may be sorted by many schemes, for example, with implementation starting from low to high investment, from high to low saving, from quick to slow return, *etc*. Nonetheless, no studies have been found that have specifically studied this topic. It is therefore of interest to see if applying different ECM sorting schemes would lead to different cost-effective green labels or if it would cause any other different effects.

This study aimed to investigate the most cost-effective green building level and the corresponding number of ECMs to be implemented in accordance with different ECM sorting schemes. Six sorting schemes were applied as follows: energy saving (from high to low); investment (from low to high); points (from high to low); payback period (PB) (from low to high); net present value (NPV) (from high to low); and internal rate of return (IRR) (from high to low). For sample buildings, two office buildings (one large and one small), one department store building, and one hotel building were selected, with electrical energy as their only source of energy. The rating systems chosen for the study were LEED v4, BEAM Plus v1.2, TREES v1.1, and Building EQ.

2. BUILDING RATING SYSTEMS

The rating systems selected comprised the three green building rating systems, LEED v4, BEAM Plus v1.2, and TREES v1.1, and one building energy rating system, ASHRAE's Building EQ. The key contents of each system are shown in Table 1. The three green building standards have a similar structure, being divided into credit categories. In each category, prerequisite topics are mandatory while scoring topics can be chosen to earn points. Through assessment, a building receives points and the process determines which green label it can achieve. The categories that provide the most points are energy and water, with only the energy category of interest in this study. Table 2 shows assessment details in each rating system's energy category. As can be seen, the same idea is used to calculate points. The points are calculated based on comparison between energy consumption of the design (or the proposed) building and that of the same building when it follows the minimum energy efficiency requirements according to the reference standard of each rating system (the reference building): LEED v4 refers to ASHRAE Standard 90.1-2010, while BEAM Plus v1.2 and TREES v1.1 refer to ASHRAE Standard 90.1-2007.

For the Building EQ rating system, the point calculation is based on comparing energy consumption of the proposed building to mean energy consumption of the building stock of the same type. This is expressed in Equation 1:

$$bEQ = \frac{SourceEUI}{MedianEUI} \times 100 \tag{1}$$

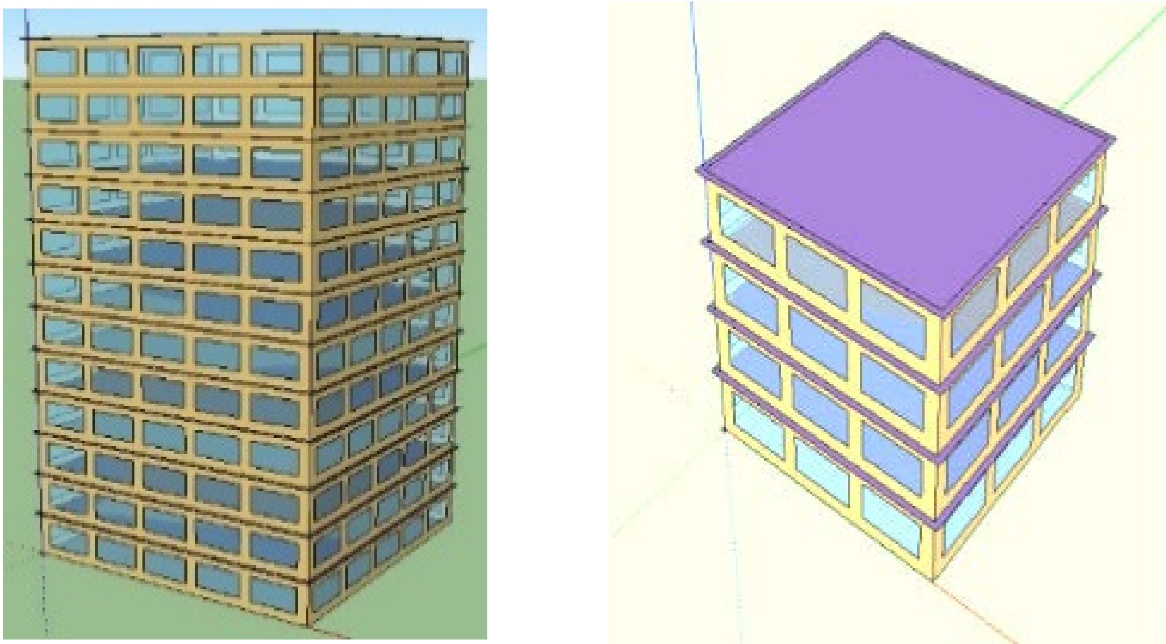
where, bEQ = points,
Source EUI = Source Energy Use Index of the proposed building,
Median EUI = Median Energy Use Index of the building stock of the same type.

As can be seen from Equation 1, lower points imply better energy efficiency. A zero (0) point score means the building is a net zero energy building. Negative points mean the building is a positive energy building. The idea behind this scoring system is that Building EQ's final goal is to achieve a net zero energy building (A+ level).

3. SAMPLE BUILDINGS

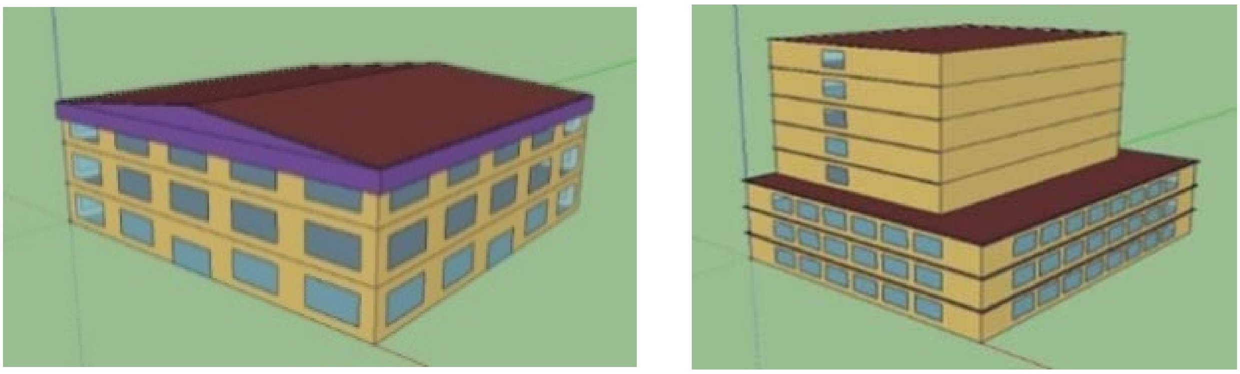
As illustrated in Figure 1, four buildings of three types were selected to be the sample buildings in this study. The sample buildings comprised two office buildings (one large building of 12,567.00 m^2 and one small building of 1,580.72 m^2), one department store building (8,280.00 m^2), and one hotel building (11,448.00 m^2). It was assumed that all buildings were located in Thailand and that they only used electrical energy.

All buildings were assumed to be new constructions, with building envelopes made of bricks with cement plaster. The windows were made of 6-mm clear glass. The air conditioning systems were central systems using water-cooled chillers. Energy consumption of the sample buildings was estimated by using EnergyPlus software which was reported to be able to achieve 2% to 5% accuracy [16], [17]. Details of the constructions and operating conditions of the sample buildings are summarized in Tables 3 to 6.



Large office

Small office



Department store

Hotel

Fig. 1. Sample buildings in this study.

Table 1. Key contents in LEED v4, BEAM Plus v1.2, TREES v1.1, and Building EQ [5], [6], [14], [15].

