

Article

Achieving Financial Feasibility and Carbon Emission Reduction: Retrofit of a Bangkok Shopping Mall Using Calibrated Simulation

Kongkun Charoenvisal ¹, Atch Sreshthaputra ² and Sarin Pinich ^{2,*} ¹ Africus Company Limited, Bangkok 10330, Thailand; kongkun@afri cvs.com² Department of Architecture, Chulalongkorn University, Bangkok 10330, Thailand; atch.s@chula.ac.th

* Correspondence: sarin.pi@chula.ac.th

Abstract: This study investigated the building energy retrofit potential of a shopping mall in Bangkok, Thailand, using a combined building energy modeling and economic analysis approach to achieve a balance between carbon emission reduction and financial feasibility. The study adopted ASHRAE Guideline 14, a standard for energy modeling accuracy, using whole-building calibrated simulation to evaluate the energy, energy cost, and operational carbon emission reduction achievable through the proposed energy conservation measures. The calibrated model demonstrated high accuracy, achieving an NMBE of 1.10% and CVRMSE of 3.77% for energy consumption, and NMBE of 0.15% and CVRMSE of 5.44% for peak energy demand compared to the monthly data. The economic analysis employed indicators such as NS, AIRR, and DPB, along with MACC analysis, to assess the financial viability of the ECMs and examine the impact of carbon credit cost savings on the analysis results. This case study highlights the critical role of energy modeling and economic analysis in evaluating building retrofits. The findings demonstrate the potential for carbon emission reduction and financial benefits with the case study building achieving up to 12.5% energy cost savings and carbon emission reduction based on a prospective building lifespan of 40 years without compromising financial sustainability.



Citation: Charoenvisal, K.; Sreshthaputra, A.; Pinich, S. Achieving Financial Feasibility and Carbon Emission Reduction: Retrofit of a Bangkok Shopping Mall Using Calibrated Simulation. *Buildings* **2024**, *14*, 2512. <https://doi.org/10.3390/buildings14082512>

Academic Editors: Yu Huang, Siwei Lou and Yukai Zou

Received: 4 July 2024

Revised: 2 August 2024

Accepted: 4 August 2024

Published: 15 August 2024



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Keywords: building energy modeling; energy model calibration; building energy retrofit; feasibility study; economic analysis; carbon emission mitigation

1. Introduction

Greenhouse gases (GHGs) are the primary cause of global warming, which has numerous negative effects on ecosystems and human health. The growing problem of global warming, which is caused by energy use and carbon emissions from various industries, is becoming notably severe. Thailand is a developing country with significant vulnerability to global warming and climate change impacts. It ranks 9th in the ‘extreme risk’ category, signifying high vulnerability to future climate-related effects over the next three decades. Regarding emissions, Thailand’s energy sector stands out as the primary source, responsible for about 70% of the country’s total GHG emissions in 2018. Thailand has set ambitious targets, including reducing GHG emissions by 30% below the predicted business-as-usual (BAU) level of 555 MtCO₂e by 2030, achieving carbon neutrality by 2050, and accomplishing net-zero GHG emissions by 2065 [1]. For a developing country such as Thailand, the lack of support from financial institutions for investments in energy efficiency and renewable energy is one of the primary challenges in reducing GHG emissions from the standpoint of energy use. Such energy efficiency and renewable energy investments entail high capital and operating costs, particularly technology and infrastructure expenses [1].

The building and construction industry currently uses 37% of all energy systems globally, which directly affects GHG emissions [2]. Based on 2023 data, Thailand’s commercial building sector consumed about 57,726 GWh, which accounts for 25% of the nation’s total

electricity consumption, with an annual growth rate of 7.4% [3]. As one of the largest electricity consumers in the commercial building sector, shopping centers consumed about 4706 GWh or 8% of the sector's energy consumption, followed by hotels and offices, which consumed about 4170 GWh (7%) and 2798 GWh (5%) [3]. In 2023, there were 7.6 million square meters of retail space in the Bangkok Metropolitan Region (BMR) and the surrounding area, whereby less than 10% of the retail space was brand-new establishments [4]. According to these recent reports, the existing shopping malls tend to be the top energy consumers and GHG emissions contributors in the commercial sector, underscoring the urgent need for building energy retrofits.

Seeley and Dhakal (2021) [5] found that while verifying the financial viability of investments in such retrofit procedures, retrofits offer the substantial potential to decrease energy consumption, energy costs, and greenhouse gas emissions. Even with the offered benefits, the stakeholders in the commercial building sector still have not been widely interested in building energy retrofits. One possible explanation for this could be the government's and financial institutions' insufficient assistance [1] with an emphasis on the necessity of public policy and leadership to promote growth in the building retrofit sector [5]. Additionally, financial barriers such as high upfront costs, regulatory challenges including complex approval processes, and informational barriers like lack of awareness and expertise among stakeholders contribute to their hesitation [1,5].

For decades, the research community has shown increasing interest in utilizing building energy model/modeling (BEM) to support the implementation of energy retrofits in buildings (for example, Augenbroe 2002 [6] and Yuan et al. 2017a [7]). Utilizing BEM for building energy retrofits commonly entails creating a calibrated reference model to represent the energy consumption of the existing building pre-retrofit, alongside proposed models illustrating the building's energy performance post-implementation of energy conservation measures (ECMs) aimed at enhancing energy efficiency. One of the challenges in applying BEM to retrofits is creating a precise, calibrated reference model. Various methods and techniques for model calibration, such as detailed audit, sensitivity analysis, and expert knowledge, have been described by ASHRAE (2023) [8] and have been examined and verified in previous research [9–12]. These studies have shown that accurate model calibration can significantly enhance the reliability of the predicted energy savings and inform cost-effective retrofit decisions. However, the research community is still looking for repeatable techniques for model calibration [7,13–19]. The selection of a method for a retrofit project is based on the knowledge and expertise of the modelers and the resources available to them. Based on previous research, the statistical measures recommended by ASHRAE Standard 14-2014 have been widely used to determine the accuracy of the calibrated model. ASHRAE Guideline 14-2014 (2014) provides statistical measures for model calibration, comprising mean bias error (MBE) and the coefficient of variation of the root-mean-square error (CVRMSE). The MBE calculates the degree to which the monthly or annual metered data matches the energy consumption projected by the model. A measure of variability or the amount of dispersion in the data is commonly used to describe the root-mean-square error (RMSE). By dividing the RMSE by the measured means of the data, we can determine the CV(RMSE) (%) [8,20]. This study builds on these previous works by applying established calibration techniques to a large, operational commercial building undergoing a retrofit. This real-world application further validates the effectiveness of these methods in practical settings and highlights areas for future research.

Energy models have been developed as a critical tool for precisely reflecting and forecasting building energy consumption [21]. A building energy model (BEM), according to ASHRAE Standard 209, is a computer representation that offers details on the systems that influence the building's energy usage [22]. Using BEM software, a building project team can simulate the energy use and demand in the stated building for a given time interval from the predesign to post-occupancy phases of the project. Comparing the energy model from the construction phase to the actual measured energy use and climate of the building when it is in use is known as the post-occupancy energy performance comparison [22].

Although ASHRAE Standard 209-2018 does not aim to offer guidelines for modifying model inputs to the measured energy uses, it offers a basic approach to any proposed calibration [22]. For example, the modeling process will occur at least twelve months after the building is first occupied, and metrics, including NMBE and CVRMSE, will be used to calculate the discrepancies between simulated data sets and measurements.

To support building retrofits, researchers have extensively employed various building energy simulation programs like DOE-2, EnergyPlus, and TRNSYS [7,19], which play a crucial role in assessing the potential impact of retrofit measures on energy performance and guiding decision-making processes aimed at improving building efficiency. Among these tools, EnergyPlus has been one of the most useful energy simulation engines [11]. The weather and occupancy are two independent input variables that are essential to the calibrated outcomes [20]. Once the calibrated reference model is developed, the retrofit project team can use it to create proposed models showcasing the building's post-energy improvement state. By comparing energy consumption results, the team can ascertain the energy savings obtained from various improvement options. These estimated energy savings data are vital not only for evaluating operational CO₂ emissions reduction, but also for assessing the economic feasibility of the proposed retrofit measures.

In particular, since there is limited external support for building efficiency [1], one of the most crucial considerations when making decisions about building retrofits for commercial buildings has become economic feasibility [5]. In addition to reducing CO₂ emissions, these retrofits may result in beneficial economic returns on investments due to lower energy and operating expenses. Energy-efficient solutions typically have higher initial capital costs than conventional ones for both new constructions and retrofit projects. As a result, economic methods that do not take into account long-term operating costs, like energy costs, may reject energy-efficient solutions and accept those with higher operational costs. Unlike other approaches that solely consider initial expenses or short-term operational costs, NIST Handbook 135 offers the life cycle cost analysis (LCCA) approach, published by the US Federal Energy Management Program (FEMP), for the evaluation of a project's long-term cost efficiency [23]. The handbook also provides a set of supplemental economic measures that can assess the long-term cost effectiveness including net savings (NS), savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), and discounted payback (DPB).

Due to the climate change crisis, there has been an increase in the adoption of numerous national and international policies aimed at mitigating climate change, alongside mandates promoting low-carbon practices and standards for products [24]. In light of the public attention to carbon emission-related issues, businesses—particularly those in carbon-intensive industries—are under greater pressure [25,26]. Any organization can measure the GHG emissions resulting from its main activities over a specified period, which are often expressed in tonnes of carbon dioxide equivalent (tCO₂e) [27]. One tonne of carbon dioxide or an equivalent quantity of other greenhouse gases that can be released into the atmosphere is equivalent to one carbon credit [28]. Determining the organization's carbon footprint is considered as a crucial first step toward developing a carbon strategy [29]. Reducing operating CO₂ emissions would require fewer CO₂ credits to be purchased by building owners who have been purchasing them to offset corporate CO₂ emissions [28]. Taking into consideration the cost savings from a decrease in CO₂ emissions, energy-efficient solutions could be financially viable for this particular group of building owners. The financial cost and abatement benefit of particular measures are measured and compared using a marginal abatement cost curve (MACCs, or MAC curves) [30,31]. An MACC shows the possible amount of emissions that could be decreased if a measure is implemented, along with the costs or savings anticipated from various possibilities. MACCs are beneficial for convincing the target audience, like stakeholders, who would not typically debate the financial and technological challenges of mitigating climate change [32]. Opportunities to lower emissions with a net economic gain are correlated with negative abatement costs; in addition, options to minimize emissions at a low cost are indicated by

the lowest abatement costs [33]. Ecosystems and human well-being suffer as a result of the intensifying global warming driven by carbon emissions. Consequently, this exerts a great deal of pressure on the real estate sector to make improvements to their existing buildings in order to minimize their energy usage and carbon emissions. This occurrence contributes to the development of reliable and efficient methods for financial viability utilizing financial metrics and BEM, which will be discussed in this paper.

A case study of utilizing BEM in a building energy retrofit project is presented in this paper. The building type in the commercial building sector with the largest energy consumption and demand is the shopping mall, which served as the case study building. This research utilized established techniques for energy model calibration. The expert knowledge method, complemented by sensitivity analysis for certain parameters, offers a comprehensive approach to addressing complex model calibration in this study. The authors were able to develop a calibrated model in which the NMBE and CVRMSE fell within the acceptable ranges given by ASHRAE Guideline 14. This study used the calibrated model to develop proposed models that represent individual and combined ECMs. The comparisons between reference and proposed model energy consumption indicated energy savings that can be converted to operational CO₂ emissions. This project used energy cost and CO₂ purchased credit savings for evaluating the economic feasibility of the proposed energy improvement options. MAC curves provide crucial decision support information for building owners and stakeholders. The authors believe that presenting a holistic view of using BEM to help a retrofit project achieve financial and CO₂ emission reduction will promote the growth of retrofit projects in Thailand, which could contribute to the country's GHG emissions reduction goals.

2. Materials and Methods

2.1. Case Study Building

The case study building is an existing community shopping mall located in Bangkok. Constructed in 2016–2018, the mall has been operational since 2018. The building comprises ten above-ground floors and one basement floor, with a total floor area of 95,000 sq. m and a gross floor area (GFA) of 60,200 sq. m. The building facilities include retail shops, a supermarket, food and beverage outlets, entertainment and recreational facilities, offices, and parking spaces. The building was built with a reinforced concrete structure. The facade system consists predominantly of aerated-panel base walls and laminated tinted glass curtain walls. The building has two types of roofs: insulated metal sheets and reinforced concrete. The non-leased areas utilize LED light fixtures. The air-conditioning and mechanical ventilation (ACMV) systems employ constant air volume (CAV) air handling units (AHUs) and fan coil units (FCUs). The waterside system consists of water-cooled centrifugal water chillers, variable-speed chilled water pumps, constant-speed condenser water pumps, and crossflow cooling towers with constant-speed axial fans. The shopping mall operates from 10:00 to 22:00 daily. Figure 1 below presents a simplified building configuration of the case study shopping mall.

