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Methodological Framework for Evaluating Cost-Effective Energy and Climate Measures in Building Clusters

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Abstract

Building renovation and energy-efficient retrofitting is a growing concern in many building stocks to improve the energy performance and energy-related greenhouse gas (GHG) emission reductions. This paper aims to present the methodological framework for energy and climate change mitigation planning in building clusters. The proposed methodology includes building energy modeling and marginal abatement cost (MAC) curve. It enables to simulate building energy use and GHG emissions associated with energy retrofit measures (ERMs) and to evaluate the cost-effectiveness. The relationship between the cost and emission reduction potentials is presented in terms of a MAC curve. Using a case study of an educational building in Bangkok, Thailand, the energy performance of four ERMs was simulated and a MAC curve was constructed. Findings showed that the baseline emissions are 310 tCO_2e and total emissions from implementing four ERMs are 250.64 tCO_2e. The improvement of air-conditioning systems contributed the largest share of mitigation potential and was followed by measures relating to building envelopes, building energy management systems, and lighting. On the cost-effectiveness, switching to efficient lighting showed the highest cost-savings of 84.59 US$ per tCO_2e. Other ERMs delivered the cost-savings from 50 to 63 US$ per tCO_2e. The proposed methodological framework would support the decision-making for the implementation of energy and climate planning at various scales from an individual building to an urban area.

Keywords: Building energy performance, Energy modeling, Energy planning, Marginal abatement cost curve

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1. Introduction

Globally, local and national governments have committed to reducing greenhouse gas (GHG) emissions. The commitment is reflected in various international agreements, for example, the Paris Agreement and the 17 UN's Sustainable Development Goals (SDGs). The achievement of these global agreements will have to come from both developed and developing countries. Thailand has announced the transition towards carbon neutrality by 2050 and net zero emissions by 2065 at the COP 26 in Glasgow in 2021. To achieve such ambitious goals, energy and climate change planning needs to be revised in all sectors at various levels. The role of building sector is well recognized in addressing energy and climate challenges and the transition to low-carbon society [1], [2]. Building sector represents high potential to implement energy-saving and climate change mitigation measures through energy retrofit measures (ERMs) and renewable energy technologies (RETs).

In Thailand, the building sector, including residential buildings and commercial buildings, represents approximately 50% of the total electricity consumption and the remaining shares are for industrial sector and others. Existing building stocks are responsible for a large amount of energy use and a significant share of total GHG emissions. Decision-makers need to decide on measures or options to be implemented based on information about the potential of abatement costs, energy usages, and GHG emission reductions. In the

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literature, a marginal abatement cost (MAC) curve is an efficient method that includes information on cost-effectiveness and potentials of mitigation measures [3], [4], [5], [6], [7], [8], [9].

MAC curves help decision-makers prioritize different measures or options based on the cost-effectiveness of ERMs, RETs, and other promising technologies. MAC curves have been gaining popularity in the area of energy and climate change planning since McKinsey & Company has published the MAC curves in 2009 [4], [7]. In Thailand, a recent work related to a MAC curve was performed by [10] to determine MAC of electricity generation from RETs. Previously, [11] presented a MAC curve for residential and building sectors in Thailand using the Asia-Pacific Integrated Model/Enduse (AIM/Enduse) to assess the energy demand and GHG emissions, and mitigation potentials from a country perspective. However, few works have been done and still limited at the building cluster level. Even previous studies have confirmed that energy efficiency improvements and RETs are the main mechanisms to reduce energy use and GHG emissions in Thailand, especially to meet Thailand's Nationally Determined Contribution target [3], [12].

This paper aims to propose a methodological framework for cost-effective energy technologies and climate change mitigation measures in building clusters, for example, university campuses. The contribution of this paper is to provide a methodology for energy and climate planning. It helps to analyze different ERMs and to visualize cost-effective energy and climate measures. The proposed methodology can be applied at various scales from an individual building to building cluster or even a whole urban area. In this paper, the proposed methodological framework was applied to an educational building as a case study. The analysis of a case study focused on answering a key question relating to ERMs of educational buildings in terms of energy savings and cost-effective GHG emission reduction potentials.

