1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

A comparative case study of remote area power supply systems using photovoltaic-battery vs thermoelectric-battery configuration

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Abstract

The paper presents a comparative study of two types of remote area power supply (RAPS) systems, which are the existing photovoltaic-based (PV) configuration and the proposed thermoelectric-based (TE) configuration. Both RAPS systems are solar-based power generators and sized according to Melbourne weather conditions (latitude 37.5° S). In this study, the RAPS system designs for both PV and TE have no backup generator and the batteries are the only device for electrical energy storage. Battery storage is used for storing solar energy during the available days for meeting the energy demand as required. The presented RAPS systems for this comparative study are PV/Battery and TE/Battery configurations. Generally, both PV and TE cells are solar-based power generating cells but they have different pre-conversion inputs. For electrical power generation, PV uses sunlight as input energy while the TE uses concentrated solar heat. The results show that the total setup cost for TE/Battery system is 66% higher than PV/Battery system under similar design requirements. Despite having higher setup cost, the TE/Battery system has the potential to harness both electrical and thermal energy for domestic purposes.

Keywords: Energy conversion; cell efficiency gains; passive cooling; phase change material

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1. Introduction

Photovoltaic (PV) panels and batteries are commonly used in remote area power supply (RAPS) systems to provide off-grid power supply in rural areas where power grids are not accessible to these regions. This type of RAPS system is called PV/Battery configuration. In principle, PV panels convert the incoming solar radiation into useful electrical energy for domestic use and the reminding energy will be stored in the batteries for backup supply during unfavourable weather conditions like rainy and cloudy days. For a typically polycrystalline type PV panel, the solar-to-electrical conversion efficiency is about 13-18% [1] and the remaining solar energy will be converted into waste heat which needs to be dissipated to avoid panel heating. The negative effect of PV panel heating is the declination of solar-to-electrical conversion efficiency (-0.5% per $^{\circ}$C) [2]. Therefore, PV/Battery configuration is not an efficient RAPS system as the residual waste heat in the PV panel poses negative impacts on the lifespan and electrical performance of the PV panels.
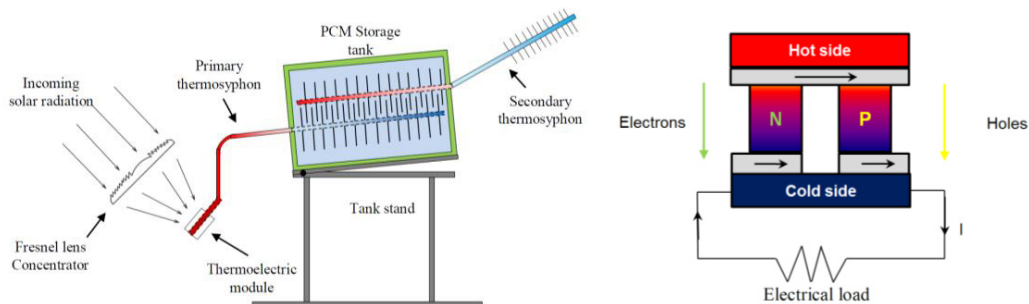

Fig. 1. CTEG-PCMTS system by Tan [3] (left) and schematic diagram of thermoelectric cell (right) [3].

In order to make RAPS system more effective and efficient, besides converting the incoming solar radiation into just electricity, the solar heat can be used for thermal conditioning purposes like space and water heating purposes for domestic applications. In order to have that cogeneration capability, Tan [3] has developed a concentrated thermoelectric generator coupled with phase change material thermal storage (CTEG-PCMTS) which can achieve dual energy production, electrical and thermal energy as illustrated in Fig. 1 (left). The cogeneration concept developed by utilising thermoelectric generator (TEG) for electricity generation and PCMTS for thermal storage. In general, TEG cell will generate electricity by providing a temperature gradient across the cell to achieve Seebeck effect shown in Fig. 1 (right). In his proposed system, the solar radiation was concentrated on the hot side of the TEG cells (solar heat) and the cold side was cooled by absorbing the waste heat into the phase change material thermal storage (PCMTS) to achieve thermoelectricity generation. The stored waste heat in the PCMTS can be then reused again for domestic space heating and hence reduce the electricity cost. For this RAPS comparative study and to be comparable to PV/Battery configuration, only batteries are integrated to the CTEG-PCMTS system to form the thermoelectric based RAPS with batteries (TE/Battery) configuration.

As mentioned earlier, both PV/Battery and TE/Battery are similar solar based power generators and uses comparable energy harvesting technology. Based on Tan's experimental prototype [3], the CTEG-PCMTS is a sustainable power generator as all components are passive devices, self-operable and capable to within high solar concentration ratios. In this comparative study, both RAPS systems are sized according to Melbourne weather conditions (latitude 37.5 $^{\circ}$S).