	LEED v4 – 2013	BEAM Plus v1.2 New Buildings	TREES v1.1	Building EQ (As Designed)
Certifying Organization	US Green Building Council (USGBC)	Hong Kong Green Building Council Limited (HKGBC)	Thai Green Building Institute (TGBI)	ASHRAE
History				
First version	1998 (v1)	1996 (HK-BEAM)	2008 (ASA and EIT)	2011 (In Operation)
Latest version	2013 (v4)	2012 (BEAM Plus v1.2)	2012 (TREES-NC v1.1)	2012 (As Designed)
Standard	– New construction and major renovations – Existing buildings – Commercial interiors, Core and shell, Schools, Retail, Healthcare, Homes, Neighborhood development	– New buildings – Existing buildings	– New construction – Major renovations	– New buildings – Existing buildings
Certified Level	Certified (40 to 49 points) Silver (50 to 59 points) Gold (60 to 79 points) Platinum (80 points and above)	Bronze (40% overall) Silver (55% overall) Gold (65% overall) Platinum (75% overall)	Certified (30 to 37 points) Silver (38 to 45 points) Gold (46 to 60 points) Platinum (61 points and above)	Unsatisfactory (F, > 145) Inefficiency (D, 116 to 145) Average (C, 86 to 115) Efficiency (B, 56 to 85) Very good (A-, 26 to 55) High performance (A, 1 to 25) Zero net energy (A+, ≤ 0)
Categories	Integrative Process 1 Regional Priority 4 Location and Transportation 16 Sustainable Sites 10 Water Efficiency 11 Energy and Atmosphere 33 Materials and Resources 13 Indoor Environmental Quality 16 Innovation 6	Site Aspects 22 + 3B Materials Aspects 22 + 1B Energy Use 42 + 2B Water Use 9 + 1B Indoor Environmental Quality 32 + 3B Innovations and Additions 5B + 1	Building Management 3 Site and Landscape 16 Water Conservation 6 Energy and Atmosphere 20 Materials and Resources 13 Indoor Environmental Quality 17 Environmental Protection 5 Green Innovation 5	Energy only

Table 2. Assessment details of 'energy' category in each rating system [5], [6], [14], [15].

	LEED v4 – 2013	BEAM Plus v1.2 New Buildings	TREES v1.1	Building EQ (As Designed)
Method	% Energy improvement	Energy performance	Energy saving or energy cost	Energy Use Index (EUI)
Simulation Tools	DOE-2, BLAST, or EnergyPlus, or complying with ASHRAE/IESNA 90.1-2010	Building Energy Code (BEC) complying with ASHRAE 90.1-2007	Complying with ASHRAE 90.1-2007	Complying with Appendix G. Performance Rating Method (PRM) Standard ANSI/ASHRAE/IES 90.1-2010
Requirements for Baseline Case	1. Whole-building energy simulation – Complying with mandatory provisions of ANSI/ASHRAE/IESNA 90.1-2010, Appendix G. 2. Prescriptive compliance: ASHRAE Advanced Energy Design Guide – Complying with mandatory provisions of ASHRAE 90.1-2010. 3. Prescriptive compliance: Advanced Buildings™ Core Performance™ Guide – Complying with mandatory provisions of ASHRAE 90.1-2010.	1. Latest edition of Building Energy Code (BEC) or 2. ASHRAE 90.1-2007	1. Whole-building simulation – Complying with mandatory provisions of Building Energy Code (BEC) 2. ASHRAE 90.1-2007 Appendix G. – Complying with mandatory provisions of ASHRAE 90.1-2007 Appendix G. 3. Thailand Energy and Environmental Assessment Method (TEEAM) – Complying with mandatory provisions of TEEAM	Complying with Standardized Model in accordance with As Designed rating
Reference	www.usgbc.org/credits (v4–LEED v4)	www.beamsociety.org.hk	TREES v1.1	http://www.buildingenergyquotient.org

Table 3. Details and operating conditions of large office building.

Detail	Baseline building	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Building EQ
		Structure		
Number of floors	12	12	12	12
Wall area (m^2)	6,934.00	6,934.00	6,934.00	6,934.00
Window area (m^2)	3,051.00	3,051.00	3,051.00	3,051.00
Window-to-wall ratio	44.00	44.00	44.00	44.00
Roof area (m^2)	1,047.25	1,047.25	1,047.25	1,047.25
Total floor area (m^2)	12,567.00	12,567.00	12,567.00	12,567.00
Type of air conditioning system	Central, water-cooled chiller	Central, water-cooled chiller	Central, water-cooled chiller	Central, water-cooled chiller
		Internal design criteria		
Occupancy level (m^2/per)	14.29	14.29	14.29	14.29
Lighting power density (W/m^2)	13.00	11.00	9.69	13.00
Equipment power density (W/m^2)	16.46	16.46	16.46	16.46
Thermostat setpoint (^oC)	25.00	25.00	25.00	25.00
Infiltration rate (ACH)	0.35	0.35	0.35	0.35
Ventilation rate ($m^3/s\text{-}m^2$)	0.000556	0.00047	0.00047	0.000556
Operating days	Mon–Sat	Mon–Sat	Mon–Sat	Mon–Sat
Operating hours	08:00 to 17:00	08:00 to 17:00	08:00 to 17:00	08:00 to 17:00

Table 4. Details and operating conditions of small office building.

Detail	Baseline building	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Building EQ
		Structure		
Number of floors	4	4	4	4
Wall area (m^2)	1,419.83	1,419.83	1,419.83	1,419.83
Window area (m^2)	610.20	610.20	610.20	610.20
Window-to-wall ratio	42.98	42.98	42.98	42.98
Roof area (m^2)	395.18	395.18	395.18	395.18
Total floor area (m^2)	1,580.72	1,580.72	1,580.72	1,580.72
Type of air conditioning system	Central, water-cooled chiller	Direct expansion fan VAV system	Direct expansion fan VAV system	Central, water-cooled chiller
		Internal design criteria		
Occupancy level (m^2/per)	14.29	14.29	14.29	14.29
Lighting power density (W/m^2)	13.00	11.00	9.69	13.00
Equipment power density (W/m^2)	16.46	16.46	16.46	16.46
Thermostat setpoint (^oC)	25.00	25.00	25.00	25.00
Infiltration rate (ACH)	0.35	0.35	0.35	0.35
Ventilation rate ($m^3/s\text{-}m^2$)	0.000556	0.00047	0.00047	0.000556
Operating days	Mon–Sat	Mon–Sat	Mon–Sat	Mon–Sat
Operating hours	08:00 to 17:00	08:00 to 17:00	08:00 to 17:00	08:00 to 17:00

Table 5. Details and operating conditions of department store building.

Detail	Baseline building	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Building EQ
Structure				
Number of floors	3	3	3	3
Wall area (m^2)	3,304.52	3,304.52	3,304.52	3,304.52
Window area (m^2)	1,208.00	1,208.00	1,208.00	1,208.00
Window-to-wall ratio	36.56	36.56	36.56	36.56
Roof area (m^2)	2,771.22	2,771.22	2,771.22	2,771.22
Total floor area (m^2)	8,280.00	8,280.00	8,280.00	8,280.00
Type of air conditioning system	Central, water-cooled chiller	Direct expansion fan VAV system	Direct expansion fan VAV system	Central, water-cooled chiller
Internal design criteria				
Occupancy level (m^2/per)	5.00	5.00	5.00	5.00
Lighting power density (W/m^2)	14.33	16.00	15.07	14.33
Equipment power density (W/m^2)	20.64	20.64	20.64	20.64
Thermostat setpoint (^oC)	25.00	25.00	25.00	25.00
Infiltration rate (ACH)	0.35	0.35	0.35	0.35
Ventilation rate (m^3/s-m^2)	0.000556	0.00132	0.00132	0.000556
Operating days	Mon–Sun	Mon–Sun	Mon–Sun	Mon–Sun
Operating hours	10:00 to 21:00	10:00 to 21:00	10:00 to 21:00	10:00 to 21:00

Table 6. Details and operating conditions of hotel building.

Detail	Baseline building	ASHRAE 90.1-2007	ASHRAE 90.1-2010	Building EQ
Structure				
Number of floors	8	8	8	8
Wall area (m^2)	4,319.00	4,319.00	4,319.00	4,319.00
Window area (m^2)	733.93	733.93	733.93	733.93
Window-to-wall ratio	16.99	16.99	16.99	16.99
Roof area (m^2)	3,052.80	3,052.80	3,052.80	3,052.80
Total floor area (m^2)	11,448.00	11,448.00	11,448.00	11,448.00
Type of air conditioning system	Central, water-cooled chiller	Central, water-cooled chiller	Central, water-cooled chiller	Central, water-cooled chiller
Internal design criteria				
Occupancy level (m^2/per)	5.00	5.00	5.00	5.00
Lighting power density (W/m^2)	8.71	11.00	10.76	8.71
Equipment power density (W/m^2)	5.53	5.53	5.53	5.53
Thermostat setpoint (^oC)	25.00	25.00	25.00	25.00
Infiltration rate (ACH)	0.35	0.35	0.35	0.35
Ventilation rate (m^3/s-m^2)	0.000556	0.000556	0.000556	0.000556
Operating days	Mon–Sun	Mon–Sun	Mon–Sun	Mon–Sun
Operating hours	24 hrs	24 hrs	24 hrs	24 hrs

4. ENERGY CONSERVATION MEASURES (ECMS)

Practical ECMs found in Thailand as well as ECMs currently implemented nowadays have been reviewed [18]. The ECMs, listed as a set in Table 7, were applied to all four sample buildings. These ECMs were selected as they are commonly implemented in Thailand. They included increasing the temperature setpoint of chilled water, replacing fluorescent lamps with light-emitting diode (LED) lamps, installing insulation on walls and roofs, installing photovoltaic (PV) panels, *etc*.

