International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0078

LIFE CYCLE COST ANALYSIS OF A RENEWABLE COOLING AND HEATING SYSTEM WITH THERMAL ENERGY STORAGE

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ABSTRACT

This paper presents a life cycle analysis of a renewable cooling and heating system with thermal energy storage. The system mainly consists of a desiccant wheel cooling system, a photovoltaic/thermal-solar air collector (PV/T-SAC) and a thermal energy storage (TES) unit using phase change material (PCM). The life cycle cost (LCC) of the system was evaluated based on annual simulations by employing this system to provide cooling and heating for a case-study house. The influence of the electricity purchase price and sell price on the sizing of the PV/T-SAC, PCM TES unit, and desiccant wheel was investigated. The results showed that the optimal values of the PV/T-SAC length and the amount of PCM used which can minimize the LCC of the system, increased with the increase of the electricity sell and purchase prices. It was also found the LCC was more influenced by the electricity sell price than the purchase price.

Keywords: renewable cooling and heating, desiccant cooling, thermal energy storage, life cycle analysis, performance simulation

NONMENCLATURE

Abbreviations	
DW	Desiccant wheel
DWC	Desiccant wheel cooling
LCC	Life cycle cost
IWEC	International weather for energy calculation
OEG	On-site energy generation
PCM	Phase change material
PV	Photovoltaic
PV/T	Photovoltaic/thermal
RCH	Renewable cooling and heating
SAC	Solar air collector
TES	Thermal energy storage
Symbols	
C_{ini}	Initial cost
C_{mt}	Maintenance cost
C_{op}	Operation cost
$E_{elec,con}$	Electricity consumption
$E_{elec,pv}$	Electricity generated by PV panels
N	Number of years
P_{pur} & P_{sell}	Electricity purchase & sell prices
t	Time
R	Discount rate
θ_{mt}	Coefficient of maintenance cost

1. INTRODUCTION

The increasing demand of space cooling and heating devices and their energy consumption are among the major challenges to be tackled in the coming decade. Many efforts have been made to develop renewable cooling and heating (RCH) systems as an alternative to conventional vapor compression systems, among which desiccant wheel cooling (DWC) has attracted extensive focus. A DWC system with on-site energy generation and thermal energy storage (OEG-TES) was recently proposed, in which photovoltaic/thermal-solar air collectors (PV/T-SAC) was used to generate electricity and thermal energy, and phase change materials (PCMs) were used for thermal energy storage [1]. However, the economic performance of such system has not yet been fully understood. A life cycle analysis of such system was therefore implemented in this study based on annual simulation results. The influence of the electricity purchase and sell prices on the sizing of the PV/T-SAC, PCM TES unit, and desiccant wheel (DW) was investigated by evaluating the life cycle cost (LCC) using different design alternatives with different electricity purchase and sell prices.

2. SYSTEM MODELLING AND LIFE CYCLE ANALYSIS

2.1 System operation and simulation

The RCH system investigated consisted of a DWC system and an OEG-TES system. The DWC system mainly included a DW, an indirect evaporative cooler (IEC), and a heat recovery unit. The OEG-TES system consisted of a PV/T-SAC and a thermal energy storage (TES) unit using PCM, as presented in Fig. 1. The DWC system was used to provide space cooling. The OEG-TES system was used to generate electricity and thermal energy, as well as manage the thermal energy using the TES unit. The TES unit consisted of a number of PCM layers arranged in parallel and each layer consisted of multiple PCM panels. The thermal energy provided by the OEG-TES system was used to regenerate the DW, and could also be used for space heating directly. The electricity generated was used to power the system, while the excess electricity was fed to the grid.