2. Marginal Abatement Cost Curves

A MAC curve is a visualization tool of the GHG abatement or mitigation potentials. It illustrates a function of abatement costs and shows mitigation measures in the order of cost-effectiveness. MAC curves have been used to support energy and climate planning at various economic sectors and scales but commonly at the country level, such as [6, 7, 9]. There have been the attempts to develop and construct MAC curves for global [4], cities [13], and building sector [1], [3], [11]. A previous study by [7] described the details of existing MAC curves from both theoretical and application aspects. A study by [1] showed that there are two approaches to calculating MAC curves in the context of building sector level, including static and dynamic MAC curves.

MAC is calculated by the differences between cost in a baseline case and mitigation case divided by the differences between GHG emissions. The MAC equation can be expressed in (1). The calculations of MAC for each ERM (i) are summarized in (1–4).

$$MAC_i = \frac{(C_{i,ERM} - C_{i,Baseline})}{(EM_{i,Baseline} - EM_{i,ERM})} \tag{1}$$

where: MAC_i is marginal abatement cost of each ERM (US$/tCO$_2$e), C refers to total discounted costs, EM represents total GHG emissions (tCO$_2$e), and baseline and ERM refer to baseline scenario and mitigation scenario. Then, C and EM can be calculated as follows:

$$C_i = \sum_{t=0}^{T} \frac{IC_i, t}{(1+r)^t} + \frac{MC_i, t}{(1+r)^t} + \frac{FC_i, t}{(1+r)^t} \tag{2}$$

$$EM_i = \sum_{t=0}^{T} \frac{AE_i, t}{(1+r)^t} \tag{3}$$

where: IC is annualized investment cost, MC is annual maintenance cost, FC is annual fuel cost, and AE is annual GHG emissions. t refers to time in years and r is discount rate. It should be noted that T refers to a period of lifetime of ERM (in years), for example, T=25 for solar PV rooftops. The annualized investment cost (IC) is calculated by (4).

$$IC_{i,t} = INV \cdot r \cdot \frac{(1+r)^n}{(1+r)^n - 1} \tag{4}$$

where: INV is the investment cost of ERM (e.g., high energy efficient appliance, building envelope retrofit, solar hot water, heat pump, etc.) and n is the economic lifetime of the ERM.

3. Methodological Framework

This section presents a proposed methodological framework and data collection. Fig. 1 illustrates the proposed methodology for planning energy and climate change mitigation for building clusters. The research approach consists of three main steps.

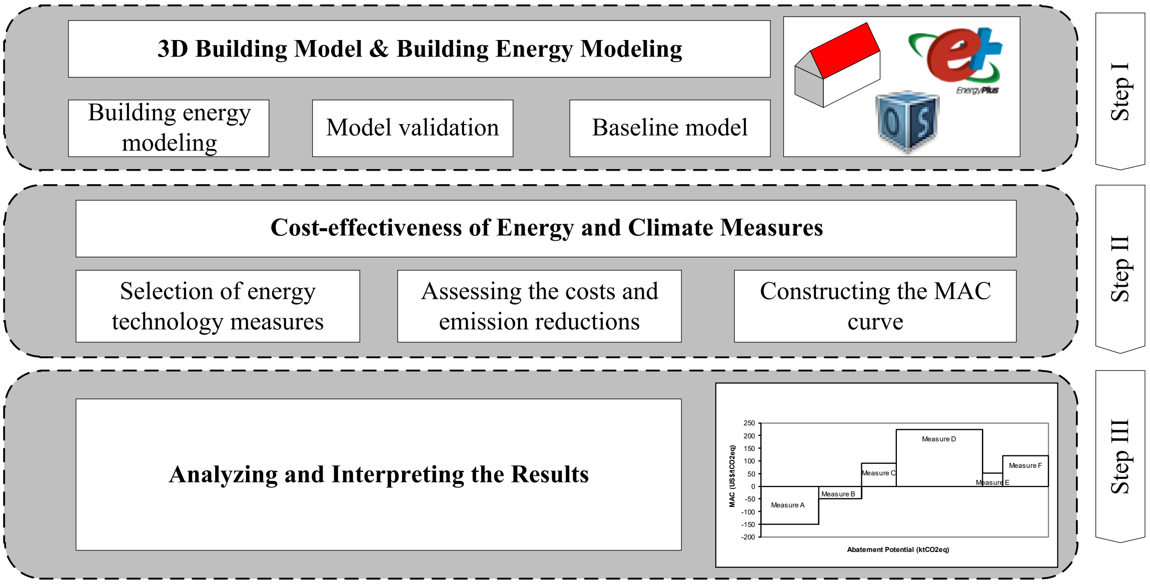

Figure 1. Methodological framework for evaluating cost-effective energy and climate measures.