The indicators, payback period, NPV, and IRR were used to determine whether the implementation of ECMs would be financially feasible or not. In this study, payback period must be less than 10 years, NPV must be positive, and IRR must be greater than 8.2644% which is the average loan interest rate of commercial banks in Thailand [19]. This interest rate was also used as the discount rate in the NPV calculations. The life of the project was assumed to be 20 years.

Table 7. Energy conservation measures (ECMs) applied to sample buildings.

ECM	Description
S1	Increase thermostat setpoint from 25°C to 26°C [17]
S2	Turn off the light from 12:00 to 13:00 [16]
S3	Increase chilled water temperature setpoint from 6.7°C to 7.2°C [16]
A1	Install variable speed drives (VSDs) at pumps [17]
L2	Use LED lamps instead of fluorescent lamps
P1	Install solar PV panels
E1	Use lightweight bricks instead of conventional bricks
E3	Install 2-inch insulation on roof
E4	Install 2-inch insulation on walls
E5	Use low-emissivity (low-e) glass instead of clear glass

Table 8. Energy saving and financial feasibility analysis of ECMs of sample small office building.

ECM	Energy use	Saving			Inv.	PB	NPV	IRR
	MWh/yr	MWh/yr	x 10^3 USD/yr	%	(x 10^3 USD)	(yr)	(x 10^3 USD)	(%)
Base	282.98	-	-	-	-	-	-	-
S1	278.93	4.04	0.48	1.43	-	-	4.62	-
S2	275.37	7.60	0.90	2.69	-	-	8.69	-
S3	281.85	1.12	0.13	0.40	-	-	1.28	-
A1	280.49	2.48	0.29	0.88	0.60	2.03	2.24	49.2
L2	241.43	41.55	4.93	14.68	0.72	0.15	46.77	687.0
P1	199.74	83.24	9.88	29.41	90.50	9.16	-14.84	6.0
E1	282.22	0.76	0.09	0.27	0.89	9.94	-0.03	7.8
E3	282.66	0.32	0.04	0.11	1.25	33.22	-0.89	-4.4
E4	281.75	1.23	0.15	0.43	2.56	17.63	-1.16	1.2
E5	280.93	2.04	0.24	0.72	6.56	27.01	-4.22	-2.7

5. RESULTS AND DISCUSSION

5.1 Energy Saving and Financial Feasibility of ECMs Applied to All Sample Buildings

Tables 8 and 9 show the analysis results of the energy saving and financial feasibility of the ECMs applied to the two sample office buildings. The first three ECMs (S1, S2, and S3) are non-investment measures and, therefore, could be implemented with ease. The ECMs related to the air conditioning (A1) and lighting systems (L2) offer relatively high saving. They also have a quicker payback period, a positive NPV, and a very high IRR. The ECM in this study that generated the highest saving was the installation of PV panels (P1) as the energy was directly produced. However, this ECM did not offer an attractive financial return owing to its relatively high investment cost which, in turn, led to a long payback period, a negative NPV, and a very low IRR. Although implementing an ECM on its own may possibly not be feasible, if implemented together with other ECMs, they could all be feasible. This is further discussed later in this section. In terms of ECMs related to the building envelope (E1, E3, E4, and E5), the study found they were not financially feasible as the saving was small, the payback period was very long, the NPV was negative, and the IRR was very low. A previous study also found that the saving from ECMs related to the building envelope was not attractive [20].

Table 9. Energy saving and financial feasibility analysis of ECMs of sample large office building.

ECM	Energy use	Saving			Inv.	PB	NPV	IRR
	MWh/yr	MWh/yr	x 10^3 USD/yr	%	(x 10^3 USD)	(yr)	(x 10^3 USD)	(%)
Base	2,043.81	-	-	-	-	-	-	-
S1	2,016.24	27.57	2.57	1.35	-	-	24.71	-
S2	1,983.13	60.68	5.44	2.97	-	-	52.36	-
S3	2,035.74	8.07	0.79	0.39	-	-	7.59	-
A1	2,008.45	35.36	3.02	1.73	4.39	1.45	24.73	68.9
L2	1,711.08	332.73	31.15	16.28	5.70	0.18	294.23	546.1
P1	1,845.91	197.90	17.71	9.68	213.43	12.05	-88.86	1.9
E1	2,040.75	3.06	0.26	0.15	4.28	16.55	-1.79	1.9
E3	2,041.59	2.22	0.19	0.11	3.32	17.81	-1.52	1.1
E4	2,038.59	5.22	0.44	0.26	12.30	28.18	-8.10	-3.1
E5	2,026.81	17.00	1.61	0.83	32.78	20.33	-17.25	-0.2

Table 10. Energy saving and financial feasibility analysis of ECMs of sample department store building.

ECM	Energy use	Saving			Inv.	PB	NPV	IRR
	MWh/yr	MWh/yr	x 10^3 USD/yr	%	(x 10^3 USD)	(yr)	(x 10^3 USD)	(%)
Base	2,156.53	-	-	-	-	-	-	-
S1	2,132.11	24.43	2.25	1.13	-	-	21.62	-
S2	2,105.25	51.28	4.58	2.38	-	-	44.14	-
S3	2,149.11	7.43	0.71	0.34	-	-	6.81	-
A1	2,093.56	62.97	5.68	2.92	3.76	0.66	50.90	151.0
L2	1,813.11	343.43	31.75	15.92	4.14	0.13	300.54	766.5
P1	1,622.54	534.00	47.84	24.76	555.60	11.61	-214.52	2.4
E1	2,148.10	8.43	0.80	0.39	2.31	2.88	5.43	34.7
E3	2,133.77	22.76	2.11	1.06	8.77	4.16	11.56	23.7
E4	2,139.30	17.24	1.63	0.80	6.64	4.09	9.01	24.2
E5	2,146.20	10.33	0.97	0.48	12.98	13.41	-3.66	4.2

Table 10 shows the energy saving and financial feasibility analysis of the ECMs applied to the sample department store building. The study found these observations were similar to those for the sample office buildings. The ECMs S1, S2, and S3 should be implemented as they did not require any investment. The ECMs A1 and L2 were considered favorable as the payback period was short, the NPV was positive, and the IRR was very high. The ECM P1 offered the highest saving. However, the investment required was very high; thus, it was not financially feasible. The ECMs E1, E3, and E4 appeared to be acceptable while the ECM E5 was not attractive as the payback period was quite long, the NPV was negative, and the IRR was low.

Table 11 shows the energy saving and financial feasibility analysis of the ECMs applied to the sample hotel building. The observations were found to be similar to those for the previous sample buildings, except that ECMs E1, E3, and E4 appeared acceptable. As the hotel operated 24 hours a day, savings occurred all the time

Table 11. Energy saving and financial feasibility analysis of ECMs of sample hotel building.