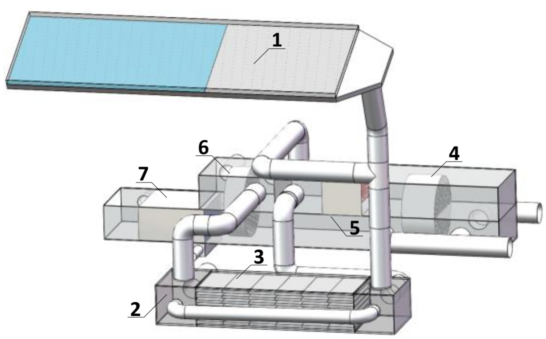


Fig 1 A DWC system with OEG-TES (1: PV/T-SAC; 2: PCM TES unit; 3: PCM bricks; 4: DW; 5: Electric heater; 6: Heat recovery unit; 7: IEC).

This system could operate under three different modes during cooling and heating seasons respectively. In Mode I, the PV/T-SAC was used to charge the PCM TES unit, and regenerate the DW for space cooling, or to provide heated air for space heating, while it was only used to charge the TES unit under Mode II when there is no cooling/heating demand from the building. In Mode III, the TES unit was used to provide heated air for DW regeneration and space heating during cooling and heating seasons, respectively. The PCM charging is suspended when the outlet air temperature from the PV/T-SAC was lower than the average surface temperature of the PCM bricks in the TES unit. The electric heater was used as a supplementary heating device for the DW regeneration and space heating. This system was simulated using TRNSYS. The performance of the PV/T-SAC and the PCM TES unit were simulated using the dynamic models developed by Fan et al [2] and Ren et al. [3], respectively. The outlet air temperature and humidity of the process air and regeneration air from the DW was predicted using an analytical solution provided in [4]. A finite-difference model developed by Chen et al. [5] was used to predict the performance of the IEC. The heat recovery unit was modelled using TRNSYS component Type 760.

2.2 Life cycle analysis

The LCC of this system was defined as the sum of three sub-costs including initial cost, operation cost, and maintenance cost. The initial cost (C_{ini}) was the initial investments of the RCH system which will be specified in Section 3, and the operation cost (C_{op}) and maintenance cost (C_{mt}) were determined using Eqs. (1) and (2) [6], respectively.

$$C_{op} = (\frac{1-(1+r)^{-n}}{r}) \sum_1^t \begin{cases} (E_{elec,con,i} - E_{elec,pv,i})P_{pur}, (if\ E_{elec,con,i} \geq E_{elec,pv,i}) \\ (E_{elec,con,i} - E_{elec,pv,i})P_{sell}, (if\ E_{elec,con,i} < E_{elec,pv,i}) \end{cases} \quad (1)$$

$$C_{mt} = (\frac{1-(1+r)^{-n}}{r}) C_{ini} \theta_{mt} \quad (2)$$

where r is the discount rate, n is the number of years, $E_{elec,con}$ is the electricity consumption of the system, $E_{elec,pv}$ is the electricity generated by the PV panels, P_{sell} and P_{pur} are the sell and purchase prices of electricity respectively, t indicates the time period of concern, and θ_{mt} is a coefficient which determines the maintenance cost based on the initial cost of the system, and was considered as 1.5% in this study [7].

3. RESULTS

3.1 Setup of the simulation

A solar decathlon house with an air-conditioned floor area of 68 m^2 was used as the case study building. During the simulation, the system was used to provide space cooling and heating for the house. The performance of the system was evaluated over the course of a year under the weather conditions of Brisbane, Australia. The cooling and heating load was generated using a DesignBuilder model of the house, and IWEC weather data was used in the simulations. A simulation plan was formulated by varying the main design parameters, including length of the PV/T-SAC, PV factor, total amount of the PCM used, and DW thickness, once at a time while maintaining the others at their reference values. The 20-year LCC of the system using different combinations of the main design parameters was then evaluated under different electricity purchase and sell prices. The prices were varied once at a time and the other was maintained at its reference value. The ranges and reference values of the main design parameters, as well as the electricity purchase and sell prices considered are summarized in Table 1. It is noted that the total usage of PCM was controlled by the number of PCM layers used. The electricity purchase and sell prices were determined based on the information provided by the Government of Queensland [8]. The other parameters used in the simulation and the life cycle analysis are listed in Table 2. The cost of DW was determined based on the cost of a DW with a thickness of 0.2 m, and the cost was linearly increased with the increase of the thickness at a rate of $10,000/m [9].

