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An Economic Analysis of Energy Saving and Carbon Mitigation by the Use of Phase Change Materials for Cool Energy Storage for an Air Conditioning System—A Case Study

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Abstract: Phase change materials are increasingly used because they can be used for cold energy storage in air conditioning systems to increase system efficiency and achieve energy savings. However, many potential adopters of phase change cold storage systems fail to consider environmental and economic factors, so feasibility assessments are difficult and significant gaps between expected benefits and actual outcomes become apparent. This study establishes an economic analysis model using a technology company in Taiwan as an example. The model determines the costs and energy-saving carbon reduction benefits of implementing phase change materials to allow businesses to achieve energy-saving, carbon reduction, and sustainable development objectives. The results of this study demonstrate that companies can achieve a 32% reduction in electricity costs, reduce energy consumption by 118,411 kWh per year, and reduce carbon emissions by 60,272 tons per year by adopting phase change materials. The dynamic payback period is as little as 2.9 years for low-load conditions. A cost–benefit analysis also shows that the use of phase change materials for energy storage, coupled with the prior construction of energy storage areas, provides the maximum economic benefits and is the optimal choice.

Keywords: phase change materials; phase change material air conditioning systems; cold storage systems; zero carbon emissions; energy-saving analysis; cost–benefit analysis; net present value; benefit–cost ratio; payback period; energy-saving rate

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1. Introduction

Due to global warming, achieving zero carbon emissions has become a shared goal for countries worldwide. There is a global demand for energy-efficient ways to reduce the use of fossil fuels, so clean production methods and energy storage solutions are being implemented to minimize energy consumption or compensate for energy shortages. A report by the Energy Information Administration (EIA) shows that global energy demand is expected to increase by 50% by 2050, so energy usage must decrease and energy efficiency must increase [1].

Energy storage systems address the shortfall in renewable energy and reduce reliance on fossil fuels [2]. In buildings, air conditioning systems account for approximately 38–40% of energy consumption [3–7], so decreasing the energy consumption of air conditioning systems yields significant energy-saving benefits. The use of phase change materials (PCMs) in energy storage systems increases the efficiency of air conditioning systems, reduces electricity costs and energy usage, and decreases energy consumption for existing systems to achieve carbon reduction goals, so it is a clean source of energy. However, there is a lack of relevant economic and feasibility analyses for the use of Phase Change Material (PCM) energy storage in air conditioning systems, therefore further economic analysis is necessary.

PCMs are substances that change their state with temperature variations and that provide latent heat [8]. The process of changing physical properties is called a phase change process, during which a PCM absorbs or releases a significant amount of latent heat [9]. Therefore, PCM has practical applications as an energy storage medium, which is significant for energy conservation and temperature control.

PCMs are the subject of many studies and are commonly used for temperature control for objects or environments. Examples include battery heat management systems [10–12], temperature control for circuit board heat sinks [13], refrigerated transportation and logistics [14], road traffic infrastructure to mitigate extreme climates [15], building cooling and energy consumption [16–18], and specialty clothing fabrics [19,20]. In recent years, research on PCM has focused on enhancing its properties, including the development of nano-phase change materials [21], nano-encapsulation [22], and combining PCMs with aluminum nitride [23]. These studies also demonstrate the potential of PCMs, which have significant energy-saving and carbon reduction benefits in practical applications and are subject to continuous optimization and energy storage.

PCMs are also a key element of sustainable development and renewable energy strategies. Li et al. combined PCM with solar power generation and found that PCM reduces the temperature of solar panels and produces a 5.18% increase in power output. The use of PCMs also reduces the need for additional cooling systems [24]. Saxena et al. incorporated two different PCM types into bricks and observed a temperature reduction of 5–6 °C in buildings, resulting in energy savings of 8% and 12% [25]. Thambidurai et al. used PCM for energy storage, combined with fans, to achieve free cooling of buildings, which has environmental benefits. The study proposed enhancing free cooling policies and PCM usage and detailed strategies for material selection, optimized air inlet, and cost reduction [26]. Ghorbani et al. integrated compressed air energy storage with three-stage PCM energy storage for a wind power system. The study used two types of PCM for energy and exergy analyses. The results show that using a PCM increases the system's efficiency by 60%. The combination of the two energy storage systems increases power generation efficiency and provides more stable and sustainable wind power [27]. These studies show that PCMs are valuable for sustainable development and renewable energy and will play an increasingly important role in future energy developments.

PCMs are used for energy storage and temperature control in air conditioning systems. Numerous studies show that PCM-based energy storage systems increase the performance of air conditioning systems and save energy. Said et al. used PCM plates of different sizes that were connected to an air conditioning system and cooled by air. Energy is stored during the night and released during the day to increase the efficiency of the air conditioning system. The results show a 12–14% increase in the system's performance and energy savings of 5.4–16% [28]. Ismail et al. combined air conditioning units with different configurations of PCM containers to determine their effect on energy savings. The results show energy savings of 6.3–8.4% over an 8 h working period [29]. Alam et al. conducted a simulation experiment using five different PCM materials to determine their effectiveness in residential buildings in eight cities. The results show energy savings of 17–23% annually [30]. Hunger et al. added micro-encapsulated PCM materials to concrete in various proportions and found that a 5% mixing ratio for PCM materials saves approximately 12% of energy consumption [31].