ECM	Energy use	Saving			Inv.	PB	NPV	IRR
	MWh/yr	MWh/yr	x 10^3 USD/yr	%	(x 10^3 USD)	(yr)	(x 10^3 USD)	(%)
Base	2,420.33	-	-	-	-	-	-	-
S1	2,394.03	26.30	2.42	1.09	-	-	23.29	-
S2	2,410.46	9.87	0.88	0.41	-	-	8.51	-
S3	2,417.95	2.38	0.23	0.10	-	-	2.17	-
A1	2,212.35	207.98	18.62	8.59	1.74	0.09	177.52	1,068.0
L2	2,212.01	208.32	19.42	8.61	3.48	0.18	180.91	557.6
P1	2,202.19	218.14	19.54	9.01	233.76	11.96	-95.88	2.0
E1	2,402.17	18.16	1.69	0.75	3.95	2.34	12.34	42.8
E3	2,396.13	24.20	2.26	1.00	9.67	4.28	12.11	23.0
E4	2,385.97	34.36	3.21	1.42	11.36	3.54	19.56	28.1
E5	2,413.74	6.59	0.61	0.27	7.89	12.84	-1.97	4.7

5.2 Order of ECM Implementation and How to Determine the Most Cost-Effective Number of ECMs

Tables 12 to 14 show the order in which ECMs are to be implemented when applying six different sorting schemes to three of the four sample buildings using Building EQ as the rating system. The exception was the sample hotel building as the Median EUI of hotels in Thailand was not available. The six sorting schemes were energy saving from high to low, investment from low to high, points from high to low, payback period from low to high, NPV from high to low, and IRR from high to low.

This study proposed that the most cost-effective number of ECMs to be implemented would be determined by accumulated investment cost per unit area per %credit of the building. The ECMs would be implemented one by one in accordance with the order in the selected sorting scheme. The most cost-effective number of ECMs for implementation was the number at the point where the investment cost per unit area per %credit was at the minimum. If the minimum point did not exist, the most cost-effective point would be where the next ECM would not add any more points. The rationale was that if more ECMs were implemented beyond this point, the rating system points would no longer be worth the increased investment. The location of the most cost-effective number of ECMs to be implemented in each sorting scheme is shaded in gray in Tables 12 to 14. In addition, the most cost-effective point must also be financially feasible, with a payback period of less than 10 years, an NPV that is positive, and an IRR greater than 8.2644% (as previously mentioned, the average loan interest rate of commercial banks in Thailand [19]).

As different rating systems have different ways of calculating points, investment cost per unit area per %credit was considered instead of investment cost per unit area per point. When comparing rating systems, the indicator must be on the same basis. Therefore, "%credit" was introduced. For example, LEED's energy points ranged from 0 to 18, BEAM Plus's energy points ranged from 0 to 15, TREES' energy points ranged from 0 to 16, and Building EQ's points ranged from -46 to 100, with all converted to 0 to 100%. The points earned from each rating system's energy category would then be adjusted to fit this 0 to 100% scale before comparing the systems.

As can be seen in Tables 12 to 14, the order of ECM implementation in each of the three pairs of sorting schemes is almost exactly the same. The first pair comprises energy saving and points sorting schemes where the most cost-effective number of ECMs to be implemented is the least. The second pair is made up of the payback period and the IRR sorting schemes where the most cost-effective number of ECMs is more than that of the first pair. The last pair is the investment and NPV sorting schemes where the most cost-effective number of ECMs is all 10 ECMs.

Table 12. Order of ECMs of sample large office building when using Building EQ.

ECM sorting schemes	Order of ECMs									
	1	2	3	4	5	6	7	8	9	10
(a) Energy saving	L2	P1	S2	A1	S1	E10	S3	E4	E1	E3
(b) Investment	S2	S1	S3	E3	E1	A1	E4	L2	E10	P1
(c) Points	L2	P1	S2	A1	S1	E10	S3	E4	E1	E3
(d) PB	S2	S1	S3	L2	A1	P1	E1	E3	E10	E4
(e) NPV	L2	S2	A1	S1	S3	E3	E1	E4	E10	P1
(f) IRR	S2	S1	S3	L2	A1	P1	E1	E3	E10	E4

Table 13. Order of ECMs of sample small office building when using Building EQ.

ECM sorting schemes	Order of ECMs									
	1	2	3	4	5	6	7	8	9	10
(a) Energy saving	P1	L2	S2	S1	A1	E10	E4	S3	E1	E3
(b) Investment	S2	S1	S3	A1	L2	E1	E3	E4	E10	P1
(c) Points	P1	L2	S2	S1	A1	E10	E4	S3	E1	E3
(d) PB	S2	S1	S3	L2	A1	P1	E1	E4	E10	E3
(e) NPV	L2	S2	S1	A1	S3	E1	E3	E4	E10	P1
(f) IRR	S2	S1	S3	L2	A1	E1	P1	E4	E10	E3

Table 14. Order of ECMs of sample department store building when using Building EQ.

ECM sorting schemes	Order of ECMs									
	1	2	3	4	5	6	7	8	9	10
(a) Energy saving	P1	L2	A1	S2	S1	E3	E4	E10	E1	S3
(b) Investment	S2	S1	S3	E1	A1	E4	E3	L2	E10	P1
(c) Points	P1	L2	A1	S2	S1	E3	E4	E10	E1	S3
(d) PB	S2	S1	S3	A1	L2	E1	E4	E3	P1	E10
(e) NPV	L2	A1	S2	S1	E3	E4	S3	E1	E10	P1
(f) IRR	S2	S1	S3	A1	L2	E1	E4	E3	E10	P1

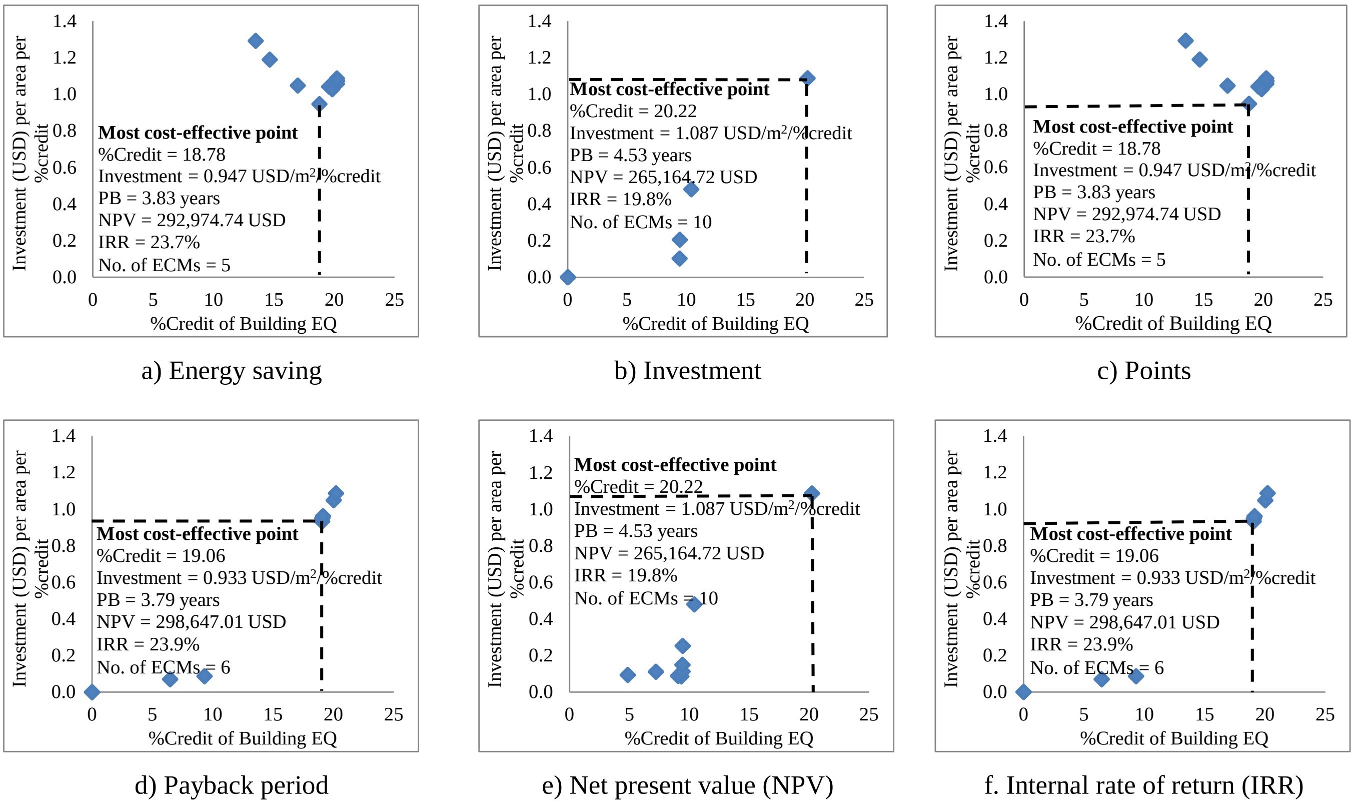
5.3 Effects of Different Sorting Schemes when using Building EQ