2.2. Building Energy Modeling

According to ASHRAE Guideline 14, using building energy model/modeling (BEM) for a retrofit project involves developing a calibrated energy baseline (reference model) and proposed retrofit models (proposed models) [20]. The reference model represents the energy performance of the actual building. The proposed models represent the energy improvements after implementing energy conservation measures (ECMs). OpenStudio with EnergyPlus 9.3.0 software was used for the modeling and simulation of both the reference and proposed models. The calibrated reference model is crucial for ensuring the accuracy of the simulation results when assessing the impact of various ECMs. The following sections describe the materials and methods used to create and calibrate the reference model and develop proposed models.

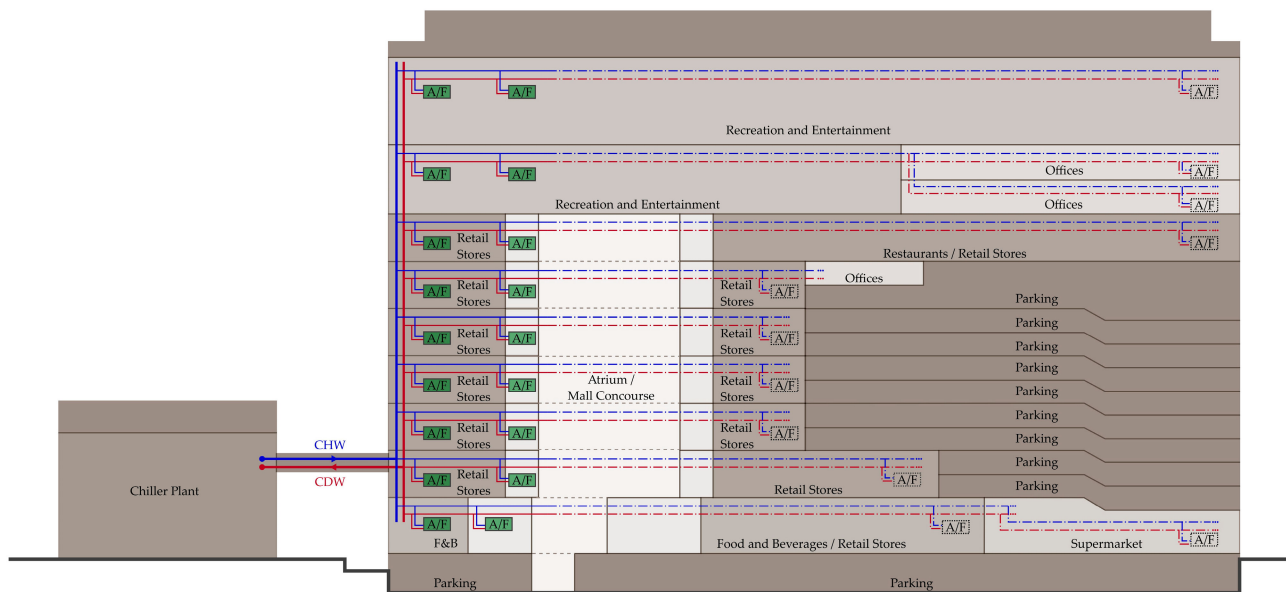


Figure 1. Simplified building configuration of the case study shopping mall.

2.2.1. Reference Model

The development of the reference model involved collecting essential building data for building energy modeling and model calibration. The building data included information about the building's space uses (e.g., number of occupants, activity levels, and space types), internal electric loads (e.g., light fixtures and electric appliances), air-conditioning and mechanical ventilation systems (e.g., system types and ventilation strategies), and operational schedules. The calibration data included information about the building's energy use and demand profiles (e.g., monthly utility bills and sub-metering data) and utility tariffs. For the case study building, the building data were obtained from as-built drawings, building system specification books, building product technical documents, utility bills, metering records, and on-site surveys. Table 1 summarizes the essential information collected for reference model development in this study. Table 2 provides an example of monthly utility data.

Table 1. Case study building information for building energy model.

Building Information	Description	Source
Orientation	175° from North	As-built drawings
Roofs	U-0.95 W/m ² K	As-built drawings, on-site surveys, specifications books, cut sheets
Walls	U-1.38 W/m ² K	
Fenestrations	U-5.02 W/m ² W/m ² K	
	SHGC-0.80	
	VT-0.84	
	WWR-0.40	
Occupancy	0.13 people/m ²	On-site surveys
Interior lighting	LPD-10.32 W/m ²	As-built drawings, on-site surveys, specifications books, cut sheets
Interior process and equipment	EPD-16.82 W/m ²	As-built drawings, on-site surveys, specifications books, cut sheets

Table 1. Cont.

Building Information	Description	Source
ACMV equipment	CAV AHUs, 0.92 kW/m ³ s; FCUs, 0.45 kW/m ³ s, Four centrifugal chillers, COP-5.86; One screw chiller, COP-5.82; Five variable-speed CHWPs, 348 kW/m ³ s;	As-built drawings, on-site surveys, specifications books, cut sheets
Chilled water plant	Five constant-speed CDWPs, 349 kW/m ³ s; Fine crossflow cooling towers with constant-speed fans, 0.38 kW/m ³ s	
Measurement and verification (M&V)/Benchmarking	Monthly electricity consumption, Monthly energy demand, Electricity tariff rates	Utility bills
	Daily chiller plant energy consumption, Chiller capacities recorded every two hours from 10:00 to 22:00	Metering records

Table 2. An example of monthly utility data from 2019 utility bills.

Month	Electricity Consumption (kWh)	Peak Electricity Demand kW
January	1,373,000	3736
February	1,312,000	3596
March	1,473,000	3696
April	1,520,000	4123
May	1,543,000	3852
June	1,418,000	3732
July	1,411,000	3572
August	1,401,000	3552
September	1,362,000	3578
October	1,452,000	3608
November	1,261,000	3166
December	1,213,000	3170

In addition to the information in Table 1, creating a calibrated reference model involves identifying key independent variables that significantly impact building energy use. These variables primarily include weather and occupancy data. The authors used Bangkok's actual meteorological year (AMY) weather data for this study. We carefully chose the 2019 meteorological year because it represented a pre-COVID-19 pandemic year with regular occupancy. For this building, we can also derive an accurate occupancy schedule using data from the building's people-counting sensors installed at the entrances.

Some data can be challenging to obtain, such as lighting and receptacle equipment loads that were not submetered. To overcome this constraint, the authors applied recommended inputs from relevant sources, including but not limited to, the Thailand Building Energy Code (BEC) [34], ASHRAE Standard 90.1 User's Manual [35], and COMNET [36]. This approach ensured consistency with established standards and practices for a similar building type.

Calibrating the energy model is an iterative process that involves creating an initial energy model, comparing the simulation results with the building's actual energy data, and refining the model until the simulations closely match the measured data. The authors initially developed a reference model following the methodology outlined in ASHRAE

Standard 209 [22]. This standard emphasizes the use of project-specific data whenever possible, minimizing reliance on assumptions and default values provided by the simulation software. We then used a combined approach for model calibration. This approach applied the expert knowledge method described in Chapter 19 of the ASHRAE Handbook Fundamentals (2023) [8], which utilizes expert knowledge or judgement in the calibration process [8]. We used our expertise in building physics, energy modeling, and system operation to make informed adjustments to the model parameters until the simulation results matched with measured data. To complement the expert knowledge method, we also employed sensitivity analysis to assess how changes in input parameters affect the model's energy predictions. This analysis was crucial for identifying factors impacting model accuracy and focusing our calibration efforts [8]. The process involved systematically varying one input parameter at a time and observing its effect on the model's output, allowing us to pinpoint the influential parameters. We interpreted the simulation results, examined discrepancies between simulated and actual energy use, and systematically changed one input at a time. Our criteria for identifying potential discrepancies included project-specific information, which was unavailable and substituted by general assumptions obtained from relevant sources and software defaults, as possible causes of inaccuracies. The key parameters examined included lighting and receptacle equipment loads that were not submetered, infiltration rates, and airflow rates. Following this structured approach ensured comprehensive and accurate model calibration, leading to high confidence in the simulation results.

As outlined above, calibrating the reference model to match simulation results and the actual consumption data is a crucial step in the modeling process. This ensures that the simulation model accurately reflects the actual performance and can be used further for reliable evaluation of ECMs. Following the recommendations in ASHRAE Guideline 14, we employed three statistical indicators to assess the agreement between the simulated and measured data.

- Normalized mean bias error (NMBE) is a statistical indicator used to assess a model's tendency to under-predict or over-predict actual consumption data during the evaluation period. A positive NMBE indicates underestimation, whereas a negative NMBE signifies overestimation. The NMBE is expressed as a percentage (%) and is calculated as shown in Equation (1).

$$\text{NMBE} = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{(n - p) \times \bar{y}} \times 100\% \quad (1)$$

- Coefficient of variance of the root mean square error (CVRMSE) is a statistical indicator used to assess the relative magnitude of the errors between simulated and measured monthly energy consumption data. A lower CVRMSE value indicates better agreement between the model and the building's actual performance. CVRMSE is expressed as a percentage (%) and is calculated as shown in Equation (2).

$$\text{CVRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{(n - p)}}}{\bar{y}} \times 100\% \quad (2)$$

where

- y = measured energy use for each month;
- $\hat{y}$ = simulated energy use for each month;
- $\bar{y}$ = arithmetic mean of the measured data;
- i = interval that the measured and simulated data are aligned to;
- n = number of intervals (greater than 1) included in the analysis;
- p = 1.

According to ASHRAE Guideline 14, a calibrated model should produce an NMBE within a range of $\pm 5\%$ and a CVRMSE no greater than 15% when using monthly data.

When using hourly data, the NMBE should be within a range of $\pm 10\%$, and CVRMSE should not exceed 30%. The available data for this study included twelve months of utility bills, as well as monthly and daily chilled water plant energy consumption data for 2019. Additionally, there was a month of chiller cooling capacity data recorded every two hours between 10:00 and 22:00 in April 2023, which is also available for model calibration.

2.2.2. Proposed Model

In this study, the authors developed proposed models to assess the potential energy savings and cost-effectiveness of various energy conservation measures (ECMs). These models replicate the building after implementing the ECMs, allowing for a direct comparison with the baseline reference model.

To formulate the ECMs, we analyzed the existing measured and simulated data to identify potential areas for energy improvements. Four energy improvement strategies are provided in Table 3. The first strategy involves applying heat protection films on laminated tinted glass windows to reduce solar heat gains. The second and third strategies focus on adding variable speed drive (VSD) controls to air handling units (AHUs) and to condenser water pumps (CDWPs) and cooling tower (CT) fans to reduce motor energy consumption. The last strategy involves adjusting chilled and condenser water temperature setpoints to improve the overall efficiency of the chiller plant. We then used these strategies to develop ECMs, as presented in Table 4.

Table 3. Energy improvement strategies.

Energy Improvement	Reference Model	Proposed Model	Quantity	Life Expectancy
Heat protection films	U-5.03 W/sq. m·k SHGC-0.76 VLT-0.87	U-4.91 W/sq. m·k SHGC-0.56 VLT-0.75	6306 sq. m	8 years or more
VSD controls on AHUs	Constant speed	Variable speed	30 sets	10 years or more
VSD controls on CDWPs and CTs	Constant speed	Variable speed	20 sets	10 years or more
Water-side system temperature setpoints	Chilled water: 6.67 °C leaving temperature 13.33 °C entering temperature 6.66 °C delta-T Condenser water: 35/28 °C Tdb/Twb 3.7 °C approach 37.8 °C entering temperature 32.2 °C leaving temperature 5.6 °C range	Chilled water: 8 °C leaving temperature 14 °C entering temperature 6 °C delta-T Condenser water: 35/28 °C Tdb/Twb 2.5 °C approach 37.7 °C entering temperature 30.5 °C leaving temperature 7.2 °C range	N/A	N/A

Developing the proposed models representing the ECMs in Table 4 required obtaining energy-related and cost information on the energy improvement strategies. For this study, the authors directly received cost information from product and equipment suppliers and manufacturers. With the data compiled in Tables 3 and 4, we then created a series of proposed models. By comparing the reference model with the proposed model simulation results, we can evaluate the energy performance, environmental impact, and economic feasibility of each ECM.

Table 4. Energy conservation measures (ECMs).