These studies demonstrate that PCMs deliver significant energy savings and temperature control. However, there is a lack of economic analysis regarding the industrial use of PCM materials in air conditioning systems, so the energy savings, carbon reduction, and cost-saving benefits are not recognized. The technology industry would reap environmental benefits from PCM materials.

This study establishes an economic analysis model for Phase Change Material Air Conditioning Systems (PCMACS) using real-world cases. This model determines the financial costs and benefits and calculates energy savings and carbon reduction. It can be used for feasibility assessments by companies considering the adoption of PCM systems

to achieve their carbon reduction goals and promote clean production and sustainable operations to mitigate the effects of global warming.

2. Materials and Methods

2.1. Use of Materials

2.1.1. PCMs

The choice of a PCM primarily depends on its characteristics, including the phase change temperature, the heat of fusion, the thermal conductivity, the density, and the specific heat capacity. [32–37]. The temperature range of PCMs that can be used in air conditioning systems is approximately 7–14 °C [38]. This study uses an inorganic hydrate salt compound as the PCM. It is encapsulated in high-density polyethylene in the shape of ice plates. The dimensions of the ice plates are 500 × 250 × 325 mm, with a weight of 5.47 kg/plate and a specific gravity of 1.62. This material was used for cold storage in the air conditioning system, providing a cooling capacity of 12.5 RT/m^2 (RT is Refrigeration Ton used to describe refrigeration and air conditioning capabilities). The thermal expansion rate is less than 2%, and the phase change temperature is 8 °C. The appearance and shape of the PCM material are shown in Figure 1, and its property details are listed in Table 1.

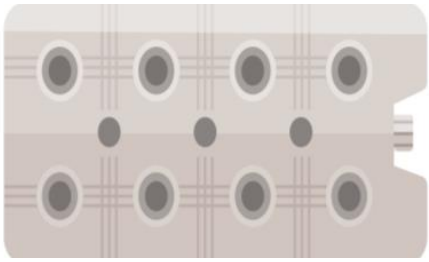


Figure 1. PCM Ice plate.

Table 1. SP-type PCM properties.

Property	Value
Phase change temperature	8 °C
Density	1503 kg/m^3
Latent heat of fusion	182 kJ/kg
Cooling capacity	12.5 RT/m^2
Specific heat capacity	1.8 kJ/kg-K
Thermal conductivity	0.8 W/m-K
Weight	5.81 kg/plate
Size	500 × 250 × 325 mm

2.1.2. Installation and Setup of PCMACS

The PCM was used for the setup of the PCM cold storage system. As shown in Figure 2, the PCM tank is coupled with a heat exchanger and then connected to the air handling unit and the chiller with pipes and valves. The PCM is charged during the night (off-peak hours) and releases cool air during the day (peak hours). Shifting the daytime peak load to the nighttime off-peak period reduces power consumption and avoids peak-hour electricity charges, so annual operating costs and carbon emissions are significantly reduced.

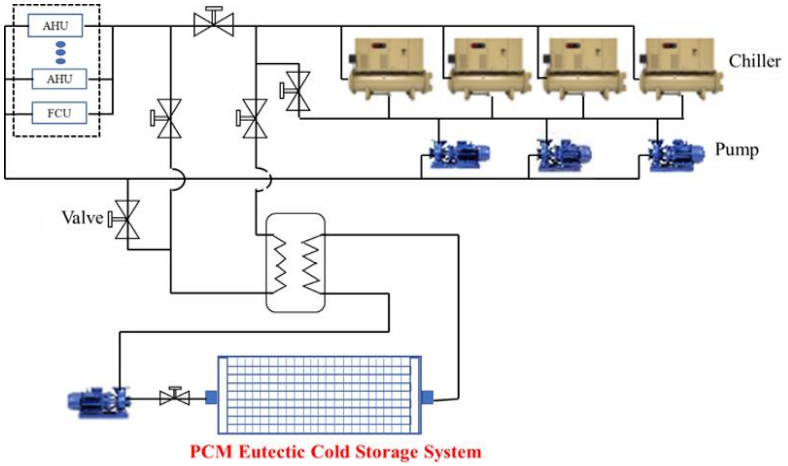


Figure 2. Setup of PCM air conditioning system.

2.2. Research Method

This study uses economic analysis methods and uses a technology company in the Hsinchu Science Park in Taiwan as an example. The literature review and data collection for practical cases is used to collect data for energy consumption, cost-savings, carbon reduction, and a cost–benefit economic analysis. The results of these analyses allow energy storage systems to be compared to increase the efficiency of air conditioning systems. The analytical model for this study is shown in Figure 3.