5.3.1 Large office building

As shown on Figure 2, when using Building EQ as the energy rating system and implementing ECMs according to the six sorting schemes on the sample large office building, the investment cost per unit area per %credit at the most cost-effective point was found to be within the range of 0.933 to 1.087 USD/m^2/%credit. The most cost-effective point was equivalent to a "C-level" achievement. As can be seen, investment costs at the most cost-effective point are not very different when using different sorting schemes. This implies that if the goal was to achieve the most cost-effective point, ECMs may be sorted by any scheme chosen by the building owner. However, if the owner chooses to sort ECMs by the energy saving and points earned schemes (Figures 2(a) and 2(c)), high investment would be required as the very first ECM, but only a maximum of five ECMs, would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 0.947 USD/m^2/%credit. If the owner chooses to sort ECMs by the payback period and the IRR (Figures 2(d) and 2(f)), the investment cost would gradually increase as incremental ECMs would be implemented but six ECMs would still have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 0.933 USD/m^2/%credit. If the owner chooses to sort ECMs by investment cost and the NPV (Figures 2(b) and 2(e)), the investment cost would gradually increase as in the previous pair of sorting schemes, but all 10 ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.087 USD/m^2/%credit.

5.3.2 Small office building

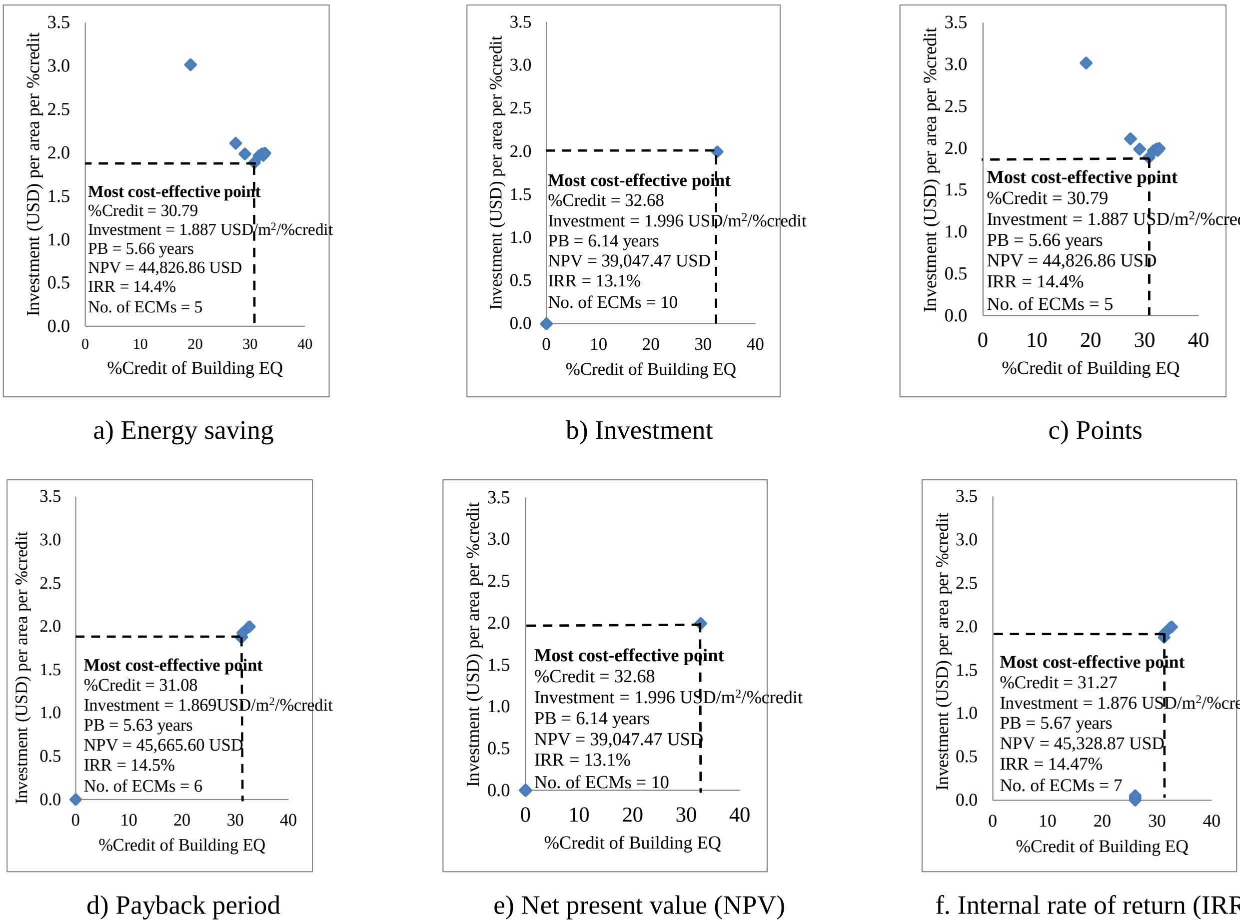
As shown in Figure 3, when using Building EQ and implementing ECMs in accordance with the six sorting schemes on the sample small office building, the investment cost at the most cost-effective point was found to be within the range of 1.887 to 1.996 USD/m^2/%credit. The most cost-effective point was equivalent to a "C-level" achievement. As with the previous sample building, investment cost at the most cost-effective point is not significantly different when using different sorting schemes. Therefore, ECMs, when sorted by any scheme, would reach about the same most cost-effective point. However, if choosing to sort ECMs by energy saving and points (Figures 3(a) and 3(c)), high investment cost would be required from the first ECM but only five ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.887 USD/m^2/%credit. If sorting by the payback period and the IRR (Figures 3(d) and 3(f)), the investment cost would gradually increase as incremental ECMs were implemented but six and seven ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.869 USD/m^2/%credit and 1.876 USD/m^2/%credit, respectively. If sorting by investment cost and the NPV (Figures 3(b) and 3(e)), investment cost would also gradually increase, but 10 ECMs would have to be implemented to achieve the most cost-effective point. The investment cost at the most cost-effective point would be 1.996 USD/m^2/%credit.



a) Energy saving b) Investment c) Points

d) Payback period e) Net present value (NPV) f. Internal rate of return (IRR)

Fig. 2. Effects of different sorting schemes on sample large office building when using Building EQ.



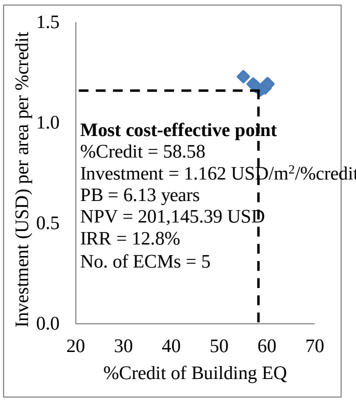
a) Energy saving b) Investment c) Points

d) Payback period e) Net present value (NPV) f. Internal rate of return (IRR)

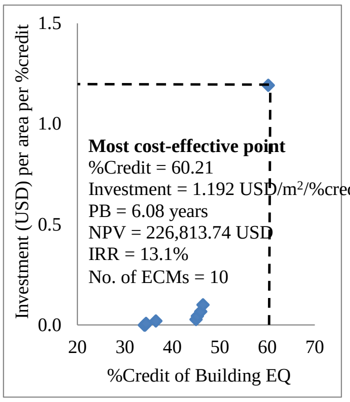
Fig. 3. Effects of different sorting schemes on sample small office building when using Building EQ.