Energy Conservation Measure (ECM)	Description	1st Year Investment Cost ^a
ECM01	Heat protection films	USD 146,218
ECM02	VSD controls on AHUs	USD 88,389
ECM03	VSD controls on CDWPs and CTs	USD 84,251
ECM04	Water-side system temperature setpoints	USD 0
ECM05	Water-side system temperature setpoints and heat protection films	USD 146,218
ECM06	Water-side system temperature setpoints and VSD controls on AHUs	USD 88,389
ECM07	Water-side system temperature setpoints and VSD controls on CDWPs and CTs	USD 84,251
ECM08	Water-side system temperature setpoints and VSD controls on AHUs and on CDWPs and CTs	USD 172,640
ECM09	Water-side system temperature setpoints, heat protection films, and VSD controls on AHUs and on CDWPs and CTs	USD 318,858

^a Cost includes the value-added tax (VAT) of 7% during the study period.

2.3. Economic Analysis

The inputs required for economic analysis included cost information (e.g., ECM investment costs and energy costs) and a set of economic variables (e.g., discount and energy escalation rates). As mentioned in the previous section, cost information can be derived from market prices and energy simulation for each ECM, but the economic analysis variables vary depending on the project's chosen analysis methods.

In this study, the authors evaluated the economic feasibility of the proposed ECMs using three economic measures adopted from NIST Handbook 135 [23]. These measures are as follows:

- Net savings (NS): This metric represents the net financial benefit of an ECM over its lifetime. It considers the present value of all cost savings generated by the ECM (e.g., reduced energy costs) minus the present value of all costs incurred (e.g., installation and maintenance costs). A positive NS value indicates a financially beneficial ECM. Equation (3) defines the NS calculation.

$$NS_{A:BC} = \sum_{t=0}^N \frac{S_t}{(1+d)^t} - \sum_{t=0}^N \frac{\Delta I_t}{(1+d)^t} \quad (3)$$

- Adjusted internal rate of return (AIRR): This measure reflects the discount rate at which the net present value of an ECM's cash flow is zero. A higher AIRR indicates a more financially attractive ECM compared to alternative investments with a lower AIRR. Equations (4) and (5) provide the calculations of the AIRR.

$$AIRR = (1-r) \times (SIR)^{\frac{1}{N}} - 1 \quad (4)$$

$$SIR_{A:BC} = \sum_{t=0}^N \frac{S_t}{(1+d)^t} / \sum_{t=0}^N \frac{\Delta I_t}{(1+d)^t} \quad (5)$$

- Discounted payback period (DPB): This metric represents the time it takes for the cumulative net cash flow from an ECM (i.e., cost savings minus costs) to equal the initial investment cost. A shorter DPB indicates a faster financial return on the investment. Equation (6) presents the formula for calculating the DPB.

$$\sum_{t=1}^y \frac{S_t - \Delta I_t}{(1+d)^t} \geq \Delta I_0 \quad (6)$$

where

- $NS_{A:BC}$ = NS, in PV dollars, of alternative (A), relative to base case (BC);
- SIR = saving-to-investment ratio;
- $SIR_{A:BC}$ = SIR of alternative (A) relative to base case (BC);
- ΔI_0 = initial investment costs associated with the alternative;
- ΔI_t = additional investment-related costs in year t associated with the alternative;
- S_t = savings in year t in operational costs associated with the alternative;
- r = reinvestment rate;
- d = discounted rate;
- N = number of years in study period;
- y = minimum length of time over which future net cash flows have to be accumulated in order to offset initial investment costs;
- t = year of occurrence (where 0 is the base date).

By evaluating these three economic measures for each ECM, we can assess its financial viability and prioritize options that deliver the most significant economic benefits.

To account for future cost fluctuations, the economic analysis incorporated energy price escalation rates, especially for electricity, as recommended by NIST Handbook 135 [23]. In Thailand, a 1% rate estimated around 2008 by the Department of Alternative Energy Development and Efficiency (DEDE) was used for electricity costs [37].

In addition to the economic measures for financial viability discussed above, this study employed marginal abatement cost curve (MACC) analysis, which offers valuable insights into the cost-effectiveness of CO₂ emission reductions induced by the ECMs [31,32]. The MACC analysis determines the CO₂ abatement cost (i.e., the cost per unit of CO₂ emissions reduced) using Equation (7). In this context, the ECMs themselves function as CO₂ mitigation measures since they reduce operational CO₂ through lower building energy use. By analyzing the CO₂ abatement cost, this study can identify ECMs that are not only financially attractive as indicated by the NS, AIRR, and DPB, but also deliver significant environmental benefits through CO₂ reduction.

$$\text{CO}_2 \text{ abatement cost} = \frac{(-1) \times NS_{A:BC} (\$, \text{USD})}{\text{Mitigated CO}_2 \text{ emissions over a study period (tonnes CO}_2)} \quad (7)$$

According to the methods outlined above, the economic analysis required several key variables: number of analysis years, discount rate, MIRR, escalation rate, and CO₂ emission factor.

- Number of analysis years: NIST Handbook 135 recommends a maximum lifespan of 40 years for buildings in economic analyses. Considering that the shopping mall has been operational for five years, the study adopted a 35-year analysis period.
- Discount rate and MIRR: A discount rate and MIRR of 7% were assumed. This value aligns with commercial lending rates in Thailand, reflecting the financial conditions relevant to the shopping mall project. It is also consistent with the rate used by Seeley and Dhakal (2021) in a similar study [5].
- Escalation rate: The electricity price escalation rate of 1% published by the DEDE was adopted. Since this rate has been in effect for over ten years, a sensitivity analysis was conducted using escalation rates of 2% and 3% to assess the impact of this variable on the analysis results.
- CO₂ emission factor: The CO₂ emission factor as of 2023 that was used in this study is 0.44 kgCO₂e per kilowatt-hour of electricity consumption, which was published by the Energy Policy and Planning Office (EPPO) [38].

In addition to the base case economic analysis, this study also examined the influence of CO₂ credit purchase on the economic feasibility of the ECMs. Driven by national carbon neutrality goals, leading real estate developers, like the owner of the case study building, are

increasingly integrating decarbonization into their environmental, social, and governance (ESG) programs. Carbon credit purchases can help developers offset their emissions and move closer to carbon neutrality. To assess this impact, we will incorporate the Thailand Greenhouse Gas Management Organization's (TGO) 2023 price of USD 2.15 per tonne CO₂ for the Thailand voluntary emission reduction (T-VER) program carbon credits. This price will be used without a future escalation rate, as recommended by Echenagucia et al. (2023) [39].

3. Results

3.1. Building Energy Modeling and Simulation Results

3.1.1. Reference Model Results

The twelve-month utility bills indicated that the case study building consumed approximately 16,739,000 kWh of electricity in 2019, which equates to 278 kWh/sq. m/year. This value is slightly lower than the national energy use index (EUI) of 295 kWh/sq. m/year [5]. The peak electricity consumption was 1,543,000 kWh in May, while the lowest was 1,213,000 kWh in December. On average, the mall consumed 1,394,917 kWh of electricity per month. The peak electricity demand was 4123 kW in April, while the lowest was 3166 kW in November.

The metering data for 2019 comprise the daily consumption for twelve months, categorized as shown in Figure 2. The tenants' electricity use accounted for 36% of the total building electricity consumption. The chiller plant's electricity consumption accounted for 34% of the total, while the owner's facilities (non-leased areas) represented 30%. The non-leased electricity consumption included lighting, receptacle, miscellaneous equipment, and the ACMV systems. Lighting, receptacle, and miscellaneous equipment accounted for 23% of the total, while ACMV systems accounted for 7%.

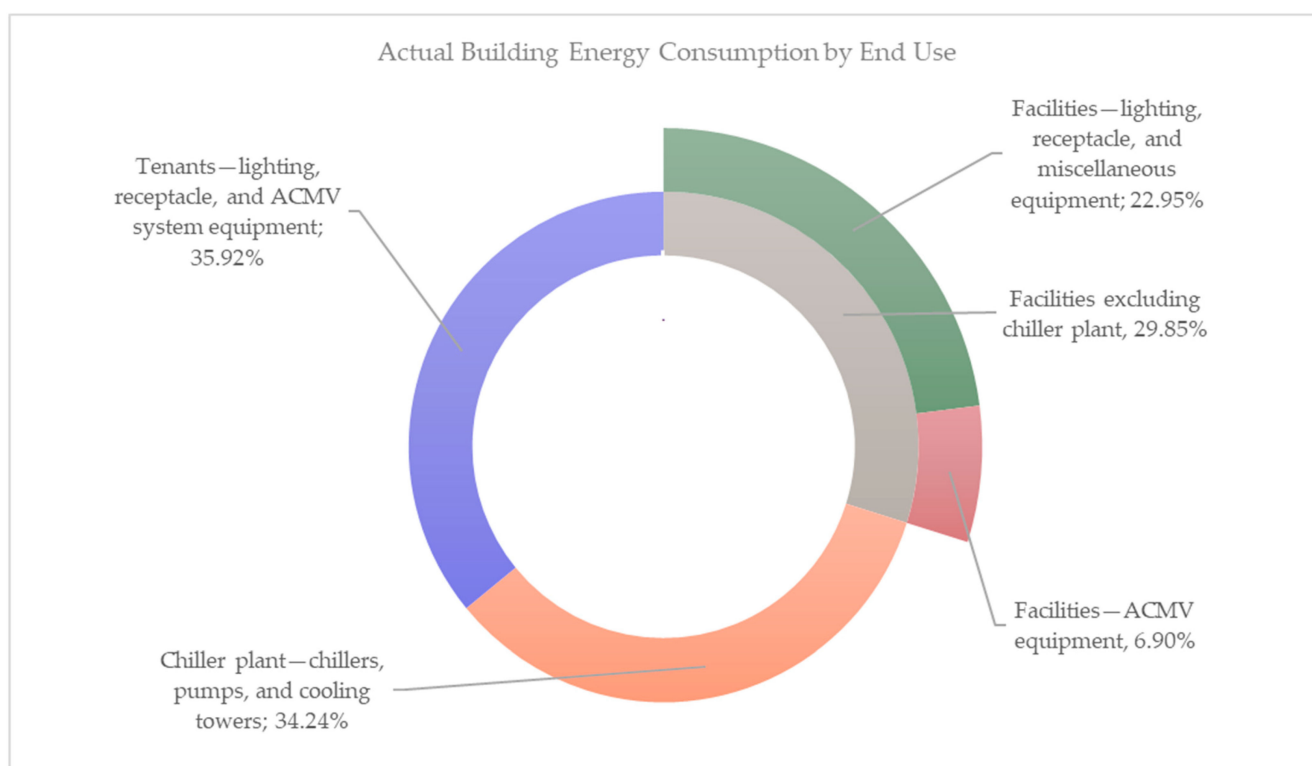


Figure 2. Actual building energy consumption by end use.

The authors used the materials and methods provided in the previous section of this paper to develop a reference model that can imitate the energy consumption and demand of the actual building. The calibration results for the reference model are presented in Table 5.

The simulated energy consumption of the reference model aligned well with the actual data, as indicated by the NMBE of 1.10% and CVRMSE of 3.77% (Figure 3). These values fall within the acceptable limits recommended by ASHRAE Guideline 14 for monthly data calibration (i.e., NMBE < 5% and CVRMSE < 10%). Similarly, the simulated peak electricity demand demonstrated good agreement with the measured data, with an NMBE of only 0.15% and CVRMSE of 5.44% (Figure 4).

Table 5. Reference model calibration results.