3.1 Step I: Building Energy Modeling

The first step is the simulation of building energy using physics-based building energy modeling. The building performance simulation (BPS) enables to simulate the energy performance and indoor environmental quality (e.g., thermal comfort and indoor air quality) as well as integrated renewable energy systems with energy storage. BPS is a widely accepted technique to test, analyze, and optimize energy and climate strategies. The scope of this study is focused on energy performance of a building only. However, other building performance aspects, such as thermal comfort, can be extended in the BPS module with various simulation tools. The EnergyPlus through OpenStudio platform was used as a building energy model to simulate the energy use. EnergyPlus is a dynamic and whole-building energy simulation [14]. It is a widely accepted and well-recognized BPS tool that simulates hourly energy use profile of a building or a group of buildings [15]. Various studies describe detailed mathematic equations used in EnergyPlus such as [14], [16], [17]. Then, a building energy model is validated by comparing simulated results of a reference building with measured data. The relevant data used for BPS in this study are presented in a case study section.

3.2 Step II: MAC Curves

This step aims to construct a MAC curve based on a quantitative basis of different or selected ERMs. The building energy modeling in Step I provides main inputs for constructing a MAC curve of ERMs. MAC curves can be constructed with either a model-based approach or an expert-based approach [1], [3], [8], [9]. The model-based approach was applied to construct a MAC curve for a case study building. This approach derives the costs and energy-related GHG emission reduction potentials from building energy simulations or energy model runs [8]. The advantage of a model-based MAC curve is that the energy use and mitigation measures are assessed together by a simulation of energy flows in a reference building. Thus, it helps to avoid inconsistencies and allows interactions between different measures [7], [13]. To construct a MAC curve, first, a baseline was determined for energy use and GHG emissions. Second, a range of ERMs was identified. Then, calculating the MAC of each mitigation measure or ERM follows (1–4), as mentioned earlier. Third, the costs and mitigation potentials of each ERM were combined to form a MAC curve. An example of MAC curve and relevant data is presented in the case study section.

3.3 Step III: Analyzing and Interpreting Results

The interpretation of MAC curve is also an important step for understanding of results and leading to decision-making. A MAC curve is a useful technique for screening and ranking mitigation measures, according to their costs and abatement potentials from lowest to highest cost-effectiveness. Each measure is presented along the curve plot. The x-axis is the GHG emission mitigation potential and the width of each step represents the abatement potential of a measure. The y-axis is the MAC of a measure and the height of each step is the net present cost of a measure over its lifetime. The negative values on the y-axis reflect the cost savings, whereas positive values reflect the measures having costs that exceed their benefits. The cost savings are associated with energy savings, as well as GHG emission reductions [13]. Findings from Step III can be used to identify the measures to be implemented to achieve the energy and climate goals.

4. A Case Study

To provide an illustrative example, a case study building is located in Dhurakij Pundit University, Bangkok, Thailand. The building is a six-story building with a total floor area of about 10,808 m^2. It was built in 1992. The area consists of the air-conditioned (AC) area of 6,859 m^2 and the non-AC area of 3,949 m^2. Building envelope materials include masonry walls, precast panels, and glass walls. The roof material is 4-mm metal sheets. The window-to-wall ratio of the building is 0.234 (North), 0.234 (South), 0.211 (East), and 0.211 (West). The building includes classrooms and offices and operates approximately 13 hours per day. The measured electricity consumption was 775,500 kWh/year or 71.75 kWh/m^2 year in 2018 [17]. The study used the year 2018 as a base year for simulation due to the building was in full operation before the COVID-19 pandemic. Fig. 2 shows the 3D representation of a case study model used in Step I. Calculation of a MAC curve requires a wide range of data, including building energy performance, technology characteristics in baseline and mitigation scenarios, and economic characteristics. Data on building geometry, building envelopes, and technical issues of a case study building are taken from [17]. Data related to economics and cost inputs of ERMs are taken from the literature [3], [4], [11], [13].