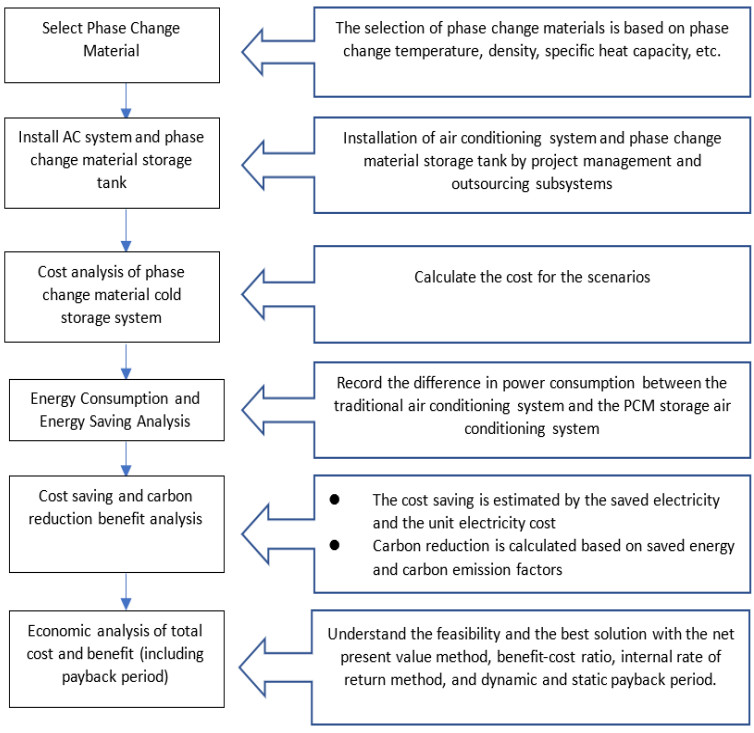


Figure 3. PCMACS economic analysis model.

2.2.1. Cost Analysis for PCMACS

The cost analysis for a PCMACS includes the initial investment cost, the maintenance cost, the operating cost, the disposal cost, and the residual value [39]. The formula to calculate the total investment cost is:

$$C_t = C_{inv} + C_o + C_m - C_s + C_w \quad (1)$$

where C_{inv} is the initial investment cost, C_o is the operating cost, C_m is the maintenance cost, C_s is the residual value and C_w is the disposal cost.

2.2.2. Energy Consumption Analysis for a PCMACS

The lifespan of a PCMACS can exceed 10 years, so this study uses a new installation, and energy consumption data are collected over a one-year period. The actual energy consumption was measured using an additional electricity meter, and the average power consumption is calculated on a monthly basis.

2.2.3. Cost-Saving and Carbon Reduction Benefits

Cost-Saving Analysis

Energy is stored by PCMs during the night, when electricity tariffs are lower than during daytime peak hours, so the air conditioning system is more economical. Air conditioning systems that use PCMs also consume less electricity, so they are cheaper to operate. The total cost savings are calculated by multiplying the energy consumption for a traditional air conditioning system by the peak electricity tariff and subtracting the energy consumption for a PCMACS multiplied by the off-peak electricity tariff. The calculation is shown in Formula (2):

$$C_{save} = (E_{conv} \times C_{Peak} - E_{pcm} \times C_{off}) \quad (2)$$

where E_{conv} is the annual total electricity consumption for a traditional air conditioning system (kWh/year), E_{pcm} is the annual total electricity consumption for a PCMACS (kWh/year), C_{Peak} is the unit electricity tariff during peak hours (NT$/kWh), and C_{off} is the unit electricity tariff during off-peak hours (NT$/kWh). The NT$ is the New Taiwan Dollar.

Carbon Reduction Analysis

Carbon reduction is calculated by multiplying the carbon emission factor by electricity consumption. The carbon emission factor is a measure of the amount of carbon dioxide (CO_2) emitted per unit of energy. It is measured in kilograms of CO_2 per kilowatt-hour (kWh) of energy. It can be obtained from the official website of the Bureau of Energy in Taiwan. Carbon emission factors vary slightly for each country, so the calculation uses the local factor [40,41]. Table 2 shows the carbon emission factor from 2015 to 2021, which is obtained from the Bureau of Energy. The calculation formula for carbon reduction is:

$$CO_{2reduce} = F_{emi} \times E_{save} \text{ (kWh)} \quad (3)$$

where F_{emi} is the carbon emission factor, which is 0.509 in the year of this case study, and E_{save} is the total annual electricity savings (kWh/year).

Table 2. Carbon Emission Factor unit: Kg CO_2/kWh.

Year	2015	2016	2017	2018	2019	2020	2021
Carbon Emission Factor	0.525	0.530	0.554	0.533	0.509	0.502	0.509

2.2.4. Cost and Benefit Analysis

A cost–benefit analysis informs investment decision-making for renewable energy and environmental systems and has been used for solar photovoltaic systems [40], renewable energy systems [41], tidal energy production [42], river restoration [43], and wastewater reuse [44]. The decision indicators for a cost–benefit analysis include net present value (NPV), benefit–cost ratio (BCR), internal rate of return (IRR), and payback period (PR). The calculations for each method are detailed in the following [45,46].

Net Present Value (NPV)

The net present value is the sum of the present difference between the total benefits and the total costs for each period. The criterion is that a larger net present value indicates a better solution. If the value is greater than zero, the solution is feasible. The calculation formula for this study is:

$$\mathrm{NPV} = \sum_{t=0}^{n}(B_t - C_t - K_t)(\frac{P}{F}, i, t) \tag{4}$$

where B_t represents the benefit in year t, C_t represents the operating cost in year t, K_t represents the investment cost for the PCMACS in year t, and $\left(\frac{P}{F}, i, t\right)$ represents the capital recovery factor obtained by table looking.

