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APPLICATION OF THERMAL ENERGY STORAGE SYSTEM FOR A LOWLAND GREENHOUSE

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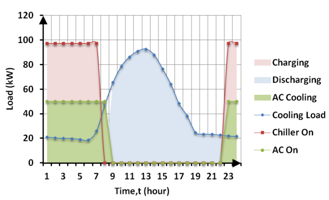
Graphical abstract



Abstract

This article presents a study to estimate the potential saving in annual operating cost of a hypothetical greenhouse used for planting strawberry, in Johor Bahru, Malaysia. The greenhouse needs to be maintained at a constant temperature of 20°C at all time. The goal of this study is to select a suitable TES system that can save the annual cost of electricity usage to meet the cooling load requirement of the greenhouse, based on a 24 hours operating duration and local electricity tariff. Comparison is made with the annual cost for running a conventional air-conditioning (AC) system to meet the cooling requirement. The cooling load requirement of the greenhouse dictates the capacity and size of the potential TES systems, which was estimated based on the highest total annual cooling load. Three TES system operating arrangements were considered in this study: TES full storage combined with AC systems, TES full storage and TES partial storage. Among these three arrangements, the TES full storage was found to have the highest an annual cost saving of about RM 58,990 compared to the cost of using the conventional AC system alone. This represents about 68 % of annual operating cost saving, which is considered very significant.

Keywords: Thermal Energy Storage (TES), lowland farming house, cooling load estimation, greenhouse air-conditioning system

1.0 INTRODUCTION

Thermal energy storage (TES) can be considered as the temporary storage of energy for later use when cooling or heating is needed. For cooling applications, energy is stored at low temperatures while for heating applications; the energy is stored at high temperatures [1]. The interest in cool storage for commercial applications grew significantly especially for countries in hot and humid regions where a very high on-peak demand load occurred in the midday but persisted for a short period of time [2]. TES technology is seen as one of the primary solutions to the electrical power imbalance between its production and continuous demand. The fundamentals, case studies, design and history of the TES are found in various literatures [3, 4]. TES may also be a potential cost-saving solution in countries where the electricity rate is on time-based. This technology can shift cooling energy usage time from on-peak periods to off-peak periods and hence avoids peak demand electricity charges.

In non-residential buildings the TES technology may become an attractive alternative if one or more of the following conditions exist [5]: short period of HVAC demand, frequently varying HVAC loads, infrequent or cyclical loads, HVAC demand and supply do not match, economic incentives are provided for using off-peak energy, energy supply is limited by the utility company, hence making it impossible to satisfy the maximum load directly, and the capacity of an existing chiller is too low to meet the peak load demand. TES technology can be promoted because it can substantially reduce the total energy consumption, conserving fossil fuels and reducing costly imports of oil and other energy resources. With TES, one can adjust the time-discrepancy or rate variance between energy supply and energy demand, thereby playing a vital role in the conservation of energy [3].

Thermal energy storage (TES) systems can be categorized into three types, namely sensible, which uses water and rock, latent, which uses water/ice and salt hydrates and thermochemical, which uses inorganic substances as the storage medium. In general, the selection of TES system depends on several factors, namely the storage period required (either diurnal or seasonal), economic viability and the operating conditions. Many research and development activities related to energy have, in practice, been concentrated on the efficient energy usage and energy savings, which in turn leading to energy-conservation. The TES appears to be one of the most attractive thermal applications for achieving these goals. The exergy analysis approach is considered to be the best tool in analyzing their performances [6].

In the sensible TES system, the energy is stored by changing the temperature of the storage medium, for example water, oil, bricks, sand, soil or rock beds. The TES system typically consists of a storage medium, a container and input/output devices. The amount of energy stored by a TES system is proportional to the difference between the storage input temperature and storage output temperature, the mass of the storage medium, and the heat capacity of the storage medium. Each storage medium has its own advantages and disadvantages. The TES systems are available for both short and long-term storage. For example the systems that use rock and earth beds, and water tanks, are for daily storage. Systems that use rock and earth beds, large water or oil tanks, solar ponds and aquifers are for monthly or annual storage.

In recent years, a combined TES systems with solar heating, hot water and cooling applications in buildings have attracted lots of interest. Many studies have been carried out particularly in the USA, Canada, Europe, Scandinavia and Japan on addressing the technical issues arising from new TES concepts. The improvements required on the performance of existing TES systems, the design of compact TES systems and the use of TES in solar applications have also been investigated. Current research on TES has been broad based and directed towards resolving specific TES issues and new TES materials.