Table 1. The investment required to deliver energy saving (US$:kWh)

Category	Cost to save energy (US$/kWh)
Heating ventilation and air conditioning (HVAC)	0.201
Lighting	0.028
Building energy management systems (BEMS)	0.043
Other initiatives, which were not commonly found across the commercial building retrofit projects	0.168
Total	**0.440**

(source: [3])

The validation showed that the simulated annual electricity consumption is 768,899 kWh, which is 0.85% different when compared with the measured data. The simulated results revealed some differences in April, September, and December because of assumptions related to occupancy schedules and spaces, usage schedules, and operating hours of major equipment. The measurement was recorded in terms of the total electricity consumption of a building. The measured data were not divided into different end-users. The simulated results were able to report the energy use by services, such as HVAC (Heating, Ventilation, and Air-conditioning) and lighting, which is helpful when simulating with proposed measures.

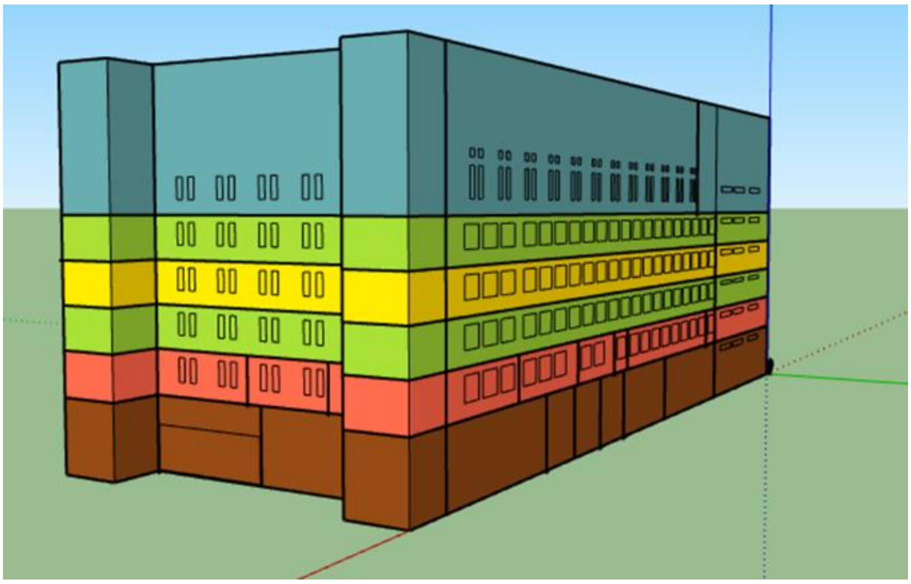

Figure 2. 3D simulation model of a case study building. Adapted from [17].

Since this work is an ongoing work and due to data available, a MAC curve was presented with limited measures. These measures were classified into four groups: ERM1(HVAC); ERM2 (Building envelope improvement); ERM3 (Lighting); and ERM4 (BEMS: Building energy management systems). It is well recognized that the improvement of HVAC systems is the most dominant ERM for buildings in Thailand. ERM2 included installation of wall insulation and replacement of glazing to Low-E with 6 mm thickness. ERM3 and ERM 4 were replacement of inefficient lightbulbs with high-efficiency lightbulbs and installation of BEMS. Results from energy modeling showed that ERM1 presents the highest energy savings, accounting for over 50% of total energy savings and followed by ERM2 (24.75%), ERM4 (11.96%), and ERM3 (10.15%), respectively. The modeling results were in line with the previous studies in [3], [11], [17], [18].

Also, findings showed that the baseline emissions are 310 tCO_2e and total emissions from implementing four ERMs are 250.64 tCO_2e.

A MAC curve was created based on modeling results and associated costs to determine the cost-effectiveness based on mitigation potential of individual ERM. The analysis was focused on assessing and comparing the selected energy retrofit measures in a case study building. Fig. 3 illustrates the MAC curve of a case study building. It shows the economic performance and abatement potential of each ERM. Results were ranked in ascending cost order. All ERM of a case study building provided negative value. Results were suggested that the cost savings overcome the investment required. These findings were agreed with other findings, as in [4].