Benefit–Cost Ratio (BCR)

The benefit–cost ratio (BCR) is calculated by dividing the investment benefit by the cost. It describes the relationship between cost and benefit. The decision criterion is that if the BCR is greater than 1.0, the project has a positive net present value. If a project's BCR is less than 1.0, the cost exceeds the benefit. Decision-makers use this ratio to choose the most suitable solution:

$$\mathrm{BCR} = \frac{\sum_{t=0}^{n} B_t/(1+r)^t}{\sum_{t=0}^{n} C_t/(1+r)^t} \tag{5}$$

where r is the discount rate and n is the end year for the investment.

Internal Rate of Return (IRR)

The internal rate of return (IRR) is a financial metric to determine the profitability of investment opportunities or projects based on projected cash flows. It represents the discount rate that results in a net present value of zero. The investment project with the highest IRR is the preferred option. The calculation formula is:

$$\mathrm{NPV} = \sum_{t=0}^{n}(B_t - C_t - K_t)(1 + IRR)^{-1} = 0 \tag{6}$$

Payback Period (PR)

The payback period is the time that is required to recover the initial investment in terms of the annual net cash inflow that is generated by the project. The initial investment is the investment expenditure during the project's construction phase, which is also known as the net investment amount or the net cash outflow. The payback period is the number of years that is required to recover the investment. The shorter the payback period, the more viable the project.

Static Payback Period

The static payback period is the time that is required to recover the entire initial investment without considering the time value of money. It is the period when the cumulative net cash flow for the investment project during the operating period exactly offsets the time that is required for the projected cash outflow during the construction period. The calculation formula is:

$$\sum_{t=0}^{T} R_t = \sum_{t=0}^{T}(B_t - C_t) = \sum_{t=0}^{n} K_t = K \tag{7}$$

where T is the static payback period, R_t is the profit in year t.

Dynamic Payback Period

The dynamic payback period is the time that is required to recover the present value of the net cash flow for the investment project, considering the time value of money. This

is the time that is required from the start of the investment for the cumulative discounted cash flow to equal zero. The calculation formula is:

$$\sum_{t=0}^{T^*} (B_t - C_t - K_t)(1 + i_0)^{-t} = 0 \quad (8)$$

where T^* is the dynamic payback period (years), i_0 is the standard discount rate.

3. Case Study

3.1. Application of PCM in an Air Conditioning System for Cold Storage

This study uses the SP type hydrated salt PCM for an LCD factory in Hsinchu, Taiwan, as shown in Figure 4. The installation process is shown in Figure 4. Figure 4a shows the feeding process for the PCM. Figure 4b shows the installation and arrangement of the PCM in the tank. Figure 4c shows the on-site installation diagram. Separate electricity meters were also installed to monitor the actual energy consumption. Energy is stored between 12 p.m. and 6 p.m. The phase change material is stored in rectangular tanks, the number of which is determined by the size and position of the area. The installation includes piping, storage tanks, motors, various valves, heat exchangers, and electronic control systems.

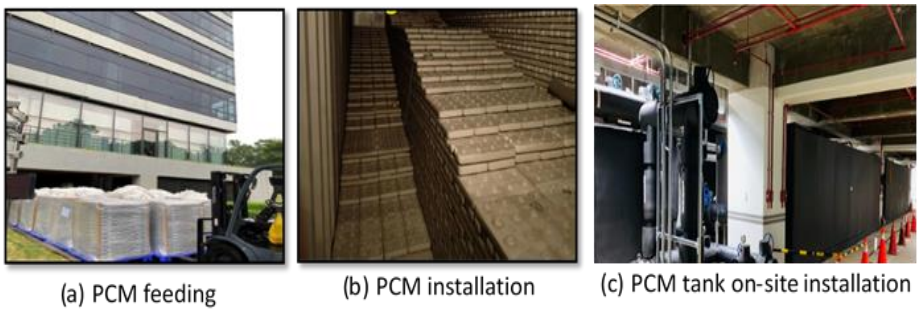


Figure 4. Application of PCM in LCD company.

3.2. Economic Analysis

3.2.1. Investment Cost Analysis

This case uses three scenarios: a conventional air conditioning system without phase change material storage (CACS), a conventional air conditioning system with phase change material storage and leased land (PCMRS), and a conventional air conditioning system with phase change material storage and pre-built land (PCMPS). The costs for each scenario include the initial investment costs, maintenance costs, operating costs, disposal costs, and residual value. The initial investment costs include the cost of modifying the air conditioning system pipes, circuit modifications, phase change material costs, insurance, transportation, and waste disposal. The maintenance costs for a PCMRS and PCMPS are approximately 9% of the investment costs, and the operating costs include electricity expenses and labor costs. Table 3 shows the details for the investment costs of scenarios in NT$, which includes the cost of piping, chiller, instrument and electrical engineering, ice plate, and other costs such as moving, cleaning, insurance, and public security.

Table 3. Investment Costs for AC systems unit: NT$.