This article presents a study on the use of TES system in a lowland greenhouse for planting strawberry. In Malaysia, Cameron Highland is one of the suitable areas to plant strawberry in the open due to its suitable ambient temperature. Strawberry grows healthy in a temperature range of 12°C - 25°C [7]. However due to insufficient land area in Cameron Highland, building greenhouses at a lowland area is seen as one of the possible solutions to this issue. Most lowland areas in Malaysia experiences temperature around 32°C all year. Conventional air conditioning (AC) systems will be required to maintain the greenhouse at the temperature needed for planting strawberry. However, such systems will consume a lot of electricity to operate continuously. This will results in high operating cost for the greenhouses. Thermal energy storage (TES) systems can therefore be considered as the way to achieve this goal since they are able to shift cooling energy use to from peak time to non-peak times. They can chill storage media such as water, ice, or a phase-change material during the periods of low cooling demand for use later to meet the air-conditioning loads.

The goal of this study is to select a suitable TES system that can help save the cost of electricity needed to meet the cooling load requirement of the greenhouse, based on a 24 hours operating duration. The cooling load requirement of the greenhouse was estimated to determine the capacity and size of the TES systems. This was done based on the highest total annual cooling load. Three TES system operating arrangements were considered in this study: TES full storage combined with AC systems, TES full storage and TES partial storage. The operating cost of the TES systems were compared in term of the total amount of electricity usage during a 24 hours operation, based on the local electricity tariff.

2.0 METHODOLOGY

The effects of operation strategy on electricity consumption of TES systems for strawberry production were estimated for three different operating strategies. These are TES full storage combined with a conventional AC system, TES full storage and TES partial storage. For the TES full storage combined with AC systems, the TES system was designed to meet all on-peak cooling loads, while the AC system meets all the off-peak cooling loads. The TES full storage was designed to meet all on-peak cooling loads from storage and the TES partial storage was designed to meet part of the cooling load requirement from the storage and the other part directly from the chiller during the on-peak period. The major components of the TES system consists of an evaporator, a condenser, a cooling tower, storage tank and water pumps, as shown in Figure 1. The evaporator is used to generate chilled water and later stored in the storage tank. The chilled water is used to cool the hypothetical green house by discharging it through the secondary chilled water pump. The heat from the green house is carried by the water to the storage tank before it is removed in the evaporator. Primary chilled water pump is used to transport the water from the storage tank to the evaporator. The condenser water pump directs cool water from the cooling tower into the condenser to absorb heat from the evaporator. The heat absorbed by the condenser is rejected to the cooling tower by the cooling water and rejected it to the surroundings. The

TES system was designed based on the specification given in Table 1.

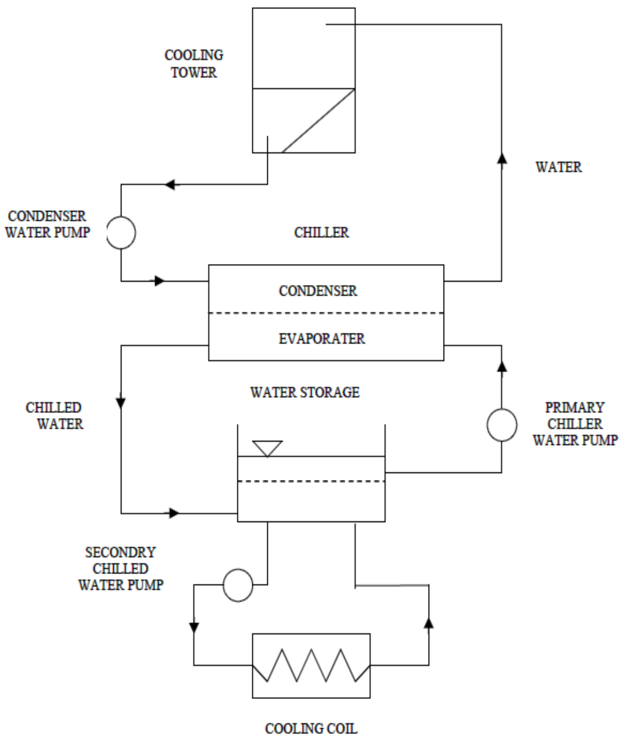


Figure 1 Schematic diagram of the TES system

Table 1 Design specification for the TES system

Parameter	Value
Indoor temperature	20°C
Chilled water supply temperature	5°C
Chilled water return temperature	15°C
Storage water supply temperature	7°C
Storage water return temperature	17°C
Condenser water supply temperature	30°C
Condenser water return temperature	35°C