According to Fig. 3, ERM relating to HVAC systems provides the largest contribution to emission reductions. The improvement of lighting has the highest return on investment. ERM related to the control of building operations using BEMS showed a potential for cost-effectiveness close to HVAC systems. This is due to the modeling assumptions, even BEMS are not widely implemented in buildings in Thailand at the moment but there are growing interests in installing BEMS in various buildings to support smart building projects. BEMS are computer-based control systems that control and monitor the mechanical and electrical equipment in buildings such as ventilation, heating, lighting, power systems, and so on. BEMS connect the building services plant back to a central computer to enable control of on/off times, humidity, temperatures, and so on. [19, p. 15]. Typical ways to access BEMS are presented in Fig. 4. BEMS enable users to monitor energy consumption, identify waste, and highlight areas for improvement and benchmark consumption against other similar buildings or organizations.

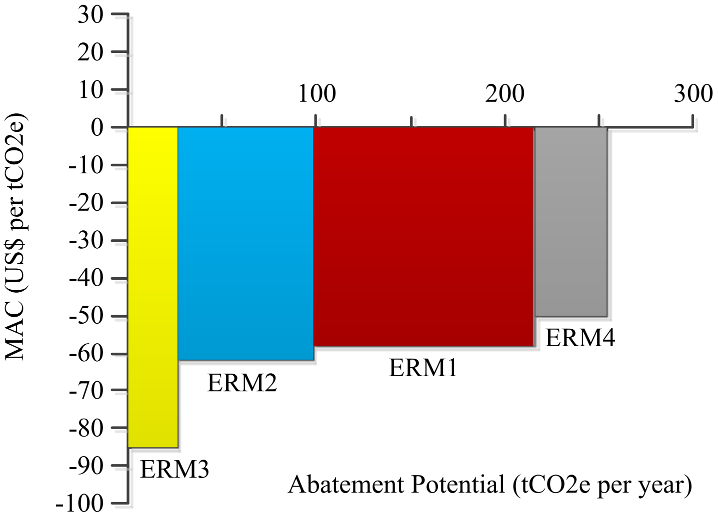

Figure 3. MAC curve for a case study building.

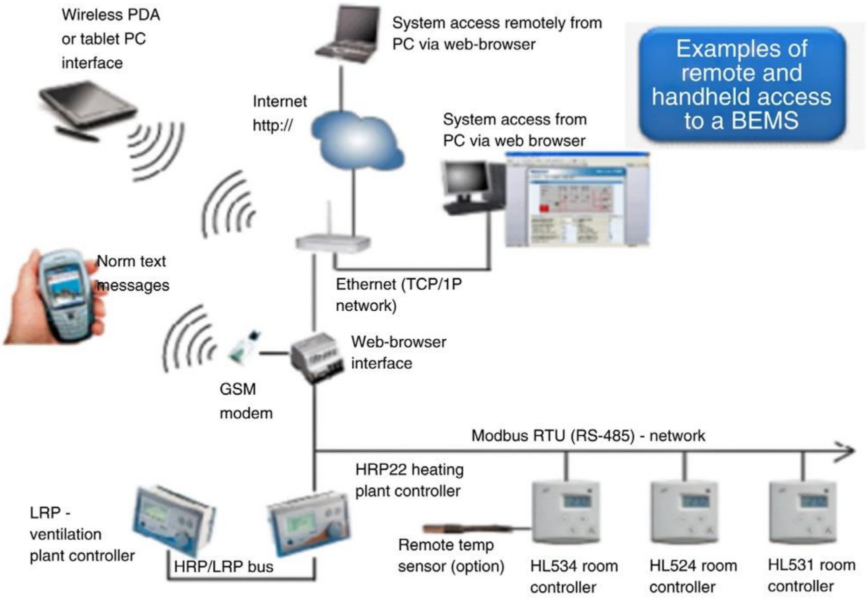

Figure 4. Typical BEMS user interfaces [19, p. 19].