AC Systems	Cost of Piping (Including Valves, Pipes, Pumps, Floats, Meters, Heat Exchangers, Insulation Materials, Construction Costs)	Cost of Chiller	Cost of Instrument and Electrical Engineering (Including Power Distribution, PLC, Temperature Sensor, Flow Meter)	Cost of Ice Plate	Other Costs (Moving, Cleaning, Insurance, Public Security)
CACS	5,053,732	6,100,000	5,500,000	0	2,150,000
PCMRS	6,891,733	1,612,000	7,744,765	936,000	3,758,252
PCMPS	3,840,000	1,612,000	6,744,765	936,000	3,237,000

3.2.2. Energy Consumption and Energy Saving Analysis

Energy consumption is calculated using scenarios with and without PCM storage. The electricity consumption is measured using meter readings. The total number of operating days in a year, excluding holidays and non-operating days, is 268. The respective quarterly electricity consumption if there is no phase change in material storage is 82,294 kWh, 63,012 kWh, 194,051 kWh, and 318,486 kWh. The respective quarterly electricity consumption with phase change material storage is 67,481 kWh, 51,670 kWh, 159,122 kWh, and 261,158 kWh. The monthly details for energy consumption and energy savings are listed in Table 4.

Table 4. PCMACS energy consumption and energy savings.

Month	Peak Hour Electricity Rate (NT$)	Off-Peak Hour Electricity Rate (NT$)	Difference in Electricity Prices (NT$)	Operation Days	CACS Monthly Electricity Consumption (kWh/month)	PCMACS Monthly Electricity Consumption (kWh/month)	Electricity Savings by PCMACS (kWh/month)
November 2020	3.33	1.39	1.94	24	23,207	19,030	4177
December 2020	3.33	1.39	1.94	24	23,562	19,321	4241
January 2021	3.33	1.39	1.94	22	21,700	17,794	3906
February 2021	3.33	1.39	1.94	20	19,545	16,027	3518
March 2021	3.33	1.39	1.94	22	21,767	17,849	3918
April 2021	3.33	1.39	1.94	22	46,694	38,289	8405
May 2021	3.33	1.39	1.94	22	55,985	45,908	10,077
Jun 2021	3.42	1.46	1.96	23	91,373	74,925	16,447
July 2021	3.42	1.46	1.96	23	110,939	90,970	19,969
August 2021	3.42	1.46	1.96	22	107,282	87,971	19,311
September 2021	3.42	1.46	1.96	22	100,265	82,218	18,048
October 2021	3.33	1.39	1.94	22	35,525	29,131	6395
Total (kWh/Year)				268	657,844	539,432	118,412

3.2.3. Cost Saving and Carbon Reduction Analysis

Cost Saving Analysis

The night-time electricity rate and daytime electricity rate for this study vary depending on the season, so they are calculated separately. Using the present year's electricity rates, the peak-hour electricity rate ranges from NT$3.33 to NT$3.42, and the off-peak electricity rate ranges from NT$1.39 to NT$1.46. The cost savings are calculated using Formula (2). However, electricity rates vary by country and region, so the calculations use local and present electricity rates.

Carbon Reduction Analysis

Carbon reduction is calculated by multiplying the monthly electricity consumption by 0.509, which is the carbon emission factor, using Formula (3). The cost savings from carbon reduction are calculated at NT$200 per metric ton of carbon. The monthly details for CO_2 mitigation and carbon fee savings are shown in Table 5.

Table 5. CO_2 mitigation and Carbon Fee Savings by PCMACS.

Month	Electricity Savings (kWh/month)	Carbon Emission Factor (Kg CO_2/kWh)	CO_2 Mitigation (Kg CO_2/month)	Carbon Fee Savings (NT$/month)
November 2020	4177	0.509	2126	425,249
December 2020	4241	0.509	2159	431,746
January 2021	3906	0.509	1988	397,632
February 2021	3518	0.509	1791	358,138
March 2021	3918	0.509	1994	398,867
April 2021	8405	0.509	4278	855,624
May 2021	10,077	0.509	5129	1,025,870
Jun 2021	16,447	0.509	8372	1,674,310
July 2021	19,969	0.509	10,164	2,032,840
August 2021	19,311	0.509	9829	1,965,838
September 2021	18,048	0.509	9186	1,837,262
October 2021	6395	0.509	3255	650,961
Total	118,412		60,272	12,054,338

3.2.4. Total Cost and Benefit Analysis

The investment costs, energy and cost savings, operating expenses, maintenance costs, and residual value for the three different schemes are listed in Table 5, and Formulas (4)–(8) were used to determine the net present value, the benefit–cost ratio, the internal rate of return, and the static and dynamic payback periods to determine the cost-effectiveness of the different schemes. The interest rate for the calculations is 10%, and the system has a lifespan of 10 years. The parameters and data for benefit and cost analysis are shown in Table 6.

Table 6. Parameters and data for Benefit and Cost analysis of AC systems Unit: NT$.

AC Systems	Parameters	Description	0	1	2	3	4	5	6	7	8	9	10	Present Value (NT$)
CACS	K	Investment Cost	18,803,732											18,803,732
	C1	Operation Costs		2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	2,227,507	13,687,067
	C2	Maintenance Costs		940,187	940,187	940,187	940,187	940,187	940,187	940,187	940,187	940,187	940,187	5,777,040
	B1	Electricity Bill Savings												-
	B2	Carbon Fee Savings												-
	D	Salvage Value											1,692,337	652,469
PCMRS	K	Investment Cost	20,942,750											20,942,750
	C1	Operation Costs		2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	2,237,710	13,749,759
	C2	Maintenance Costs		1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	1,884,848	11,581,572
	B1	Electricity Bill Savings		709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	4,361,397
	B2	Carbon Fee Savings		12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	74,068,688
	D	Salvage Value											1,884,849	726,691
PCMPS	K	Investment Cost	16,369,765											16,369,765
	C1	Operation Costs		1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	1,937,710	11,906,389
	C2	Maintenance costs		1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	1,473,279	9,052,661
	B1	Electricity Bill Savings		709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	709,797	4,361,397
	B2	Carbon Fee Savings		12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	12,054,338	74,068,688
	D	Salvage Value											1,473,280	568,013

4. Results and Discussion

This study determines the energy savings, feasibility, and optimal solution for the use of PCMs in air-conditioning systems in terms of cost and environmental benefits to construct a model for the introduction of refrigeration and air-conditioning systems.