The hypothetical greenhouse is a single gable type with a single-peaked roof, measuring 60 x 10 x 4 m and is covered with polyethylene material for both the walls and roof. The greenhouse is to be located in Johor Bahru, Malaysia, in which the location is 1.3° North and 103.7° East. Figure 2 illustrates the layout of the strawberry planting arrangement in the greenhouse.

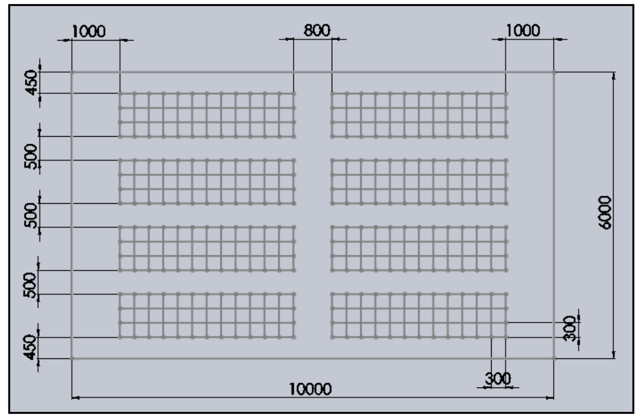


Figure 2 Layout of strawberry plants (in mm) in the hypothetical greenhouse

The electricity cost for operating the TES systems was estimated by first estimating the cooling load of the hypothetical greenhouse for strawberry production. This information is then used to determine the capacity and size of the TES systems. The total cooling load for the greenhouse consists of external as well as internal thermal loads. The external thermal load is due to heat transfer by conduction through the walls, roof, floor and doors. The internal thermal loads are due to the sensible and latent heat transfer from the occupants, appliances and the strawberry plants. The cooling load calculation for the hypothetical greenhouse was performed using a TROPICA software [8] that was developed based on a weighting factor method. Figure 3 shows the flow chart of this software.

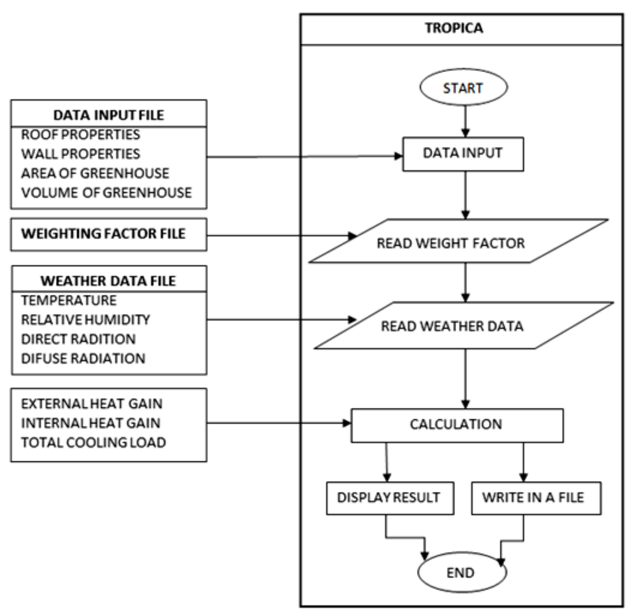


Figure 3 Flow chart of the TROPICA software [10]

2.1 TES Full Storage Combined with AC System

The TES full storage combined with AC systems consist of a TES system (chiller and storage) and a conventional AC system. The AC system includes a cooling tower and water pumps. The chiller system was selected based on the highest total cooling load during the on-peak hours. The highest total cooling load during on-peak occurs between the month of May and June which is about 822 kW. The chiller operating schedule was then determined to estimate the hourly storage balance. It is done based on the total cooling load during the on-peak hours and the cooling capacity of the selected chiller system. The combined TES and AC systems are designed to operate for 24 hours. The conventional AC system was selected based on the highest cooling load during the off-peak hours which is about 47 kW. In this arrangement, the AC system will operate to meet the cooling load demand of the greenhouse during off-peak hours. The TES system will be in a charging mode during this period. During the on-peak hours, the AC system will be shut off and the cooling load demand of the greenhouse is met by the fully charged TES system.