Table 1. Variation ranges of main parameters, and electricity purchase and sell prices.

Parameter/Price	Range	Ref. value
PV/T-SAC length (m)	[6, 10]	8
PV factor	[0.6, 0.8]	0.6
Number of PCM layers	{5,6…,20}	10
Desiccant wheel thickness (m)	[0.2, 0.4]	0.3
P_{pur} ($/kWh)	[0.1, 0.5]	0.3
P_{sell} ($/kWh)	[0.1, 0.4]	0.1

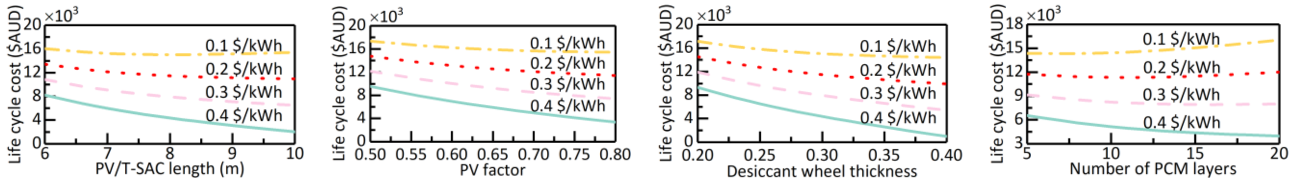
Table 2. Main parameters used in the simulation.

Parameter/Price	Value
PV/T-SAC width (m)	4.0
PV/T-SAC slope (^{o})	18.4
PV/T-SAC rated flow rate (cooling / heating) (kg/h)	900 / 1200
DW diameter (m)	0.4
DW rotation speed (rph)	10-24
IEC length × width × height (m)	1.0 × 0.4 × 0.3
IEC extra ratio	0.3
Thermal efficiency of HRU	0.75
Electrical efficiency of fan	0.65
TES unit length × width (m)	3.0 × 1.2
PCM heat storage capacity (kJ/kg)	250
Cost of PV/T collectors ($/m2)	250
Cost of SAC ($/m2)	100
Cost of PCM ($/kg)	5
Cost of DW ($)	2000
Cost of heat recovery unit ($/each)	650
Cost of IEC ($/each)	510
Cost of fan, electric heater and ducting ($)	910