5. Conclusions

Building sector represents significant energy use and GHG emissions. This research is an ongoing work. Thus, common ERMs were included in the analysis. Using a case study building, a building energy model and a MAC curve were developed to provide decision support into the relationship between the GHG emission abatement potentials and the cost of each ERM. Findings from a case study showed that all ERMs provide negative values. The negative MACs show not only positive financial feasibility and net economic savings from the investment but also reduced impacts on the environment. The proposed methodology integrated with BPS and MAC curve techniques can be applied to develop energy and climate planning for any building cluster and can extend to district and urban levels. However, the limitation of the proposed methodology is that it covers only the building sector. For district or urban areas including other sectors, such as industrial and transport sectors, additional tools will need to be integrated with the proposed methodology. It would also provide a framework for the interaction and achievement of SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

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References

[1] G. Timilsina, A. Sikharulidze, E. Karapoghosyan, S. Shatvoryan, Development of marginal abatement cost curves for the building sector in Armenia and Georgia, Energy Policy 108 (2017) 29 – 43.
[2] Y. Lou, Y. Ye, Y. Yang, W. Zuo, Long-term carbon emission reduction potential of building retrofits with dynamically changing electricity emission factors, Building and Environment 210 (2022) 108683.
[3] C. Seeley, S. Dhakal, Energy efficiency retrofits in commercial buildings: An environmental, financial, and technical analysis of case studies in Thailand, Energies 14(9) (2021) 2571.
[4] McKinsey, Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve. Technical Report, McKinsey & Company, 2009.

[5] F. Kesicki, Marginal abatement cost curves: Combining energy system modelling and decomposition analysis, Environmental Modeling & Assessment 18 (2013) 27 – 37.
[6] A. Vogt-Schilb, S. Hallegatte, C. Gouvello, Marginal abatement cost curves and the quality of emission reductions: a case study on Brazil, Climate Policy DOI: 10.1080/14693062.2014.953908 (2014) 703 – 723.
[7] A. Vogt-Schilb, S. Hallegatte, Marginal abatement cost curves and the optimal timing of mitigation measures, Energy Policy 66 (2014) 645 – 653.
[8] F. Levihn, C. Nuur, S. Laestadius, Marginal abatement cost curves and abatement strategies: Taking option interdependency and investments unrelated to climate change into account, Energy 76 (2014) 336 – 344.
[9] C. Sotiriou, A. Michopoulos, T. Zachariadis, On the cost-effectiveness of national economy-wide greenhouse gas emissions abatement measures, Energy Policy 128 (2019) 519 – 529.
[10] P. Muangjai, W. Wongsapai, R. Bunchuaidee, N. Tridech, D. Damrongsak, C. Ritkrekkrai, Marginal abatement cost of electricity generation from renewable energy in Thailand, Energy Reports 6 (2020) 767 – 773.
[11] K. Promjiraprawat, P. Winyuchakrit, B. Limmeechokchai, T. Masui, T. Hanaoka, Y. Matsuoka, CO2 mitigation potential and marginal abatement costs in Thai residential and building sectors, Energy and Buildings 80 (2014) 631 – 639.
[12] A. Chaichaloempreecha, P. Chunark, B. Limmeechokchai, Assessment of Thailand's energy policy on CO2 emissions: Implication of national energy plans to achieve NDC target, International Energy Journal 19(2) (2019) 47 – 60.
[13] N. Ibrahim, C. Kennedy, A methodology for constructing marginal abatement cost curves for climate action in cities, Energies 9(4) (2016) 227.
[14] EnergyPlus, Engineering References, US Department of Energy, 2019.
[15] A. Al-janabi, M. Kavgic, A. Mohammadzadeh, A. Azzouz, Comparison of EnergyPlus and IES to model a complex university building using three scenarios: free-floating, ideal air load system, and detailed, Journal of Building Engineering 22 (2019) 262 – 280.
[16] N. Kampelis, G. I. Papayiannis, D. Kolokotsa, G. N. Galanis, D. Isidori, C. Cristalli, A. N. Yannacopoulos, An integrated energy simulation model for buildings, Energies 13 (2020) 1170.
[17] P. Rittidatch, A. Phdungsilp, S. Vorarat, Evaluation of energy renovation measures of the building envelope in educational building using building energy modeling: a case study in Dhurakij Pundit University, Pathumwan Academic Journal, 11(31) (2021) 128 – 142.
[18] V. Yungchareon, B. Limmeechokchai, Energy analysis of the commercial sector in Thailand: Potential savings of selected options in commercial building, The Joint International Conference on Sustainable Energy and Environment (SEE), 2004, pp. 496 – 501.
[19] Y. Sayed, H. A. Gabbar, Energy conservation in residential, commercial, and industrial facilities, Wiley-IEEE Press, New Jersey, 2018.