Energy Use Data	Acceptance Criteria	Calibration Result
Monthly electricity consumption, 2019	−5% < NMBE < 5% CVRMSE < 15%	1.10% 3.77%
Monthly electricity demand, 2019	−5% < NMBE < 5% CVRMSE < 15%	0.15% 5.44%
Monthly chiller plant electricity consumption, 2019	−5% < NMBE < 5% CVRMSE < 15%	3.69% 9.81%
Daily chiller plant energy consumption, 2019	N/A N/A	4.88% 13.00%
One month of chiller plant capacities recorded every two hours between 10:00 and 22:00, April 2023	N/A N/A	1.92% 25.05%

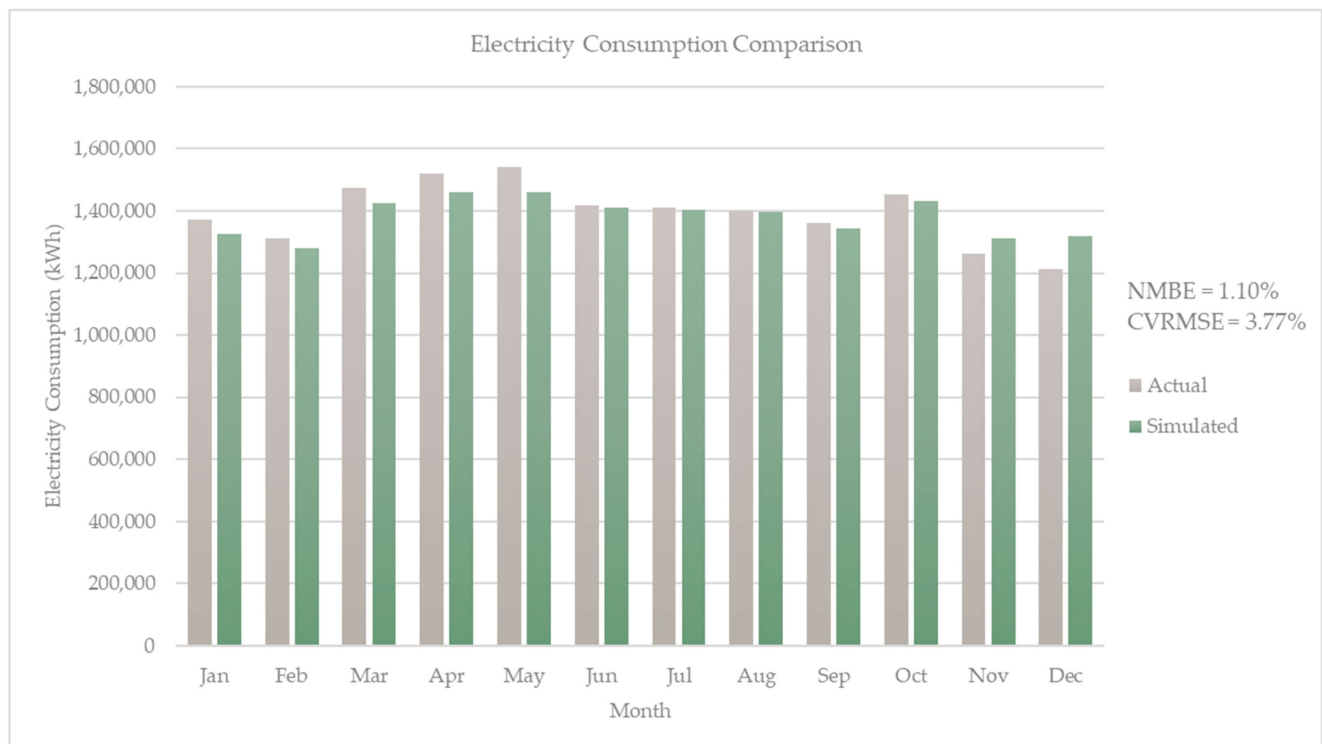


Figure 3. A comparison of actual and simulated monthly electricity consumption data with an NMBE of 0.15% and CVRMSE of 5.44%.

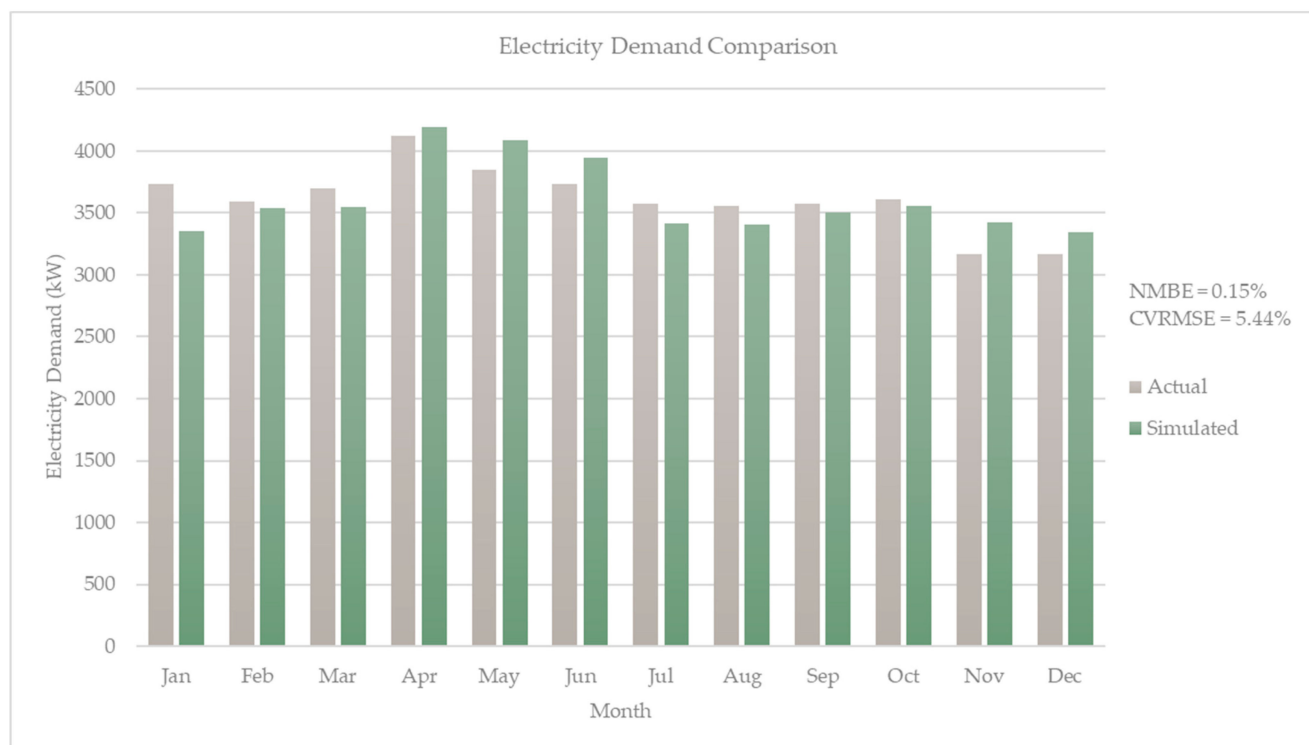


Figure 4. A comparison of actual and simulated monthly peak electricity demand data with an NMBE of 0.15% and CVRMSE of 5.44%.

The reference model achieved good calibration results with the monthly data and higher-resolution data sets, including daily and bi-hourly intervals, as presented in Table 5. While ASHRAE Standard 14 [20] does not provide specific NMBE and CVRMSE thresholds for these shorter time intervals, achieving good calibration across different data granularities demonstrates the robustness of the reference model.

The simulated energy consumption of the reference model was 16,570,497 kWh per year, which resulted in an EUI of 275 kWh/sq. m/year. This EUI is slightly lower than the actual building EUI of 278 kWh/sq. m/year. On average, the monthly electricity consumption of the reference model was estimated to be 1,380,875 kWh. Figure 5 summarizes the energy consumption by end use of the reference model. As observed in the figure, the chiller plant accounted for 33% of the total energy consumption, which is quite similar to the actual data, where the chiller plant represented 34% of the total consumption. Apart from the energy consumption, the peak energy demand predicted by the reference model was 4192 kW in April. These simulation outputs together with the model calibration results suggest that the reference model can accurately capture the building's energy behavior under various conditions.

3.1.2. Proposed Model Results

The simulation results from the reference model provided valuable insights into the building's energy consumption profile. Notably, the model revealed that air-conditioning systems, encompassing mechanical ventilation and chiller plant operations, account for 48% of the building's total energy consumption. Explicitly, mechanical ventilation accounted for 15%, while the chiller plant was responsible for 33% of the total consumption (Figure 5). Recognizing these end uses as significant contributors to the building's energy footprint, we formulated a series of ECMs explicitly targeting these areas for improvement. This section presents the results of the energy performance evaluation for the implemented ECMs. We will discuss the impact of ECMs on the building's energy consumption and overall energy savings achieved.

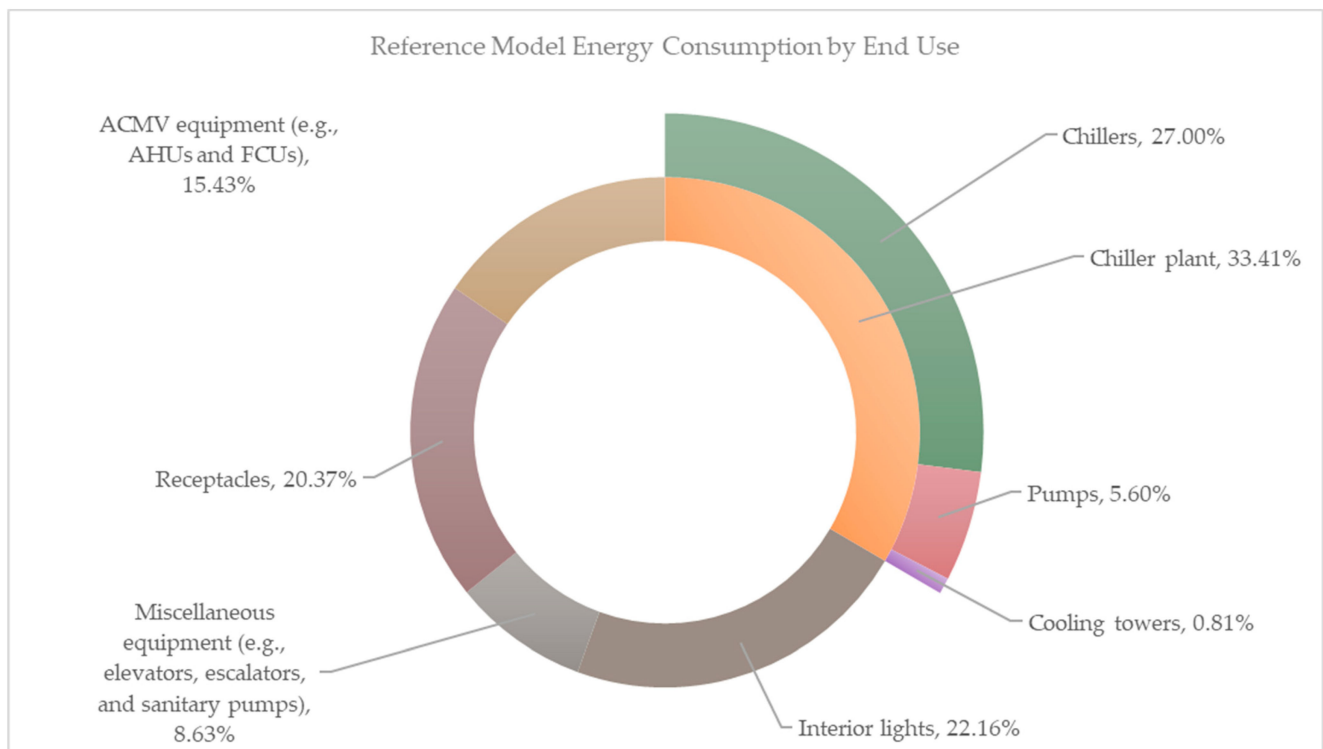


Figure 5. Reference model energy consumption by end use.

Table 6 provides a detailed breakdown of the energy performance of, and energy savings achieved by, the proposed ECMs. Before the implementation of the ECMs, the reference model consumed 16,570,497 kWh/year, with an EUI of 275 kWh/sq. m/year. The ECMs resulted in annual energy savings ranging from 157,128 kWh/year (achieved by ECM03) to an impressive 2,066,350 kWh/year (achieved by ECM09). This translates to an overall reduction in EUI between 0.95% (for ECM03) and 12.47% (for ECM09). Implementing a combination of building envelope, ACMV systems, and chilled water plant efficiency improvements (ECM09) resulted in the most significant energy savings and EUI reduction, as shown in Table 6. On the other hand, the addition of variable speed drive (VSD) controls on CHW pumps and cooling towers (ECM3) yielded the least improvement. The CO₂ reduction potential of the ECMs followed the same trend observed in energy savings. ECM09 has the greatest potential for reducing CO₂ emissions, with a 909 tCO₂/year reduction, while ECM3 provided the smallest reduction (79 tCO₂/year).

Table 6. Proposed model simulation results.

Energy Conservation Measure, ECM	Energy Consumption (kWh)	Energy Savings (kWh)	EUI (kWh/sq. m)	Operational CO ₂ Mitigation (tCO ₂)	Percent Savings
Reference model	16,570,497	-	275	-	-
ECM01—Heat protection films	16,391,389	179,108	272	79	1.08%
ECM02—VSD controls on AHUs	15,136,128	1,434,369	251	631	8.66%
ECM03—VSD controls on CDWPs and CTs	16,413,369	157,128	273	69	0.95%
ECM04—Water-side system temperature setpoints	16,166,894	403,603	269	178	2.44%
ECM05—Water-side system temperature setpoints and heat protection films	16,001,653	568,844	266	250	3.43%

Table 6. Cont.