5.3.3 Department store building

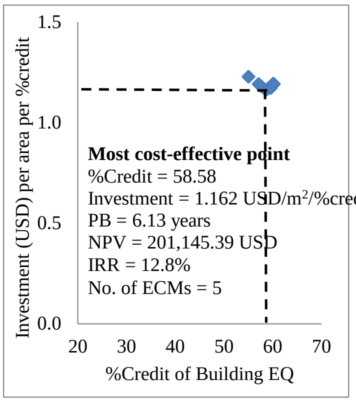
As shown in Figure 4, when using Building EQ and implementing ECMs in accordance with the six sorting schemes on the sample department store building, the investment cost at the most cost-effective point was found to be within the range of 1.162 to 1.192 USD/m^2/%credit. The most cost-effective point was equivalent to an "A-level" accomplishment. As with the previous sample buildings, the investment cost at the most cost-effective point was not significantly different when using different sorting schemes. Thus, ECMs, when sorted by any scheme, would reach about the same most cost-effective point. However, if choosing to sort ECMs by energy saving and points (Figures 4(a) and 4(c)), high investment cost would be required from the first ECM, but only five ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.162 USD/m^2/%credit. If sorting by the payback period and the IRR (Figures 4(d) and 4(f)), investment cost would gradually increase as incremental ECMs were implemented. However, 9 and 10 ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.175 and 1.192 USD/m^2/%credit, respectively. If sorting by investment cost and the NPV (Figures 4(b) and 4(e)), investment cost would also gradually increase but all 10 ECMs would have to be implemented to reach the most cost-effective point. The investment cost at the most cost-effective point would be 1.192 USD/m^2/%credit.



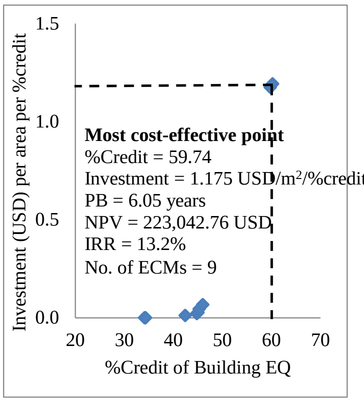
a) Energy saving



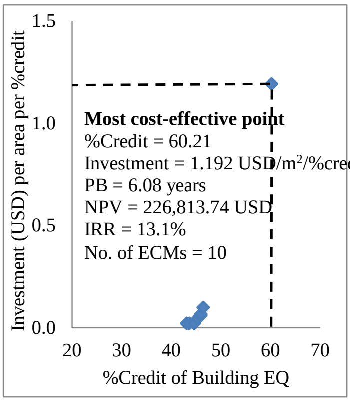
b) Investment



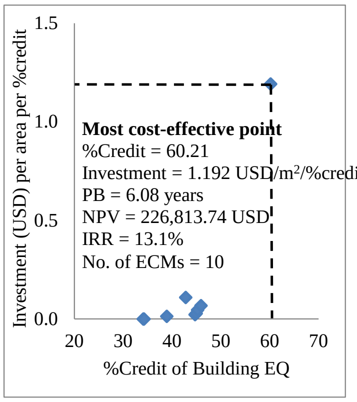
c) Points



d) Payback period



e) Net present value (NPV)



f. Internal rate of return (IRR)

Fig. 4. Effects of different sorting schemes on sample department store building when using Building EQ.

5.3.4 Discussion on all sample buildings

When considering the application of the Building EQ rating system to all sample buildings, the study found that using different ECM sorting schemes led to different numbers of ECMs being implemented to reach the most cost-effective point. As shown in Tables 12 to 14 and Figures 2 to 4, if the sorting scheme chosen was energy saving or points earned, only five ECMs would need to be implemented but the trade-off would be high investment cost from the first ECM to be implemented. If the payback period or the IRR were selected as the sorting scheme, more ECMs would be required but the investment in ECMs would start low and gradually increase to high. If sorting ECMs by investment cost or the NPV, 10 ECMs would have to be implemented and investment cost in ECMs would also gradually increase.

At the most cost-effective point of all sorting schemes, investment cost per unit area per %credit was not significantly different. The implication was that if the building owner's goal was to implement ECMs until the most cost-effective point was reached, any sorting scheme could be applied depending only on the owner's preference. If the owner wanted to implement the least number of ECMs and had no problem with spending a large amount of money from the beginning, the owner might choose to sort ECMs by energy saving or points earned from the rating system and, thus, would reach the most cost-effective point faster. However, if the owner wanted to start with low investment ECMs first, then one of the other sorting schemes should be selected.

5.4 Effects of Different Sorting Schemes when using LEED v4

The same methodology, as discussed in Section 5.3, was used for all four sample buildings in this part of the study, but the rating system employed was the LEED v4 energy topic. Trends in the findings were similar to when Building EQ was applied. If sorting ECMs by energy saving or points, only some ECMs would need to be implemented but the trade-off, from the first ECM, was high investment cost. If sorting by the payback period or the IRR, 9 or 10 ECMs would need to be implemented (except for the small office building). However, investment cost in ECMs would gradually increase from low to high. If sorting by investment cost or the NPV, all ECMs would have to be implemented and investment cost in ECMs would also gradually increase.

At the most cost-effective point of every sorting scheme, investment cost per unit area per %credit was not significantly different. The implication was that if the building owner's goal was to implement ECMs until the most cost-effective point was reached, any sorting scheme could be used, with this being reliant on the owner's decision.

To save space, the effects of the different sorting schemes, when using LEED v4 energy category as the rating system, are presented in the form of summary tables as shown in Tables 15 to 18.

Table 15. Data at most cost-effective point of sample large office building when using LEED v4.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	8	3.00	18.00	1.188	4.40	273.05	20.4
Investment	10	3.00	17.96	1.224	4.53	265.16	19.8
Points	8	3.00	18.00	1.188	4.40	273.05	20.4
PB	9	3.00	17.16	1.224	4.35	274.37	20.7
NPV	10	3.00	17.96	1.224	4.53	265.16	19.8
IRR	9	3.00	17.16	1.224	4.35	274.37	20.7

Table 16. Data at most cost-effective point of sample small office building when using LEED v4.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	5	16.00	90.42	0.642	5.66	44.83	14.4
Investment	10	16.00	93.05	0.701	6.14	38.83	13.1
Points	5	16.00	90.42	0.642	5.66	44.83	14.4
PB	6	16.00	90.83	0.640	5.63	45.67	14.5
NPV	10	16.00	91.47	0.668	5.87	39.05	13.1
IRR	7	16.00	91.11	0.644	5.67	45.33	14.4

Table 17. Data at most cost-effective point of sample department store building when using LEED v4.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	5	18.00	100.00	0.681	6.13	201.15	12.8
Investment	10	18.00	100.00	0.720	6.08	226.81	13.1
Points	5	18.00	100.00	0.681	6.13	201.15	12.8
PB	9	18.00	100.00	0.702	6.05	223.31	13.2
NPV	10	18.00	100.00	0.720	6.08	226.81	13.1
IRR	10	18.00	100.00	0.720	6.05	226.81	13.1

Table 18. Data at the cost-effective point of sample hotel building when using LEED v4.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	9	4.00	24.09	0.99	3.23	486.63	28.9
Investment	10	4.00	23.71	1.00	3.23	484.83	28.8
Points	9	4.00	24.09	0.99	3.23	486.63	28.9
PB	10	4.00	23.71	1.00	3.23	484.83	28.8
NPV	10	4.00	23.71	1.00	3.23	484.83	28.8
IRR	10	4.00	23.71	1.00	3.23	484.83	28.8

5.5 Effects of Different Sorting Schemes when using BEAM Plus

The same methodology, as described in Sections 5.3 and 5.4, was used for all four sample buildings with the BEAM Plus v1.2 energy topic applied as the rating system. The findings were similar to when Building EQ and LEED were applied. Tables 19 to 22 summarize the effects of different sorting schemes when using the BEAM Plus v1.2 energy topic as the rating system.