2.2 TES Full Storage System

In this TES system arrangement, the chiller will operate at its full capacity during the off-peak hours, i.e. from 10:00 pm until 8:00 am, to charge the system and at the same time meet the cooling loads demand of the greenhouse. During the on-peak hour which is from 9 am until 10 pm, the charged TES system will be used to meet all cooling requirements by the greenhouse. The chiller for this TES system was selected based on the highest total cooling load in a day, which is about 1056 kW. This highest cooling load occurs between the month of May and June. The full storage system is also designed for 24 hours operation.

2.3 TES Partial Storage System

The TES partial storage system is designed to meet part of the cooling load from its storage during the on-peak hours. The other part is supplied directly from its chiller system. The chiller system will be in the charging mode when the cooling load requirement is less than the output of the chiller. The chiller will be in the discharging mode when the cooling load requirement of the greenhouse is greater than the output of the chiller. For this TES arrangement, the chiller system was selected based on the highest total cooling load during the on-peak hours, which is about 822 kW. This highest total cooling load occurs between the month of May and June. This TES system is also designed for the chiller to operate at full capacity for 24 hours.

2.4 Operating Cost Analysis

The total cost of electricity usage by the TES systems depends on the power rating of the electric motor of each equipment in the systems, the operating duration of the equipment and the local electric tariff, during both the on-peak and off-peak hours. Table 2 shows the electric tariff of the on-peak and off-peak hours in Johor Bahru, Malaysia.

Table 2 Electricity tariff in Johor Bahru, Malaysia

On-peak	8:00 am - 10:00 pm	RM 0.312 /kWh
Off-peak	10:00 pm - 8:00 am	RM 0.192 /kWh

Table 3 shows the power rating of the electric motor for all the three TES system arrangements. The equipment operating schedule during the off- and on-peak hours is also shown in the table. The electric motor ratings were obtained from the corresponding manufacturers.

Table 3 Electric motor rating and operating schedule of the TES systems

Equipment	Motor Rating (KW)	Off-Peak Hours	On-Peak Hours
TES full storage with AC systems:			
Chiller	31.19	9	0
Cooling tower	0.7456	9	0
Chilled water pump	0.75	9	0
Distribution water pump	0.75	0	14
Condenser water pump	1.1	9	0
AC system	19.3	10	0
TES full storage system:			
Chiller	37.95	9	0
Cooling tower	1.12	9	0
Chilled water pump	0.75	9	0
Distribution water pump	0.75	1	14
Condenser water pump	1.1	9	0
TES partial storage system:			
Chiller	19.71	10	8
Cooling tower	0.37	10	8
Chilled water pump	0.55	10	8
Distribution water pump	0.55	0	14
Condenser water pump	0.75	10	8

3.0 RESULTS AND DISCUSSION

3.1 Cooling Loads of Hypothetical Green House

Figure 4 shows the hourly cooling loads profile of the hypothetical green house in a year. The profile of the cooling load reflects the local weather data which dictates the amount of sensible heat conduction into the green house and the magnitude of solar heat gain. From 10 am to 1 pm, conduction heat gain and solar load increases, resulting in the increase of cooling loads. The peak cooling loads occur at about 1 hour past noon time. As the external heat gains drop past the noon time, the cabin air temperature exhibits a similar decreasing trend. The maximum cooling load occurs between the month of January and February, which is about 100 kW.