Energy Conservation Measure, ECM	Energy Consumption (kWh)	Energy Savings (kWh)	EUI (kWh/sq. m)	Operational CO ₂ Mitigation (tCO ₂)	Percent Savings
ECM06—Water-side system temperature setpoints and VSD controls on AHUs	14,754,425	1,816,072	245	799	10.96%
ECM07—Water-side system temperature setpoints and VSD controls on CDWPs and CTs	16,041,989	528,508	266	233	3.19%
ECM08—Water-side system temperature setpoints and VSD controls on AHUs and on CDWPs and CTs	14,607,158	1,963,339	243	864	11.85%
ECM09—Water-side system temperature setpoints, heat protection films, and VSD controls on AHUs and on CDWPs and CTs	14,504,147	2,066,350	241	909	12.47%

ECM09 offered the maximum energy savings and CO₂ reduction, but its financial practicality depends on the returns on investment. Therefore, it is crucial to conduct a feasibility study alongside building energy modeling to determine the project's financial viability after retrofitting. In the next section, we will discuss the results of the economic feasibility analysis in further detail.

3.2. Economic Analysis Results

This section presents the economic feasibility study that was conducted to evaluate the proposed ECMs. The analysis assessed the profitability of implementing each ECM based on net savings (NS), annual internal rate of return (AIRR), and discounted payback (DPB). Additionally, a marginal abatement cost curve (MACC) analysis was performed to examine the CO₂ abatement benefits offered by the ECMs.

Figures 6–8 display the NS, AIRR, and DPB outcomes for each ECM, considering different calculation scenarios. The “Base Case” scenario represents the situation when the project did not pursue the procurement of carbon credits. On the other hand, the “CO₂ Credit Purchasing” scenario reflects the situation where the project purchased carbon credits to neutralize its CO₂ emissions. The calculations for each scenario considered 1%, 2%, and 3% electricity escalation rate assumptions.

Based on the positive NS results, Figure 6 demonstrates that most of the proposed ECMs are economically feasible for investment. Among all the ECMs, ECM08, which involves integrated improvements to the ACMV systems and chilled water plant, achieved the highest NS results in all calculation scenarios. Assuming escalation rates of 1%, 2%, and 3% ECM08 achieved around USD 3,015,900, USD 3,462,600, and USD 4,001,000 of net savings, respectively, under the base case scenario. With CO₂ credit purchasing, ECM08 achieved around USD 3,040,000, USD 3,486,700, and USD 4,025,000 of net savings, assuming escalation rates of 1%, 2%, and 3%, respectively. The results showed that savings from lowering the purchase of CO₂ credits did not significantly impact the NS, with a less than 1% increase. On the other hand, the results showed that the changing electricity escalation rates noticeably influenced the NS results. For instance, the NS of ECM08 increased by around 15% and 33% when 2% and 3% escalation rates were assumed compared to when a 1% escalation rate was assumed. Unlike ECM08, ECM01 was the only ECM with negative NS results when a 1% escalation rate was assumed. This is because the investment costs over the study period were greater than the energy cost savings offered by ECM01. However, ECM01 still achieved positive NS results when 2% and 3% rates were assumed.

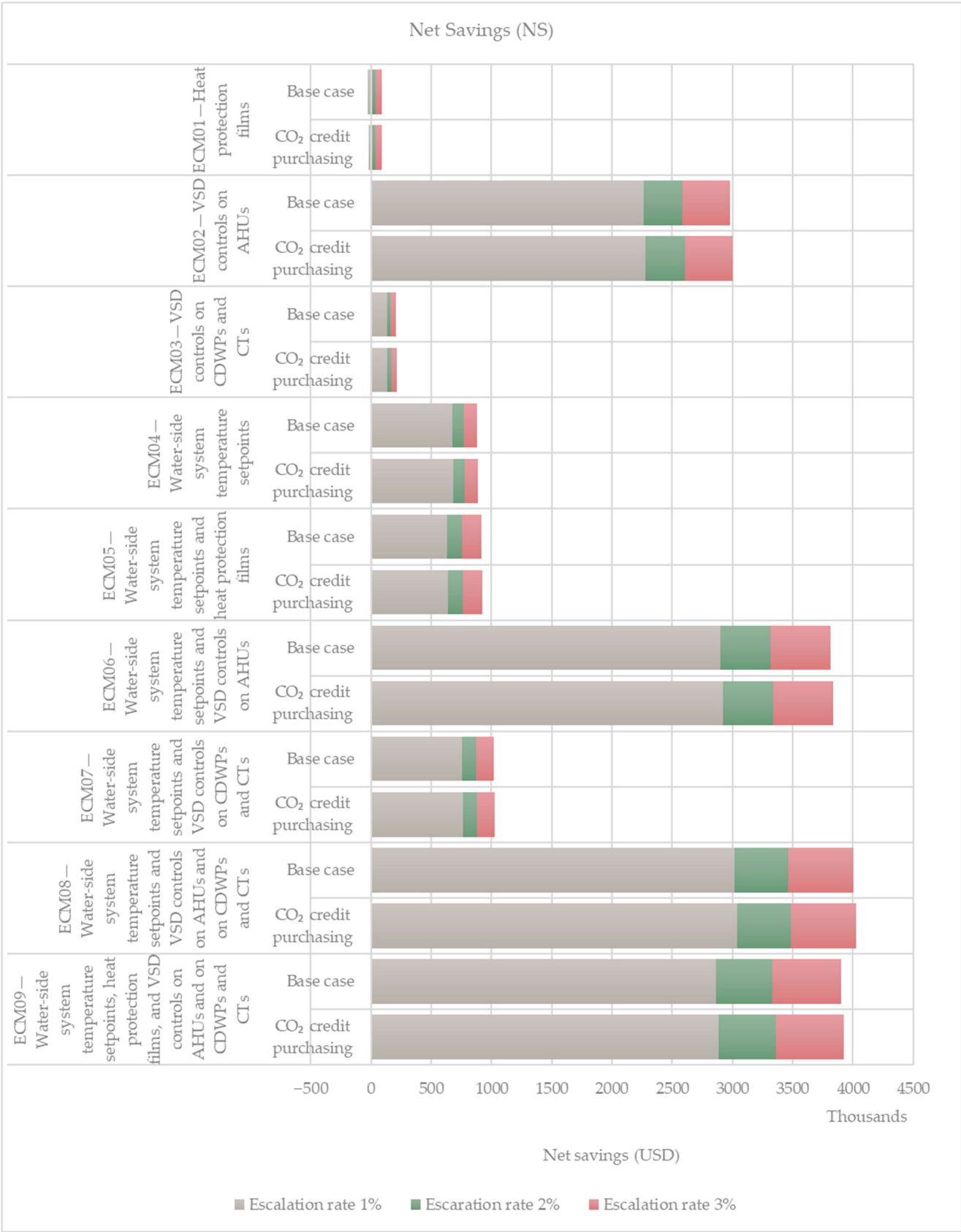


Figure 6. Net savings (NS) results.

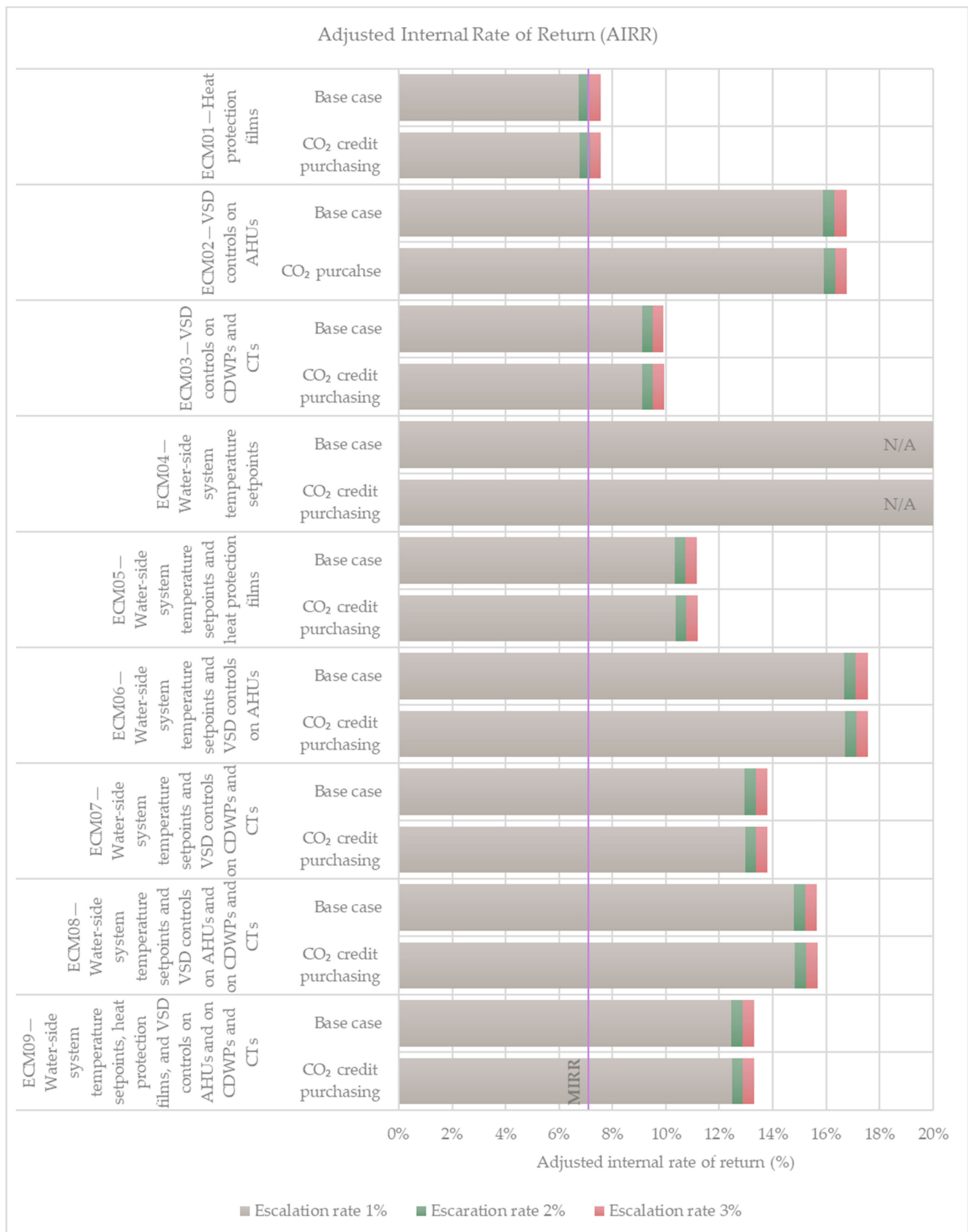


Figure 7. Adjusted internal rate of return (AIRR) results.

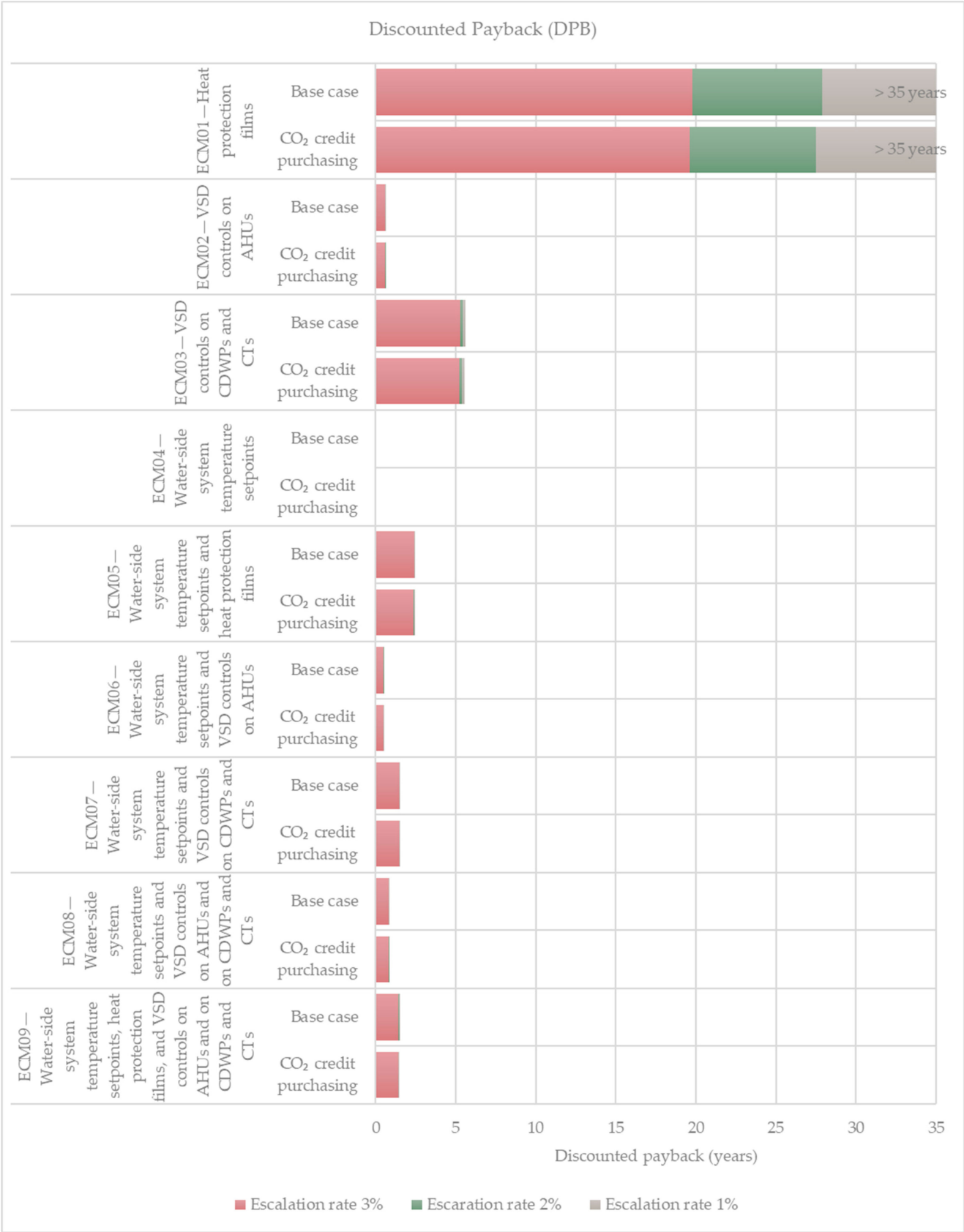


Figure 8. Discounted payback (DPB) results.