Table 19. Data at most cost-effective point of sample large office building when using BEAM Plus v1.2.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	7	6.00	42.95	0.475	4.24	279.79	21.2
Investment	10	6.00	44.09	0.499	4.53	265.16	19.8
Points	7	6.00	42.95	0.475	4.24	279.79	21.2
PB	6	6.00	40.50	0.439	3.79	298.65	23.9
NPV	10	6.00	44.09	0.499	4.53	265.16	19.8
IRR	6	6.00	40.50	0.439	3.79	298.65	23.9

Table 20. Data at most cost-effective point of sample small office building when using BEAM Plus v1.2.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	5	14.00	98.24	0.591	5.66	44.83	14.4
Investment	10	15.00	100.00	0.652	6.14	39.05	13.1
Points	5	14.00	98.24	0.591	5.66	44.83	14.4
PB	6	15.00	98.61	0.589	5.63	45.67	14.5
NPV	10	15.00	100.00	0.652	6.14	39.05	13.1
IRR	7	15.00	98.85	0.593	5.67	45.33	14.4

Table 21. Data at most cost-effective point of sample department store building when using BEAM Plus v1.2.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	5	15.00	100.00	0.681	6.13	201.15	12.8
Investment	10	15.00	100.00	0.720	6.08	226.81	13.1
Points	5	15.00	100.00	0.681	6.13	201.15	12.8
PB	9	15.00	100.00	0.702	6.05	223.31	13.2
NPV	10	15.00	100.00	0.720	6.08	226.81	13.1
IRR	9	15.00	100.00	0.720	6.05	226.81	13.1

Table 22. Data at most cost-effective point of sample hotel building when using BEAM Plus v1.2.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	6	7	47.57	0.48	3.20	469.07	29.0
Investment	10	7	51.67	0.46	3.23	484.83	28.8
Points	6	7	47.57	0.48	3.20	469.07	29.0
PB	9	7	48.37	0.48	3.23	470.63	28.8
NPV	10	7	51.67	0.46	3.23	484.83	28.8
IRR	10	7	51.67	0.46	3.23	484.83	28.8

5.6 Effects of Different Sorting Schemes when using TREES

The same methodology, as described in Sections 5.3, 5.4, and 5.5, was used for all four sample buildings, with the TREES v1.1 energy topic applied as the rating system. The findings were similar to when Building EQ, LEED, and BEAM Plus were applied. Tables 23 to 26 summarize the effects of different sorting schemes when using the TREES v1.1 energy topic as the rating system.

Table 23. Data at most cost-effective point of sample large office building when using TREES v1.1.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	7	8.00	47.03	0.434	4.24	279.79	21.3
Investment	10	8.00	48.25	0.456	4.53	265.16	19.8
Points	7	8.00	47.03	0.434	4.24	279.79	21.3
PB	9	8.00	47.60	0.441	4.35	274.37	20.7
NPV	10	8.00	48.25	0.456	4.53	265.16	19.8
IRR	9	8.00	47.60	0.441	4.35	274.37	20.7

Table 24. Data at most cost-effective point of sample small office building when using TREES v1.1.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	5	16.00	100.00	0.581	5.66	44.83	14.4
Investment	10	16.00	100.00	0.652	6.14	39.05	13.1
Points	5	16.00	100.00	0.581	5.66	44.83	14.4
PB	6	16.00	100.00	0.581	5.63	45.67	14.5
NPV	10	16.00	100.00	0.652	6.14	39.05	13.1
IRR	7	16.00	100.00	0.587	5.67	45.33	14.4

Table 25. Data at most cost-effective point of sample department store building when using TREES v1.1.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	7	16.00	100.00	0.699	6.05	221.23	13.1
Investment	10	16.00	100.00	0.718	6.08	226.81	13.1
Points	7	16.00	100.00	0.699	6.05	221.23	13.1
PB	9	16.00	100.00	0.702	6.05	223.31	13.2
NPV	10	16.00	100.00	0.718	6.08	226.81	13.1
IRR	10	16.00	100.00	0.718	6.08	226.81	13.1

Table 26. Data at most cost-effective point of sample hotel building when using TREES v1.1.

Sorting scheme	No. of ECMs	Energy point	%Credit	Investment cost (USD/m^2/%credit)	PB (yr)	NPV (x 10^3 USD)	IRR (%)
Energy saving	6	8.00	52.03	0.44	3.20	469.07	29.0
Investment	10	8.00	56.62	0.42	3.23	484.83	28.8
Points	6	8.00	52.03	0.44	3.20	469.07	29.0
PB	9	8.00	52.92	0.44	3.23	470.63	28.8
NPV	10	8.00	56.62	0.42	3.23	484.83	28.8
IRR	10	8.00	56.62	0.42	3.23	484.83	28.8

5.7 Result Comparison among Building Energy Rating Systems

Figures 5 to 10 show the relationships between %credit and the accumulated investment cost of implementing ECMs in accordance with the six sorting schemes on the sample large office building when using all four rating systems. Only the results for the large office building are discussed as the trends are similar for the other sample buildings. As can be seen, at the same %credit, using BEAM Plus and TREES would need a lower investment. LEED and Building EQ would require higher investment as their requirements are more stringent [7], [8]. LEED v4 refers to the newer version of ASHRAE Standard 90.1-2010 which is more rigorous than ASHRAE Standard 90.1-2007 to which BEAM Plus v1.2 and TREES v1.1 refer. For example, lighting power density limit in Standard 90.1-2010 is 9.69 W/m^2 compared with 11.00 W/m^2, as specified in Standard 90.1-2007. For Building EQ, the points are calculated by comparing the Source Energy Use Index (Source EUI) of the proposed building with the Median EUI of the building stock of the same building type. If the Median EUI is low (meaning that buildings in the building stock have high energy efficiency) then it would be difficult to earn points. This study used the Median EUI of the building stock of Thailand from 2010 to 2013 which had a relatively low value (994.078 MJ/m^2/y). Earning points in this study was therefore quite difficult.

The study made the additional observation that applying the Building EQ rating system could earn points quickly from the first ECMs. The reason is that a building can earn points even when it still consumes more energy than the reference Median EUI. However, earning points seems more difficult later as the final target of Building EQ is for the building to become net zero energy.

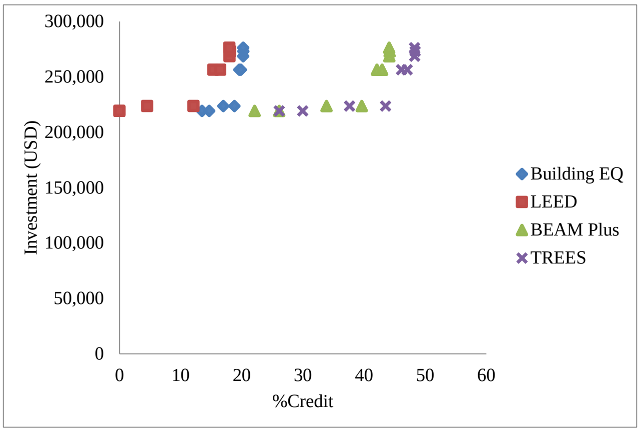


Fig. 5. Effects of sorting ECMs by energy saving of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

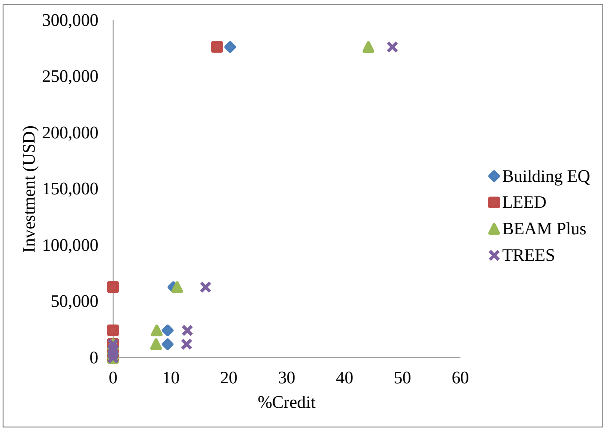


Fig. 6. Effects of sorting ECMs by investment cost of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

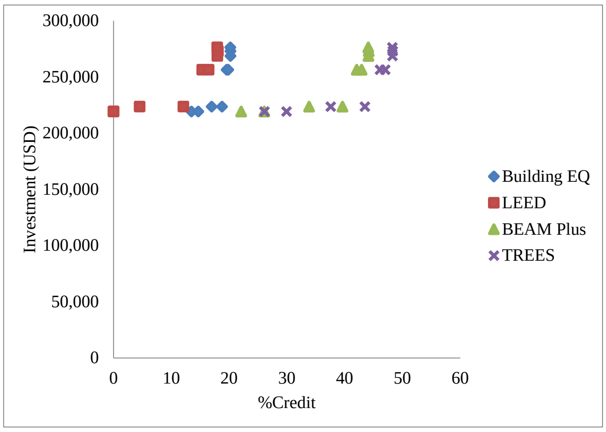


Fig. 7. Effects of sorting ECMs by points of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