4.1. Results for Investment Cost Analysis

The investment cost analysis for each scheme is shown in Figure 5. The investment cost is the greatest cost. PCMPS has the lowest investment cost of NT$16,369,765, followed by CACS at NT$18,803,7322, and PCMRS at NT$20,942,750. Option 3 requires the least capital to begin investing, and it is a more affordable choice without considering environmental benefits or energy savings. In terms of operating costs, PCMPS is cheaper than PCMRS and CACS. The maintenance cost for PCMRS and PCMPS is greater than that for CACS. PCMRS has the highest residual value for equipment, followed by PCMPS and CACS. There are significant differences between the three investment schemes in terms of investment costs, operating costs and maintenance costs. Further cost and benefit analysis is required to determine the most efficient plan.

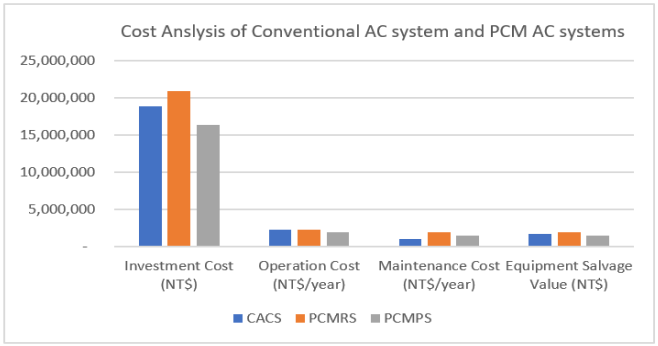


Figure 5. Cost comparison for a conventional AC system and PCM AC systems.

4.2. Analysis Results for Energy Consumption and Energy Savings

The annual energy consumption varies according to demand, the length of operation, and the frequency of use. As shown in Figure 6, in terms of seasonal differences, energy usage varies with the season due to changes in weather and temperature. In the third quarter, the usage rate is higher due to the higher local temperature. However, there is a significant difference in the monthly energy consumption for an air-conditioning system without a phase change material and an air-conditioning system with a phase change material storage tank. The annual electricity consumption is 657,844 kWh/year for a traditional air-conditioning system and 539,432 kWh/year for a PCM air-conditioning system. The difference in annual electricity consumption is 118,411 kWh/year, and the energy-saving ratio is 18%.

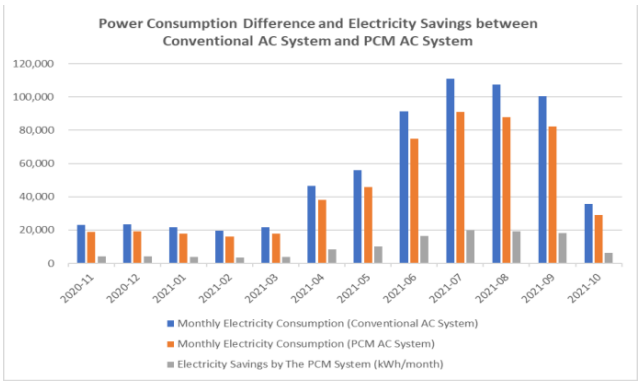


Figure 6. Power consumption and electricity savings.

4.3. Analysis Results of Cost Savings and Carbon Reduction Benefits

The cost saving is the difference in the electricity price due to the difference in power consumption, and the carbon reduction benefit is measured in terms of the reduction in power consumption. The cost-saving benefits and carbon-reduction benefits are described in the following:

4.3.1. Results for Cost Savings and Benefits

Figure 7 shows the difference in monthly savings between a traditional air-conditioning system and a PCM air-conditioning system. The monthly electricity bill for a traditional air-conditioning system is greater than that for a PCM air-conditioning system. The electricity bill for the year is NT$ 2,227,507 for a traditional air-conditioning system and NT$ 1,517,710 for a phase change material air-conditioning system, which is a saving of 32%. In the third quarter, the usage is greater due to the higher temperature, so cost savings are more significant. In July, the cost saving is NT$ 132,896; in August it is NT$ 131,109; and in September, it is NT$ 107,111.