Figure 7 demonstrates that most of the proposed ECMs achieved AIRR results higher than the MIRR of 7%, which makes them acceptable for investment. However, for ECM04, the AIRR calculation could not be determined because the costs of adjusting the chilled and condenser water setpoints were significantly small. Excluding ECM04, among all the other ECMs, ECM06 provided the highest AIRR of 16.67%, 17.10%, and 17.55% when 1%, 2%, and 3% escalation rates were considered under the base case scenario. Regarding CO₂ credit purchasing, the AIRR results for ECM06 were 16.70%, 17.12%, and 17.57%, respectively. On the other hand, ECM01 achieved an AIRR of 6.75% under the base case scenario when a 1% escalation rate was assumed, which is lower than the MIRR and unacceptable for investment. However, ECM01 can still be considered for investment, as it produced acceptable AIRR results when 2% and 3% escalation were assumed. Interestingly, the AIRR results were visibly influenced by the escalation rates, while the carbon credit cost savings had an insignificant impact.

The DPB results for each ECM are demonstrated in Figure 8. ECM04 required zero to no costs, which means it tends to pay back as soon as it is implemented. On the other hand, ECM01 did not pay back within the analysis period of 35 years when a 1% escalation rate was assumed. However, it still paid back within 35 years when the escalation rate was 2% or 3%. All the proposed ECMs, except for ECM01, were paid back within five years. In contrast to the NS and AIRR results, Figure 8 shows that the CO₂ credit cost savings and escalation rates did not significantly impact the DPB results.

The assumed electricity price escalation rates significantly influenced the economic feasibility of the ECMs. As evident in Figures 6–8, higher escalation rates (2% and 3%) resulted in considerably increased profitability compared to a 1% escalation rate. This highlights the importance of considering future energy price trends when evaluating the economic viability of long-term projects. Interestingly, the cost of purchasing carbon credits had a minimal impact on the overall economic feasibility of the ECMs, as demonstrated by the negligible changes in NS, AIRR, and DPB across the different carbon credit scenarios (Figures 6–8).

In addition to the economic indicators, the authors used MACC analysis to examine the CO₂ abatement benefits the proposed ECMs could offer. The analysis results are displayed in Figures 9–11, corresponding to 1%, 2%, and 3% escalation rates, respectively. Each figure shows the analysis results under the base case and CO₂ credit purchasing scenarios. The analysis revealed that all ECMs, except for ECM01, had negative CO₂ abatement costs. ECM04 mitigated around 180 tonnes of CO₂ (tCO₂) annually and offered the lowest CO₂ abatement costs of USD 110 per tCO₂. Meanwhile, ECM09, ECM08, and ECM06 could potentially reduce CO₂ emissions by 909, 864, and 799 tCO₂ per year, respectively, with CO₂ abatement costs of USD 90, USD 100, and USD 103 per tCO₂. The MACC analysis results showed a similar trend to the NS and AIRR results, where the escalation rates significantly impacted the outcome. With higher escalation rates, even ECM01 could be implemented with negative CO₂ abatement costs, as shown in Figures 10 and 11.

To better understand how the carbon credit cost affects the economic feasibility of the ECMs, we performed a sensitivity analysis of the economic indicators (NS, AIRR, and DPB) of ECM09 under different carbon credit cost scenarios. Specifically, we looked at scenarios where the carbon credit cost increased by five (5×), ten (10×), fifteen (15×), and twenty (20×) times the initial cost of USD 2.15. The analysis results, depicted in Figure 12a, show that as the carbon credit cost increased from USD 2.15 to USD 43.00, the NS also increased from USD 2,887,726 to USD 3,368,734 (a 16.7% increase). Raising the carbon credit cost to USD 43.00 would be similar to costs in countries like the United Kingdom, Austria, and Germany [40]. Along with the increase in net savings, the AIRR improved from 12.49% to 12.90% (Figure 12b), and the DPB decreased from 1.46 to 1.25 years (Figure 12c) as the carbon credit cost increased. These results indicate that higher carbon credit costs positively impact the economic viability of the ECMs, highlighting the potential financial benefits of considering carbon credits in retrofit projects.

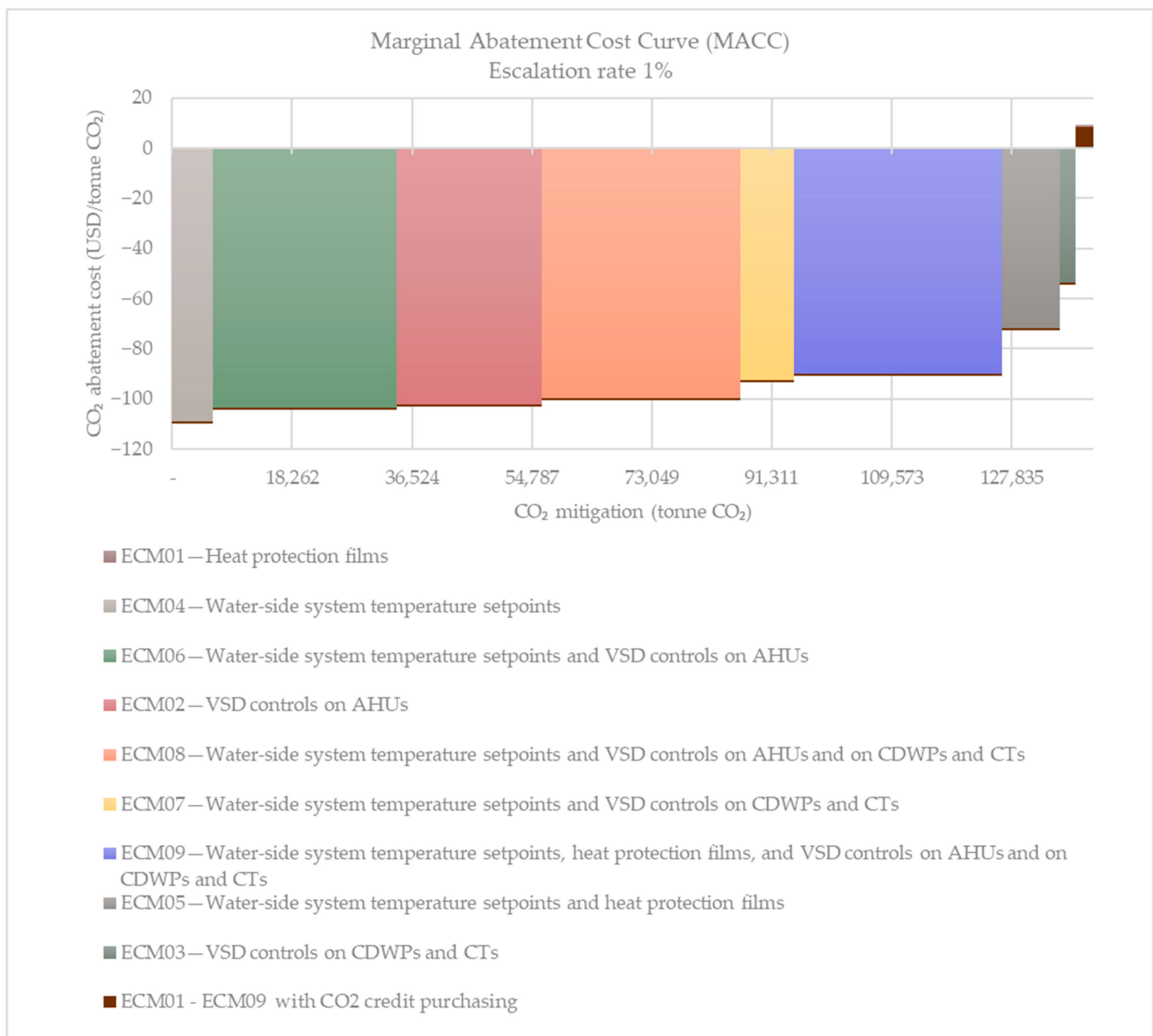


Figure 9. MACC analysis results based on a 1% escalation rate.

Based on the analysis results, ECM09 stood out as the most impactful ECM, achieving the highest energy and CO₂ reduction (approximately 12.5%). As detailed in Figure 6, ECM09 resulted in the highest annual energy consumption reduction of 2,066,350 kWh and CO₂ reduction of 909 tCO₂. Additionally, ECM09 demonstrated acceptable NS, AIRR, and DPB results (Figures 6–8) and a low CO₂ abatement cost of USD 90/tCO₂ (Figure 9). This makes ECM09 an attractive option if maximizing environmental benefits is the primary objective. However, if the project has budget constraints, ECM08 and ECM06 also offer significant energy and CO₂ reduction (around 10%) with positive economic indicators (Figures 6–8). Selecting one of these ECMs may be more suitable depending on the project's budget limitations.

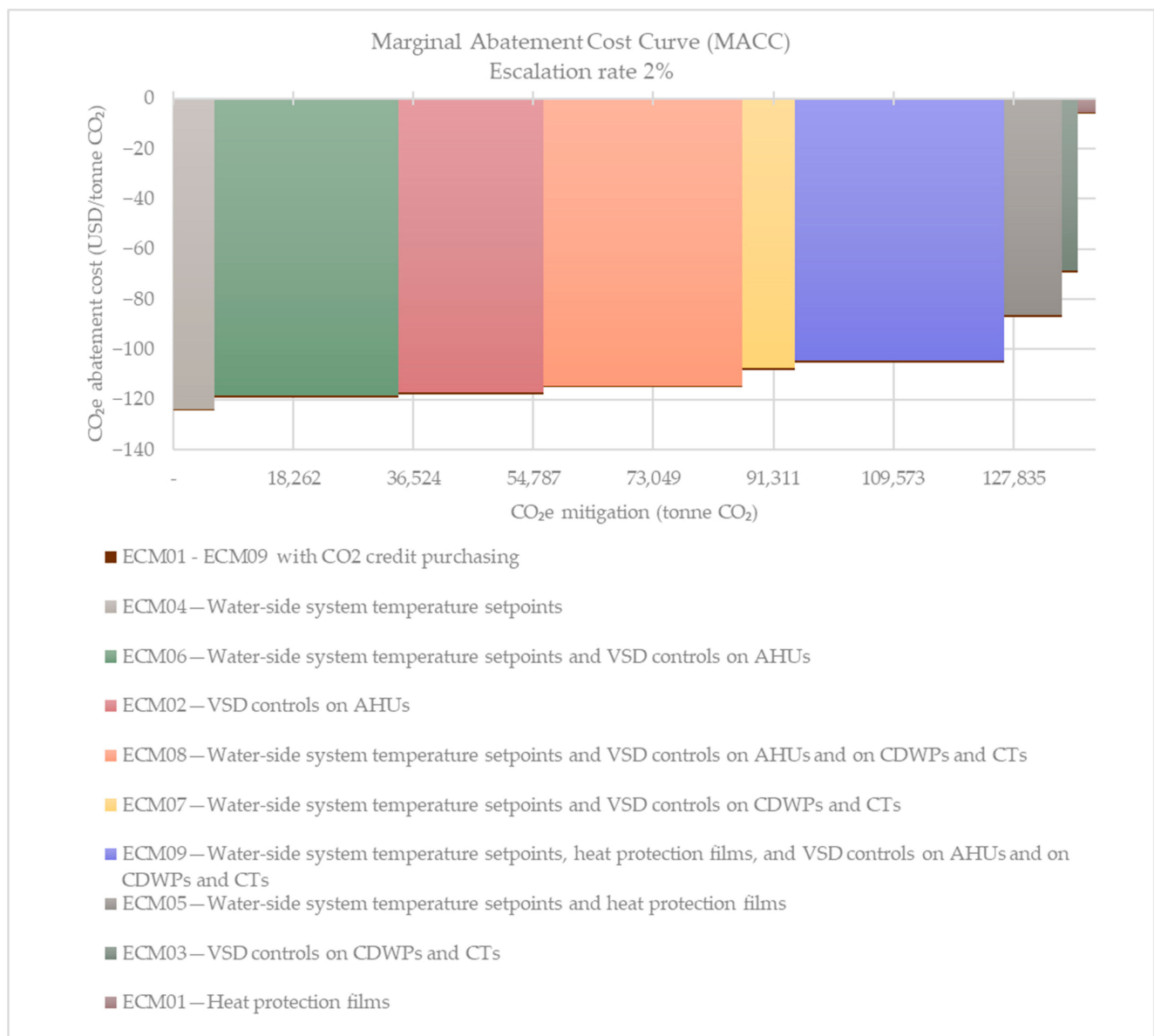


Figure 10. MACC analysis results based on a 2% escalation rate.