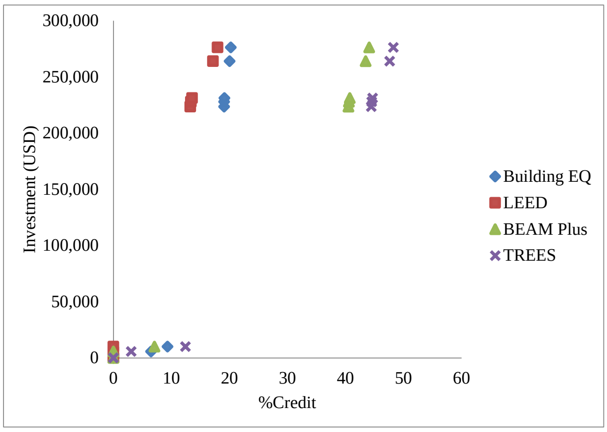


Fig. 8. Effects of sorting ECMs by payback period of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

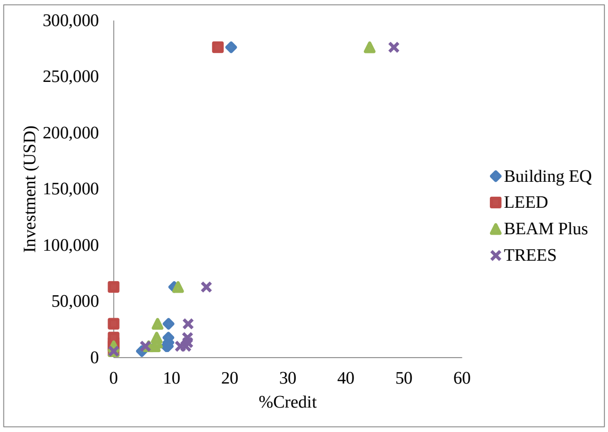


Fig. 9. Effects of sorting ECMs by NPV of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

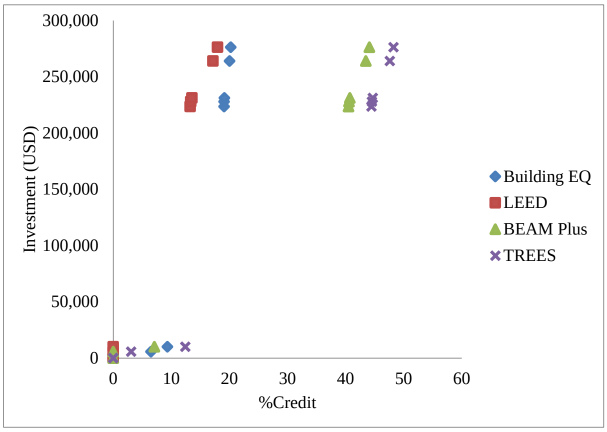


Fig. 10. Effects of sorting ECMs by IRR of sample large office building using Building EQ, LEED, BEAM Plus, and TREES rating systems.

5.8 Result Comparison between Building Types

Tables 27 to 30 show the ratio of the investment cost of ECMs to the total investment cost of building construction at the most cost-effective point for all sample buildings. As can be seen, the two larger buildings, the large office building and the hotel building (12,567.00 m^2 and 11,448.00 m^2, respectively), have a lower percentage of ECM investment cost to total investment cost (2.375% to 2.935% and 3.396% to 3.551%, respectively). Conversely, the small office building and the department store building with their smaller area (1,580.72 m^2 and 8,280.00 m^2, respectively) have a higher percentage of ECM investment cost (7.815% to 8.774% and 7.968% to 8.403%, respectively). This can be explained as a case of the application of "economy of scale".

To be clearer, ECM P1 (installing PV panels) which, in investment cost, is the most expensive ECM is considered as an example. For the large office building, spending of 213,433.31 USD is required and can save energy by 9.68%. The percentage of investment cost in this ECM to the total investment cost is only 2.27%. For the small office building, only 90,503.47 USD is required to install PV panels, with this ECM being able to save energy by as much as 29.41%. However, the investment cost in this ECM is 7.70% of the total investment cost which is relatively high. Therefore, it can be said that it is more economic to implement expensive ECMs in a larger building.

In terms of the number of ECMs at the most cost-effective point, no significant difference was found between buildings of different types or sizes.

Table 27. Percentage of investment cost in ECMs to total investment cost and corresponding number of ECMs at most cost-effective point of sample large office building.

Standard	Energy saving		Investment cost		Points		PB		NPV		IRR	
	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs
Building EQ	2.38	5	2.94	10	2.38	5	2.80	9	2.94	10	2.80	9
LEED	2.85	8	2.94	10	2.85	8	2.80	9	2.94	10	2.80	9
TREES	2.72	7	2.94	10	2.72	7	2.80	9	2.94	10	2.80	9
BEAM Plus	7.72	7	2.94	10	2.72	7	2.38	6	2.94	10	2.38	6

Table 28. Percentage of investment cost in ECMs to total investment cost and corresponding number of ECMs at most cost-effective point of sample small office building.

Standard	Energy saving		Investment cost		Points		PB		NPV		IRR	
	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs
Building EQ	7.82	5	8.78	10	7.82	5	7.82	6	8.78	10	7.90	7
LEED	7.82	5	8.78	10	7.82	5	7.82	6	8.78	10	7.90	7
TREES	7.82	5	8.78	10	7.82	5	7.82	6	8.78	10	7.90	7
BEAM Plus	7.82	5	8.78	10	7.82	5	7.82	6	8.78	10	7.90	7

Table 29. Percentage of investment cost in ECMs to total investment cost and corresponding number of ECMs at most cost-effective point of sample department store building.

Standard	Energy saving		Investment cost		Points		PB		NPV		IRR	
	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs
Building EQ	7.97	5	8.40	10	7.97	5	8.23	9	8.40	10	8.40	10
LEED	7.97	5	8.40	10	7.97	5	8.23	9	8.40	10	8.40	10
TREES	8.19	7	8.40	10	8.19	7	8.23	9	8.40	10	8.40	10
BEAM Plus	7.97	5	8.40	10	7.97	5	8.23	9	8.40	10	8.40	10

Table 30. Percentage of investment cost in ECMs to total investment cost and corresponding number of ECMs at most cost-effective point of sample hotel building.

Standard	Energy saving		Investment cost		Points		PB		NPV		IRR	
	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs	%	No. of ECMs
LEED	3.55	9	3.55	10	3.55	9	3.55	10	3.55	10	3.55	10
TREES	3.40	6	3.55	10	3.40	6	3.45	9	3.55	10	3.55	10
BEAM Plus	3.40	6	3.55	10	3.40	6	3.45	9	3.55	10	3.55	10

6. CONCLUSIONS

This paper reports on the effects of different ECM sorting schemes on the most cost-effective number of ECMs to be implemented in accordance with the referenced energy rating systems. It also discusses other aspects of interest. In total, 10 common ECMs were selected. Four sample buildings were studied, with ASHRAE's Building EQ and the energy topic in LEED, BEAM Plus, and TREES chosen to be the rating systems. The six sorting schemes studied were energy saving from high to low, investment cost from low to high, points from high to low, payback period from low to high, NPV from high to low, and IRR from high to low. The results of the study can be concluded as follows:

1. Any of the ECM sorting schemes would lead to literally the same cost-effective point, but different sorting schemes may require different numbers of ECMs to be implemented.
2. If the building owner chose to sort ECMs by investment cost, payback period, NPV, or IRR, the

investment cost in ECMs would gradually increase while incremental ECMs were being implemented. However, almost or all ECMs would have to be implemented. Conversely, if the owner chose to sort ECMs by energy saving or points, high investment cost in ECMs would be required from the first ECM. However, the number of ECMs to be implemented would be significantly less than in the four sorting schemes previously mentioned.

3. BEAM Plus and TREES rating systems tend to require lower investment in ECMs (in terms of USD/m^2/%credit) than LEED and Building EQ as the latter two are more stringent in the method used for calculating points. LEED refers to a newer version of ASHRAE Standard 90.1 while the final goal of Building EQ is a net zero energy building.
4. Economy of scale is found to apply in this study. Larger buildings have a lower percentage of ECM investment cost to total investment in building construction than in smaller buildings. Therefore, investing in expensive ECMs would be more attractive if carried out in larger buildings.

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