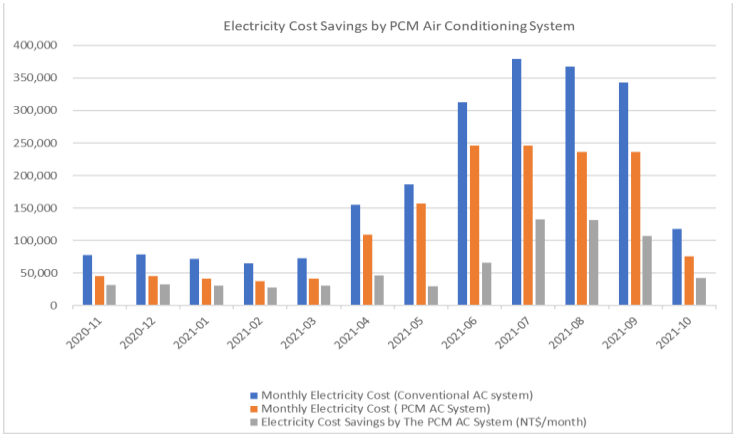


Figure 7. Electricity cost savings.

4.3.2. Results for Carbon Reduction

Figure 8 shows monthly data for CO_2 reduction and carbon bill savings for PCM air-conditioning systems over a specific time period. The CO_2 reduction value is the reduction in CO_2 emissions per month, and the carbon fee savings are the monetary savings that are achieved through the implementation of the carbon pricing mechanism.

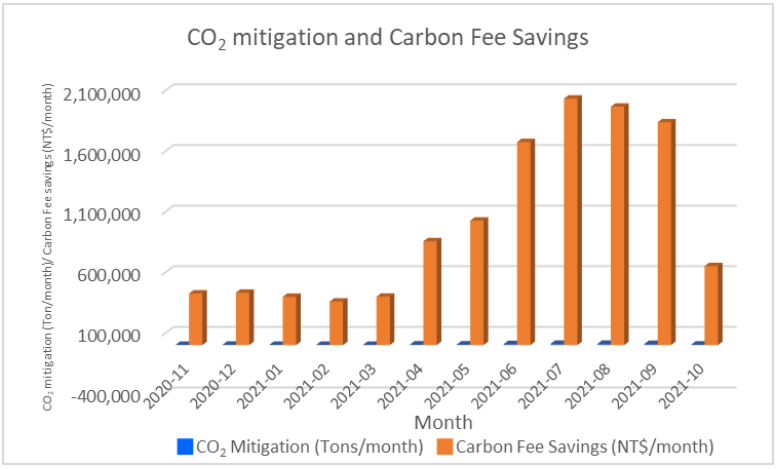


Figure 8. CO_2 Mitigation and carbon fee savings.

The data shows that the reduction in CO_2 varies from month to month. The greatest reduction in CO_2 emissions is for July 2021, with a reduction of 10,164 tons, followed by June 2021, with a reduction of 8371 tons. The lowest figure for CO_2 mitigation was achieved in February 2021, with 1790 tons. These fluctuations in CO_2 mitigation are influenced by seasonal variations, changes in energy consumption patterns, or the implementation of specific carbon reduction initiatives during specific months.

The carbon fee savings are also variable. The highest savings were recorded in July 2021, at NT$2,032,840, followed by June 2021 with NT$1,674,310. The lowest savings were recorded in February 2021, with NT$358,138. These variations in carbon fee savings are attributed to changes in the carbon fee rate, changes in energy consumption, or the effectiveness of carbon reduction measures during specific periods.

In terms of the total CO_2 mitigation over the 12-month period, the cumulative value is 60,271.689 tons. The total carbon fee savings are NT$12,054,338. These figures show the overall impact of the carbon pricing mechanism on reducing carbon dioxide emissions and generating financial savings. The results of this study demonstrate the effectiveness of PCM air-conditioning systems in terms of reducing CO_2 emissions and carbon charges.

The CO_2 reduction values demonstrate that PCMACS reduce energy usage, carbon emissions, and costs and encourage cleaner, more sustainable practices. The substantial savings in carbon fees underscore the economic benefits of reducing carbon emissions and the potential for a transition to a low-carbon economy, but this is a limited dataset. More comprehensive conclusions require consideration of factors such as the use of different phase change materials, the specific sectors or industries that are targeted by the carbon pricing mechanism, the level of compliance of different entities, and any supplements that are implemented in conjunction with the carbon pricing regime policies or measures. A longer time frame and more extensive data will increase the accuracy and reliability of the research results and allow a more comprehensive analysis of the impact of PCMACS and carbon pricing mechanisms on reductions in CO_2 emissions and economic savings.

4.4. Results for the Cost and Benefit Analysis

The cost and benefit analysis for this study uses net present value, the cost–benefit ratio, the internal rate of return, and the payback period. The results for each indicator are shown in Table 7, which also shows the results for the cost–benefit analysis for three different scenarios: CACS, PCMRS, and PCMPS. These metrics demonstrate each option's feasibility, energy savings, and carbon reduction.

Table 7. Cost–benefit analysis indicators for different scenarios.

Item	CACS	PCMRS	PCMPS
Net Present Value (NT$)	−37,615,370	32,882,693	41,669,282
Benefit–cost ratio	−0.17	0.41	0.57
Internal rate of return (%)	-	39.8%	56.5%
Payback period (year)	−5.9	2.4	1.8
Dynamic payback period (year)	−4.9	2.9	2.0

- Net Present Value (NPV):

In the table, the NPV for PCMRS is NT$32,882,693, so carbon reduction is greater for a phase change air conditioning system. CACS has a negative net present value (NPV) of -NT$37,615,370, so it does not generate carbon-reduction benefits. PCMPS has a positive NPV of NT$41,669,282.54, giving it the greatest carbon-reduction and financial advantage.