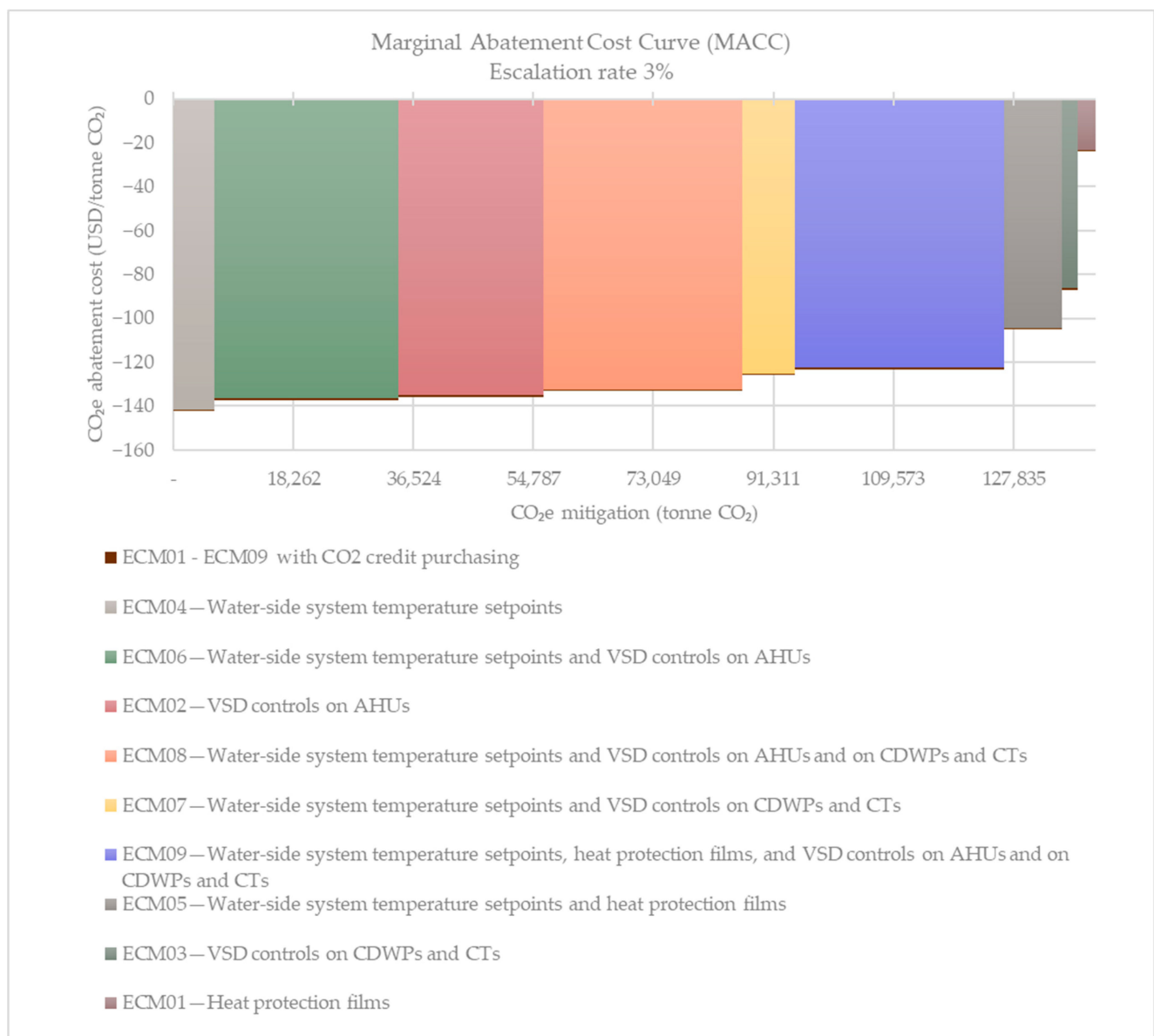
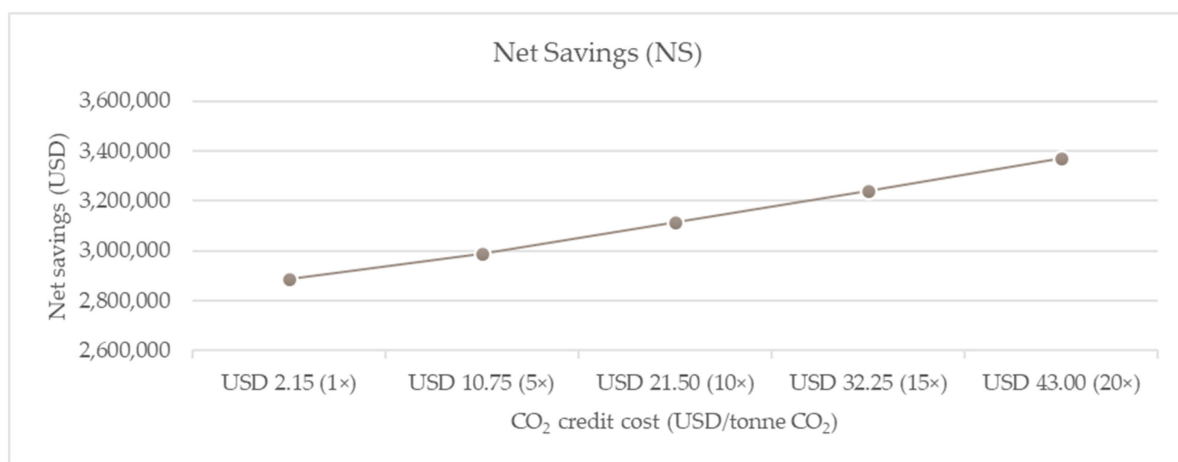
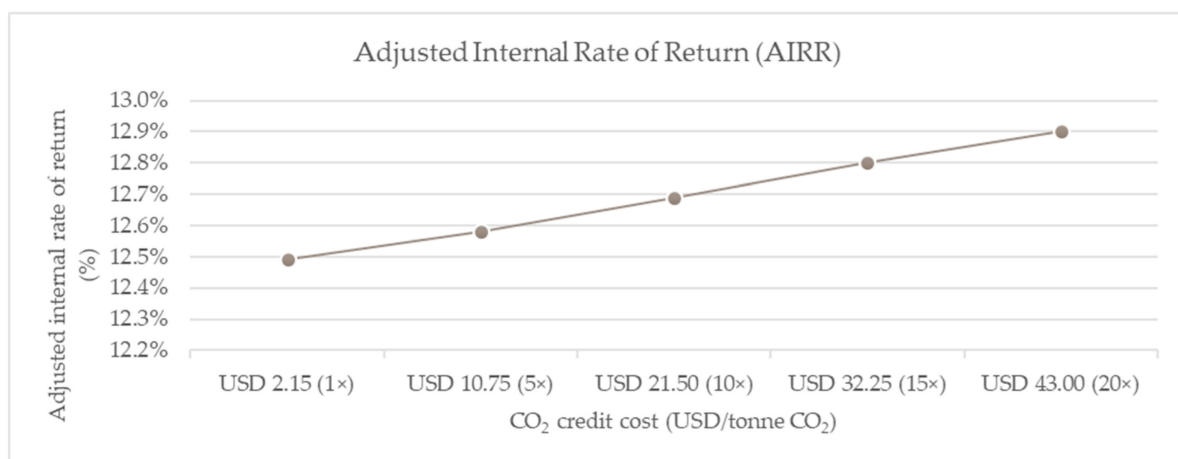


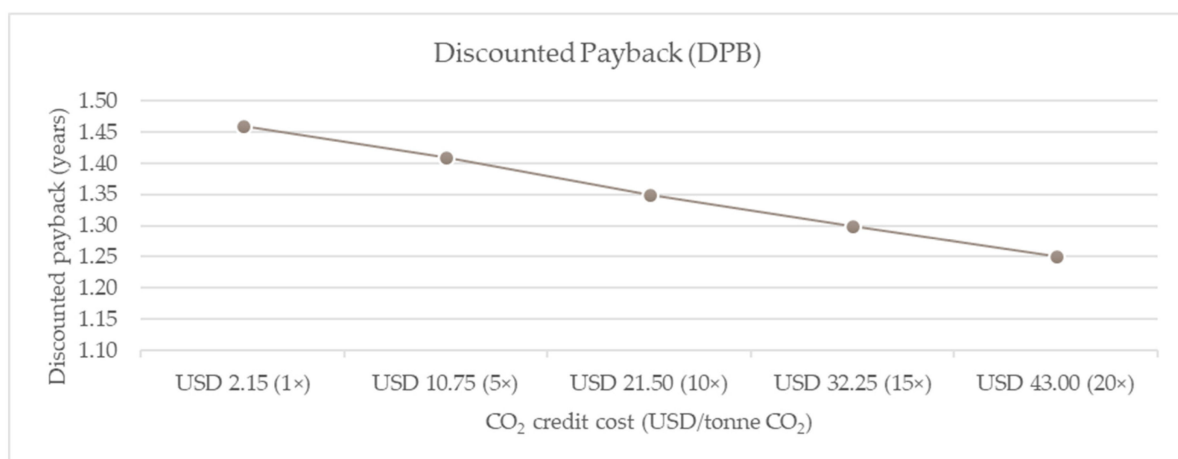
Figure 11. MACC analysis results based on a 3% escalation rate.



(a)



(b)



(c)

Figure 12. The results of a sensitivity analysis of economic indicators for ECM09 under different carbon credit cost scenarios: (a) NS results, (b) AIRR results, and (c) DPB results.

4. Discussion

The reference model achieved an NMBE of 1.10% and a CVRMSE of 3.77% for energy consumption, and an NMBE of 0.15% and a CVRMSE of 5.44% for peak energy demand when calibrated against monthly utility data. This achievement is due to a meticulous approach to data acquisition and utilization that goes beyond just achieving good agreement with monthly utility bill data. First, access to rich building data minimized the need for assumptions and facilitated a more precise representation of the building's energy consumption patterns. These rich data included details on building envelope properties, ACMV and chilled water systems, occupancy schedules, and internal loads—all crucial for accurately replicating the building's energy use profile. Secondly, this study utilized the AMY weather data from the same year as the utility bill data, which significantly enhanced the accuracy of the model calibration. Third, the study went beyond monthly calibration by meticulously calibrating the model at daily and even bi-hourly intervals. This granular calibration approach ensures a more comprehensive understanding of the building's dynamic energy behavior, capturing the influence of factors like chilled water plant energy use and chiller capacities on the total building energy consumption. Furthermore, the analysis employed a triangulation method by comparing the percentage of total energy consumed by the chilled water plant end use between the metered and the simulated data. This additional layer of verification strengthened the confidence in the model's ability to accurately represent not only overall energy consumption but also the contribution of specific building systems. This comprehensive approach to model calibration fosters a high level of trust in the model's predictions and serves as a solid foundation for evaluating the effectiveness of the proposed ECMs.