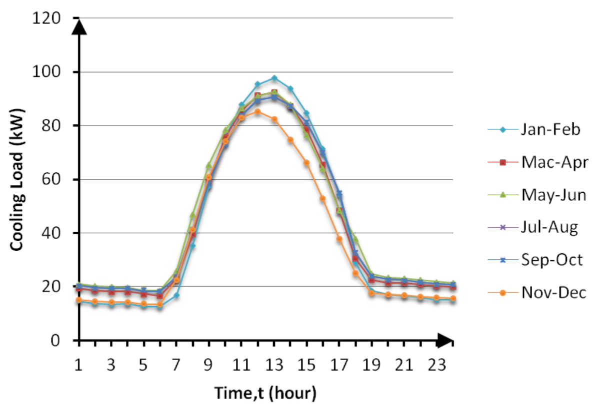


Figure 4 Hourly cooling load profiles for the hypothetical green house in a year

3.2 Combined TES Full Storage and AC Systems

Figure 5 shows the hourly cooling loads profile of the hypothetical green house when the combined TES full storage and AC systems are employed to meet the cooling load demand. In this arrangement, the TES system is designed to meet all the on-peak cooling loads, while the AC system meets all the off-peak cooling loads. As seen from the figure, the chiller of the TES system is charged from 10 pm until 8 am during the off-peak hours. During this period, the AC system is used to meet the cooling load demand of the green house. It can be seen that the chiller charging capacity is close to 100 kW.

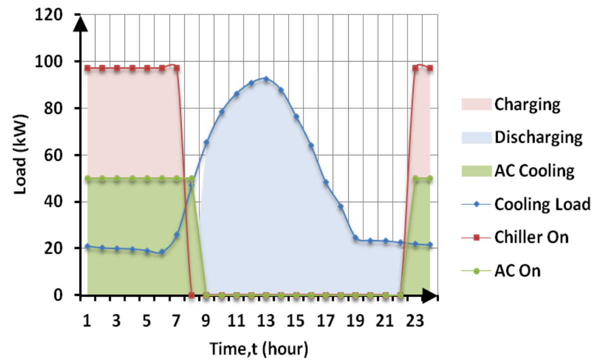


Figure 5 Hourly cooling load profiles for combined TES full storage and AC systems

The AC system is operating at a capacity of about 50 kW when the cooling load requirement of the green house is about 20 kW. The AC system is running with cooling capacity much higher than the cooling load requirement. This is obviously not economical. However, since this occurs during an off-peak period in which the electric tariff is lower, a potential saving of cooling cost can still be achieved. The figure also shows that from 8 am until 10 pm, which is during the on-peak hours where the electric tariff is higher, the cooling load requirement of the green house is met by the energy stored by the TES system. During this time, the AC system is turned off to further save electricity consumption. The same cycle will be repeated for the next 24 hours period.

3.3 TES Full Storage System Only

Figure 6 shows the hourly cooling loads profile of the green house when only the TES full storage system is employed. In this case the TES system is designed to solely meet all the cooling load demand, during both the off-peak and on-peak period. As before, the TES system is charged from 10 pm to 8 am, i.e. during the off-peak period. The chiller capacity of this system is now about 120 kW. The extra 20 kW of cooling capacity is used to meet the cooling load requirement of the green house.

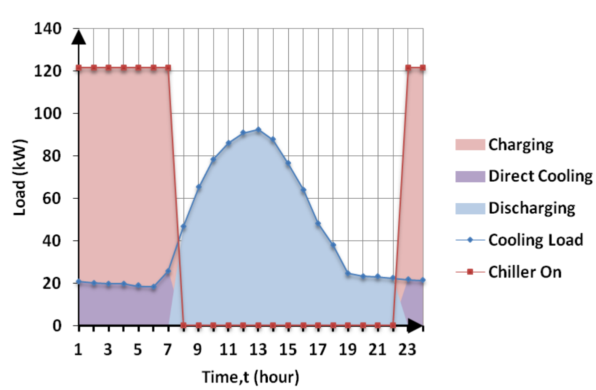


Figure 6 Hourly cooling load profiles for TES full storage system

3.4 TES Partial Storage System

Figure 7 shows the hourly cooling loads profile of the green house when the TES partial storage system is used. With this system, the TES is charged from 10 pm to 5 pm. The chiller runs at a capacity of about 61 kW during the charging period. This is the lowest charging capacity compared to the previous arrangements. In this arrangement, the chill water produced during charging is directly used to meet the cooling load demand of the green house. At same time, the excess chill water is stored in the storage tank. When the cooling load exceeds the chiller capacity, the additional chill water will be discharged from the storage tank. This happens from the period of 9 am to 4 pm which is the on-peak hours.