3.2 Results from the simulation

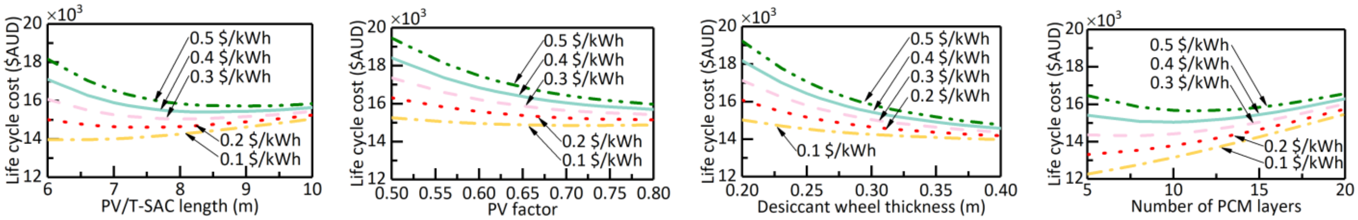
The influence of main design parameters and electricity sell price on the LCC of the system is presented in Fig. 2, while the results for the electricity purchase price is presented in Fig. 3. The LCC always decreased with the increase of the sell price (Fig. 2). It can be observed that the variation trends of the LCC when increasing the PV/T-SAC length (Fig. 2a) and the number of PCM layers (Fig. 2d) was changed from a monotonically decrease to a concave shape with the decrease of the sell price. The variation trends of the LCC when varying the PV factor (Fig. 2b) and the DW thickness (Fig. 2c) was also slightly changed under different electricity sell prices, while the LCC generally decreased with the increase of the PV factor and the DW thickness. It can be observed from Fig. 3 that the LCC of the system always increased with the increase of the electricity purchase price. The variation trend of the LCC when varying the PV/T-SAC length was generally in a concave shape under different electricity purchase prices (Fig. 3a). However, the optimal length that minimized the LCC increased with the increase of the purchase price. Similar trends were also observed for the number of PCM layers (Fig. 3d). Similar variation trends of the LCC when varying the PV factor and the number of PCM layers as those observed in Fig. 2 were also found in Fig. 3. It can also be observed that the influence of the electricity purchase price was reduced when the values of all four main parameters increased. A breakdown of the LCC under different electricity sell prices, and the electricity generation and consumption of the system when varying the PV/T-SAC length is presented in Fig. 4. It can be observed that the initial and maintenance costs both increased with the increase of the PV/T-SAC length, while the operation cost decreased with the increase of the PV/T-SAC length and with the increase of the sell price (Fig. 4a). It is noted that the operation cost could be less than zero, which means that the value of the electricity sold back to the grid was higher than the purchased. This can be explained by the increased electricity generation and decreased electricity consumption with the increase of the PV/T-SAC length (Fig. 4b).

The above results showed that the LCC of the system could be largely reduced and a large PV/T-SAC length or a high PV factor should be used when a relatively high sell-back tariff was available, or the electricity purchase price was high. The 20-year LCC cost of the system could be as low as $983 when the thickness of the DW was 0.4 m (Fig. 2c). On the other hand, the PCM TES could help reduce the LCC if the electricity purchase price was relatively high. The electricity sell price influenced the LCC of the system more significantly as compared to the purchase price.



a) PV/T-SAC length b) PV factor c) Desiccant wheel thickness d) Number of PCM layers

Fig 2 Influence of main design parameters and electricity sell price on the life cycle cost of the system

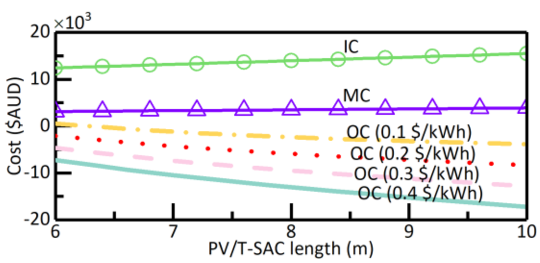


a) PV/T-SAC length b) PV factor c) Desiccant wheel thickness d) Number of PCM layers

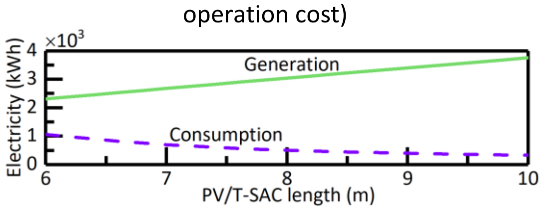
Fig 3 Influence of main design parameters and electricity purchase price on the life cycle cost of the system

4. CONCLUSIONS

This paper investigated the LCC of a DWC system integrated with the PV/T-SAC and PCM TES unit. The annual simulation results under Australian Brisbane weather conditions were generated using a simulation system developed using TRNSYS, based on which the LCC was evaluated. The results showed that the optimal values of the PV/T-SAC length and the amount of PCM used, which minimized the LCC of the system, were varied under different electricity purchase and sell prices. It was also found the LCC was more influenced by the electricity sell price than the purchase price. The result could facilitate optimal design of such systems.



a) Costs (IC: initial cost; MC: maintenance cost; OC: operation cost)



b) Annual electricity generaiton and consumption

Fig 4 Breakdown of LCC and electricity generaiton and consumption when varying PV/T-SAC length

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