The high level of accuracy achieved in the model calibration (refer to previous section for details) signifies a robust foundation for formulating and assessing the proposed energy conservation measures (ECMs). Leveraging the calibrated reference model, a crucial insight emerged: the combined energy consumption of the air-conditioning and mechanical ventilation (ACMV) systems and chilled water plant represents approximately 50% of the building's total energy use. This granular understanding of the building's energy use profile, facilitated by the calibrated simulation, enabled the identification of four key areas for improvement:

- Building envelope: Strategies to reduce solar heat gain through the building envelope were explored.
- ACMV system equipment: Measures to enhance the efficiency of the ACMV system equipment were investigated.
- Chilled water plant equipment: Optimization strategies for the chilled water plant equipment were evaluated.
- Chilled and condenser water settings: The potential benefits of adjusting the chilled and condenser water settings were analyzed.

The proposed ECMs encompass individual and combined interventions targeting these key areas. Notably, ECM09, which combines all four strategies, demonstrated the greatest potential for energy cost savings and operational CO₂ reduction, achieving a maximum of 12.5%. This comprehensive approach offers a synergistic benefit by addressing both cooling load reduction and equipment efficiency improvement.

Following closely behind, ECM08, focusing solely on improving the efficiency of the ACMV and chilled water plant equipment, achieved an 11.85% reduction. Similarly, ECM06, targeting ACMV equipment efficiency improvements, delivered a 10.96% reduction. Importantly, adjusting chilled and condenser water settings (ECM04) represented a low-to-zero-cost project. Recognizing its economic viability, this strategy was incorporated into ECM09, ECM08, and ECM06 to maximize their effectiveness. These findings underscore the substantial benefits achievable through improving the efficiency of ACMV and chilled water plant systems in existing buildings, particularly shopping malls.

The economic analysis further underscored the practical and financially attractive nature of all these proposed ECMs. Interestingly, the application of heat protection films

on windows (ECM01) emerged as the least effective strategy. This could be attributed to the dominance of internal loads in shopping malls, where lighting and appliances contribute more significantly to cooling requirements compared to the building envelope. Furthermore, the initial financial analysis assumed a lifespan for the films based solely on their eight-year warranty period. The resulting replacement costs over the building's lifetime could potentially erode the overall financial benefit. However, advancements in material technology offering more durable heat protection films could significantly improve their financial viability. The study also observed that combining heat protection films with adjusting chilled and condenser water settings (ECM05) demonstrably enhanced the effectiveness of using films alone.

This study examined the impact of CO₂ credit cost savings on the financial viability of the ECMs. The inclusion of CO₂ credit cost savings in the financial analysis revealed an improved outcome. However, even with this consideration, the current CO₂ credit price in Thailand might not be a strong enough financial incentive to independently drive building retrofits. This finding highlights the potential need for policy interventions. The decreasing EUI up to 12.5% from the national reference could be a compelling argument for government agencies like the Department of Energy Development and Efficiency (DEDE) to offer building energy retrofit programs. Incentives such as grants, tax breaks, or higher CO₂ credit prices could further encourage building owners to consider energy-saving retrofits, ultimately contributing to national energy efficiency goals.

This retrofit project for a shopping mall in Bangkok, Thailand, aimed to achieve a balance between energy and carbon emission reduction and financial feasibility. Building energy modeling and economic analysis were employed to assess the potential of various energy conservation measures to achieve these goals. In addition to the findings above, it is worthwhile to discuss the limitations encountered and opportunities for future research in the context of building retrofits in Thailand.

Based on the calibration and simulation results presented in this paper, the reference model demonstrated good agreement with the actual building data. The model accurately reflected the overall energy consumption patterns and end-use breakdown, particularly for the chiller plant. This well-calibrated reference model can serve as a solid foundation for developing the proposed model and evaluating the impact of various energy conservation measures.

It is important to acknowledge that developing and calibrating a building energy model can be a challenging and iterative process, as we experienced during this study. Some of the key lessons learned from this process are as follows:

- Accurate building information is crucial for developing a reference model. For this study, valid information for energy modeling can be obtained for a building that has been operational for five years. However, for older buildings, the availability of accurate information may be limited, leading to the need for modeling assumptions and software defaults. This, in turn, may result in a discrepancy between the simulated and actual energy use of the building [11].
- Independent variables, particularly weather and occupancy data, are critical during model calibration. We strongly suggest utilizing the AMY weather data for this purpose. Occupancy data are also important but can be among the most uncertain inputs [11]. In this project, occupancy data significantly accelerated the calibration process.
- Multiple-objective calibration is essential for achieving a well-calibrated model. Focusing solely on fine-tuning the model with a single objective, such as matching only the monthly energy consumption and demand, may not be sufficient. In our recent study, examining various aspects of energy use, including chiller plant energy consumption and capacity data, was crucial for effective calibration.
- Metering data are vital for model calibration. However, the limitations in the building's energy monitoring system hindered our ability to collect detailed data on specific end uses like lighting. If feasible, advanced metering infrastructure could be a valuable

investment for new buildings to facilitate more comprehensive data collection for future modeling efforts [41].

- Model calibration methods deserve further exploration. Using an expert knowledge method for model calibration heavily relies on the modeler's knowledge and judgment. This approach can be time-consuming and may not yield consistent results for future projects. To address this, we concur with previous literature, like Reddy (2006), that emphasizes the need for replicable procedural methods to improve the model calibration process [9–12]. This area warrants further investigation in future studies.

As discussed above, the identified limitations concerning calibrated simulation involve the availability and accuracy of modeling data and replicable procedural calibration methods. The availability and accuracy of building information are crucial for calibrated simulations whereby limited data necessitate assumptions and software defaults, leading to potential discrepancies between the simulated and actual energy use. Variations in actual building performance could also affect the results. For example, the performance of the installed ACMV equipment may be different than that of the designed one. Future research should consider system audits and incorporate temporary or permanent sensors and monitoring systems to collect data and fill in missing information. Furthermore, the calibration methods used can significantly affect the results. The reliance on expert knowledge for model calibration could be time-consuming and yield inconsistent outcomes. Future research should explore replicable procedural methods to improve calibration, reduce dependence on individual expertise, and enhance consistency. These methods should consider multiple calibration objectives, addressing various aspects of energy use such as chiller plant energy consumption and capacity data.

The calibrated reference model provided valuable insights for developing energy-saving ECMs. Building energy modeling also allows the project to examine the energy performance of combined energy improvement strategies, which can be a limitation for other approaches. However, determining the costs associated with implementing these ECMs presented a significant challenge for the retrofit project in Thailand due to the absence of readily available cost information sources like RS Means Data (US). This potentially introduces uncertainty into the economic analysis, particularly for NS, AIRR, and DPB calculations. To mitigate this limitation, future projects should involve cost estimators or contractors early on, as recommended by ASHRAE Standard 209 [22]. Additionally, developing a localized cost database for building construction and retrofit would significantly improve the accuracy of future economic feasibility analyses.

This study's findings from the economic feasibility analysis indicated the critical role of financial variables such as discounted rate and building service lifespan in the analysis results. Notably, the electricity escalation rate, as discussed in this paper, significantly impacted the analysis outcomes. For instance, our analysis with 2% and 3% electricity escalation rates resulted in a noticeable increase in profitability compared to a 1% escalation rate. This aligns with the recommendation by NIST Handbook 135 to include energy escalation rates in the financial analysis for energy-related projects [23]. Therefore, a dedicated study on energy escalation rates for Thailand, similar to those conducted by NIST, would be valuable for future economic feasibility assessments. Furthermore, due to the international agreement on reducing carbon emissions, electricity rates could be higher if energy sources need to be renewable.

Besides financial variables, this study examined the impact of CO₂ credit cost savings on economic analysis. The findings indicated that accounting for the CO₂ credit cost savings in the analysis does not significantly impact the NS, AIRR, DPB, and MACC results. This is likely because the T-VER CO₂ credit price in Thailand is relatively low compared to other regions, as reported by Kasikorn Research Center (2022) [42]. According to the same source, the T-VER program was developed using national/subnational crediting mechanisms and could only be used for carbon offsetting in Thailand. However, as TGO has been extending the program employing independent credit mechanisms (e.g., verified carbon standard (VCS)) to support international carbon offsetting, the CO₂ credit price

will tend to increase in the future [42,43]. Therefore, the impact of CO₂ credit purchasing should still be examined in future research. Furthermore, the limited impact of CO₂ credit cost savings highlights the necessity for government support in encouraging building retrofits. For example, policymakers should contemplate implementing regulations and financial incentives, including tax credits, low-interest loans, and subsidies [1,5]. These measures would help reduce the nation's carbon footprint and foster economic growth by lowering business operational costs. Thus, future research should examine the influence of regulations and financial incentives as part of economic feasibility analyses.

While this study focused on retrofitting a shopping mall in Thailand, the research methodology and findings have broader applicability to other building types and regions. The processes and standards we adopted, such as those outlined in ASHRAE Standard 209, ASHRAE Guideline 14, and NIST Handbook 135, are widely recognized and used in BEM and by financial practitioners globally, making them relevant across various building types and climatic regions. Our findings related to energy performance improvements, environmental contributions, and economic feasibility can benefit other building types within the commercial building sector, including offices, retail stores, and hotels. These building categories often share similar characteristics, such as curtain walls and central ACMV systems, despite differences in operation schedules and occupancy patterns. Therefore, while the degree of benefits each ECM provides may vary depending on these factors, the general principles remain applicable. However, the applicability of our findings is limited to residential buildings due to distinct differences in building components, systems, features, operation schedules, and occupancy patterns. Additionally, the energy improvement strategies discussed may not be directly transferable to regions with different climatic characteristics. Nonetheless, building projects in other areas can adapt our methodology to develop region-specific solutions, ensuring that the underlying principles guide effective and tailored energy retrofit strategies.

Based on the study's methodology and findings, the following practical steps are recommended for undertaking similar retrofit projects:

1. Conduct a preliminary energy audit: Assess the building's current energy performance to understand its energy use characteristics and identify potential areas for energy savings.
2. Develop a calibrated energy model: Gather and use building information, independent variables, and historical energy use data to create a calibrated energy model of the building. This model will be critical for evaluating the impact of different ECMs.
3. Evaluate ECMs: Identify and analyze various ECMs using the calibrated energy model. Consider factors such as energy savings, costs, and implementation practicality.
4. Perform economic analysis: Conduct a detailed economic analysis considering financial variables such as electricity escalation rates, carbon credit prices, and potential incentives. Assess the NS, AIRR, DPB, or other economic indicators of interest for each ECM.
5. Prioritize ECMs: Based on the energy and economic analysis, prioritize ECMs that offer the highest energy savings, environmental benefits, and financial returns. The MACC is a valuable tool for prioritizing the ECMs.
6. Develop an implementation plan: Create a detailed plan for implementing the selected ECMs, including timeframe, budget, and resource allocation.
7. Monitor and verify performance: After implementation, continuously monitor the building's energy performance and compare it with the expected outcomes to ensure that the ECMs deliver the anticipated benefits.

5. Conclusions

This study successfully employed building energy modeling and economic analysis to assess the retrofit potential of a shopping mall in Bangkok, Thailand. The well-calibrated building energy model facilitated the evaluation of various energy conservation measures (ECMs) to achieve energy, energy cost, and carbon emission reductions. Because calibrated

simulation is beneficial for building retrofit projects, it is crucial for future research to investigate practical methods for energy model calibration. The economic analysis revealed the critical role of financial variables, particularly electricity escalation rates, in determining the profitability of the ECMs. The study also explored the impact of CO₂ credit cost savings on the economic analysis results, finding minimal influence due to the current low price in Thailand. However, the potential future increase in CO₂ credit prices suggests the need for further research in this area. This research highlights the importance of considering both carbon emission reduction and financial feasibility in building retrofits. The findings demonstrate the potential for carbon emission reduction and economic benefits achievable through the proposed ECMs in the case study shopping mall project. This information can inform decision-making for the project and pave the way for more sustainable building practices in Thailand's commercial building sector.

Author Contributions: Conceptualization, K.C. and A.S.; methodology, K.C.; software, K.C.; validation, K.C., A.S. and S.P.; formal analysis, K.C.; investigation, K.C.; resources, A.S.; data curation, K.C.; writing—original draft preparation, K.C. and S.P.; writing—review and editing, K.C., A.S. and S.P.; visualization, K.C.; supervision, A.S.; project administration, A.S.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank Africus Company Limited and Chulalongkorn University for their tremendous support and generosity. We would like to acknowledge Nitichot Swangsang for his assistance and technical support in building energy modeling. His expertise and contributions significantly enhanced the quality and accuracy of this study.

Conflicts of Interest: Author Kongkun Charoenvisal was employed by the company Africus Company Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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