- Benefit Cost Ratio (BCR):

The BCR for PCMPS is 0.57 and for PCMRS is 0.41, so both reduce carbon, but at a significant cost. CACS has a BCR of less than 1 with a value of −0.17, so the benefits do not justify the costs.

- Internal Rate of Return (IRR):

PCMPS has an IRR of 56.5%, which means a high rate of return. PCMRS has an IRR of 39.8%. Therefore, both PCMPS and PCMRS are viable investment options for carbon reduction. However, no IRR for CACS is provided, so cash flow in this case does not yield a positive NPV for any discount rate.

- Payback Period:

PCMPS had the shortest payback period of 1.8 years, followed by PCMRS at 2.4 years. CACS has a significantly longer payback period of 5.9 years, so this scenario involves greater risk.

- Dynamic payback period:

The dynamic payback period is similar to the payback period but accounts for the time value of money. PCMPS has a dynamic payback period of 2.0 years, followed by PCMRS at 2.9 years. CACS has a dynamic payback period of 4.9 years, which is significantly longer because CACS does not generate energy-saving and carbon-reduction benefits.

In conclusion, PCMRS and PCMPS are more feasible options than CACS in terms of cost–benefit analysis metrics. PCMRS has a positive NPV, BCR, and IRR. PCMPS also has favorable but slightly lower values. The NPV and BCR for CACS are negative, so there is a high cost and no carbon reduction benefit. There is also a long payback period and a dynamic payback period, so there is a slower return on investment. These results show the most viable options for prioritizing PCM air conditioning systems.

4.5. Discussion

This study combines economic analysis methods for PCMs. The sustainability and energy-saving results are also considered. The model aligns with the present global energy demand, and demand for zero-carbon emissions can be used to mitigate global climate change as its usage becomes more widespread.

The economic analysis results show that in the initial stage of plant construction, if land planning and reserved space for phase change energy storage are implemented, installation costs are reduced and economic benefits are greatest. The investment cost is reduced by approximately 13% compared to that for traditional air conditioning systems. PCMACS using land leasing schemes involve construction costs that are approximately 11% greater than those for traditional systems, but the cost-saving and carbon reduction benefits are significant. The greater the difference in electricity prices in a region, the greater the cost savings.

The results of this study show that the cost savings in electricity expenses is NT$ 709,797 annually. The initial construction cost is affected by increases in prices and labor costs. PCM energy storage in air conditioning systems produces significant savings in electricity, but the significant initial modification cost is inhibitive. Inflation and rising construction costs mean that the cost of using phase change materials in air conditioning systems must be reduced. The cost–benefit analysis shows that PCMACS are beneficial and feasible, but the benefits are maximized by pre-planning, cost reduction during construction, and increasing utilization rates.

4.5.1. Operational Mode for a Phase Change Material Air Conditioning System

Phase change material energy storage is a form of physical energy storage. Compared to other forms, such as compressed air energy storage, chemical energy storage, and mechanical energy storage, phase change materials are more suitable for air conditioning systems. The energy-saving and carbon-reduction benefits are significant. However, investment and material costs are high. Companies that introduce such systems must invest their own capital or make leasing arrangements through Energy Service Companies (ESCOs) to obtain higher economic benefits and reduce risks. ESCOs provide comprehensive services to increase energy efficiency, assist the commercial and industrial sectors in formulating energy-saving plans, and cover the required costs through increases in energy utilization

efficiency, so additional capital borrowing is unnecessary and energy users find it cheaper to implement energy-saving plans. However, the ESCO model is not relevant to companies with phase change air conditioning system services, primarily due to the high construction costs and negative net present value.

4.5.2. Future Research

There is a wide variety of PCMs with different phase change temperatures, packaging methods, and storage tank shapes, but all have different energy-saving effects. Therefore, different combinations can be used in practical applications to reduce energy consumption. The cost of phase change material energy storage affects the utilization rate and benefit.

5. Conclusions

This study establishes an economic analysis model for the use of phase change materials in air conditioning systems using real-life case studies. It determines the benefits from an energy-saving and carbon reduction perspective, making it more practically valuable than other studies.

1. The economic analysis results show significant energy-saving and carbon reduction benefits for phase change material cold storage systems, with energy savings of 18% compared to traditional methods and an annual carbon reduction of 60,271 tons. This translates to an annual saving of NT$12,054,337 in carbon emission fees and a payback period of only 2.9 years.
2. Due to temperature variations, there are differences in the frequency of air conditioning system usage with the seasons. The greater the frequency of usage, the more significant the energy savings for a PCM.
3. The initial investment cost for phase change materials is 11–13% greater than that for traditional methods, so Energy Service Company (ESCO) contracts, such as leasing instead of purchasing, increase the willingness to adopt phase change material air conditioning systems and reduce costs.
4. If the construction of phase change material air conditioning systems involves modifying existing systems, the construction cost is prohibitively high. However, if the planning and configuration of a traditional air conditioning system includes provisions for phase change materials from the beginning, some construction costs can be saved. Both approaches are feasible from an energy-saving and carbon reduction perspective.
5. Future research will determine the effect of different phase change materials, different phase change temperatures, or different storage tank methods to improve energy-saving performance.

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