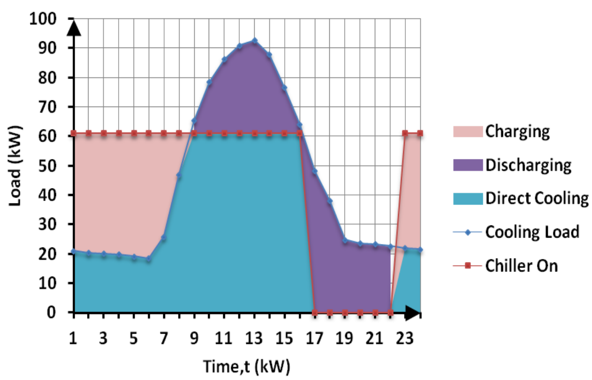


Figure 7 Hourly cooling load profiles for TES partial storage system

3.5 Estimation of Electricity Cost

An economic evaluation of the cooling systems requires estimation of the annual operating cost of the system. The operating costs are affected by several factors such as cooling system capacities, the operating time period and the usage of the conventional AC system. Higher chiller capacity obviously results in higher electricity consumption, which increases the operating cost. Longer period of time taken to charge the chiller will also increase the electricity consumption. Therefore, the operating cost will also increase. Whether the systems operate only during off-peak or during both the off-peak and the on-peak period, it will also have an impact on the operating costs because the electric tariff is higher during the on-peak period. The use of conventional AC system will further increase the electricity consumption and thus the operating cost. Table 4 shows the cost estimation of the electricity usage for the three TES system operating arrangements as described above.

Table 4 Cost estimation of various TES system operating arrangements

Time/Cost (RM)	Type of System			
	AC System	Full Storage With AC System	Full Storage	Partial Storage
A Day	235.27	98.66	75.13	96.83
A Month	7,058.10	2,959.80	2,253.90	2,904.90
A Year	84,697.20	35,517.60	27,046.80	34,858.80

As seen from Table 4, if the conventional AC system is used to meet the cooling load demand of the greenhouse, it would cost about RM 84,697 to operate it in a year. It can also be seen that the operating cost is significantly reduced when TES systems are employed to meet the cooling load demand of the greenhouse. Although the TES full storage system has the highest of chiller charging capacity of 121.5 kW, the system actually has the lowest annual operating cost of about RM 27,047 compared with the other two arrangements. This is because the system used electricity only for charging and this is done during the off-peak hours when the electrical tariff is low. When the system is used to meet the cooling load demand of the greenhouse, no electricity is consumed by the system. Although the TES partial storage system has the lowest chiller charging capacity of 61 kW, the system costs about RM 34,859 to run in a year, which is much higher than the TES full storage system. This is because this system does not only operate during off-peak hour, but also during on-peak hour, when electricity tariff is high. It is also seen from the table that the combination of TES full storage system with AC system has a higher operating cost among all TES systems. In this arrangement, the AC system is used to meet the cooling load demand of the greenhouse during off-peak hours, while the chiller is charging the TES system. However, the AC system is operating with capacity higher than what is required by the greenhouse, thus consumes more electricity than required. Although the off-peak hour electricity tariff is low, the operating cost is high because the power consumption of the AC system is generally high.

Table 5 shows the possible amount annual saving on the operating cost of the TES systems when compared to the conventional AC system. It is seen that the TES full storage system can give the highest cost saving of about 68 % compared to the conventional AC system. The TES partial storage system offers the second highest cost saving of about 59 %, followed by the TES full storage combined with the AC system, which offers a cost saving of 58 %.

Table 5 Annual saving on the operating cost of the cooling systems using TES compared to the conventional AC system

System	Saving (RM)	Percentage (%)
TES Full Storage With AC System	50,518.80	58.06
TES Full Storage	58,989.60	68.07
TES Partial Storage	51,177.60	58.84

4.0 CONCLUSION

This study investigates potential saving in electricity cost to operate a hypothetical greenhouse for planting strawberry in Johor Bahru, Malaysia. It was found that if a conventional air-conditioning (AC) system is used to meet the cooling load demand of the greenhouse the annual operating cost in term of electricity usage would amount to RM 84,697, based on the local off-peak and on-peak hour electricity tariff. The use of thermal energy storage (TES) system has a potential to help save the operating cost of the greenhouse. Three operating arrangements have been considered: combine TES full storage with AC system, TES full storage system and TES partial storage system. Among these three arrangements, the TES full storage was found to have the highest an annual cost saving of about RM 58,990 compared to the cost of using the conventional AC system alone. This represents about 68 % of annual operating cost saving, which is considered very significant.

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