2. Framework of comparative studies

In this comparative study, the RAPS system designs for both PV/Battery and TE/battery have no backup generator and the batteries required are sized for the month with the lowest solar insolation. Battery storage is the chosen electrical energy storage means for storing solar energy during the available days for meeting the energy

demand as required. Generally, PV cells and TEG cells are solar-based power generating cells but they have different pre-conversion inputs. For electrical power generation, PV uses sunlight as input energy while the TEG uses solar heat. The technologies are similar and a comparative study is possible if the CTEG-PCMTS system uses comparable technology to that used in the panel system. The assumptions and limitations of this study are:

- The main energy is solar energy.
- No backup generator is included in either RAPS system design.
- Batteries are the only energy storage means.
- The same electrical load is used for both systems. Typical values for energy consumption were taken from the literature [4] with a constant average daily load of 10.7 kWh/day.
- The electrical efficiency of the stand-alone DC–AC inverter is assumed to be 90 %. The adjusted constant average daily load is 11.9 kWh/day to account for the DC-AC inverter efficiency.
- For the PV/Battery configuration, the PV modules are standard mono-crystalline silicon modules and the PV arrays are sized to the charging requirement of the battery bank. The system sizing and peripherals for the PV/Battery configuration are referenced from Richards and Conibeer [4].
- For the TE/Battery configuration, the TEG modules are made from Bismuth Telluride (Bi_2Te_3) which is similar to the modules used in the experimental system presented by Tan [3]. The CTEG array is sized according to the design requirements of the PV/Battery configuration system as suggested by Richards and Conibeer [4].

2.1 Solar energy resource in Australia

The comparative study was based on weather conditions in Melbourne (latitude 37.5 ºS). Melbourne was selected due to the availability of excellent solar insolation as shown in Fig. 2.
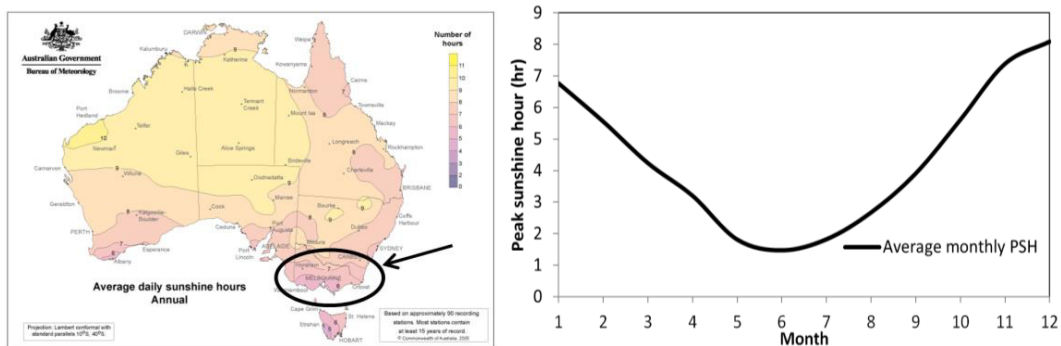

Fig. 2. Number of hours of full sunshine in Australia (left) and monthly average peak sunshine hour (PSH) of Melbourne (right) [5].

Monthly average solar exposure data for the year 2012 were obtained from the Australian Bureau of Meteorology [5]. The presented monthly average peak sunshine hour (PSH) data are for Melbourne. PSH refers to the number of hours when the sunshine is at its maximum level (solar irradiance=1000 W/m^2). The PSH values are usually highest in clear sun conditions during the summer and lowest during winter seasons. According to the data above, the monthly average PSH values in summer are approximately four times higher than in winter. The yearly average PSH value for Melbourne is 4.38 hours.

2.2 PV system with battery storage (PV/Battery)

The PV/Battery configuration sizing used in this comparative study is referenced from Richards and Conibeer [4]. The specifications of the suggested combined inverter–charger are 48 VDC input and 3500 W continuous 240 VAC

output, and the selected batteries charged by the inverter are Deep-cycle lead–acid batteries (6 VDC per cell, 900 Ah). The Australian standard [6] recommends 5-10 days of autonomy for a RAPS system with no backup generator. Richards and Conibeer [4] suggest 7.5 days of autonomy for Melbourne in agreement with the recommended battery storage capacities designated for 37.5° South latitude [5]. Therefore battery storage capacities of 3537 Ah are recommended for Melbourne. To account for the efficiency of the batteries which is assumed at 85 %, the adjusted average daily load to be supplied by the PV panels is increased to 291 Ah/day. The chosen PV technology is a typical screen-printed mono-crystalline silicon module (BP Solar, Model 4170, 170 Wp, A=1.2 m^2) and has a cell efficiency of 13.5 %. The PV array was sized according to the worst PSH value of 3.31 during winter in Melbourne.

2.3 CTEG-PCMTS system with battery storage (TE/Battery)

For comparable evaluation, the TE/Battery configuration uses a similar setup to that of the above PV/Battery configuration suggested by Richards and Conibeer [4]. The designated solar concentration is 130 suns and the TEG power unit is made up of two installed TEGs. Under 130 sun solar concentration, each TEG module is able to generate a maximum power output of 9.7 W, voltage output at 5.5 V and current output at 1.76 A based on the validated mathematical model [3]. The predicted TEG hot side temperature is 285 °C and the cold side temperature is 95 °C which is within the operational limit of the TEG as recommended by the manufacturer [7]. It is noted that electrically series-connection increases voltage with constant current and parallel-connection increases current with constant voltage. In order to meet the electrical requirements of the inverter, 9 sets of series-connected TEG power units are required to meet the 48 VDC requirement of the inverter. 50 sets of parallel-connected TEGs power units are required to supply the current output to meet the daily load requirement which is 291Ah/d as quoted by Richards and Conibeer [4]. Hence, the total number of TEGs required for the matrix array is 900. Fig. 3 shows the schematic diagram of the TE /Battery electrical connection matrix.
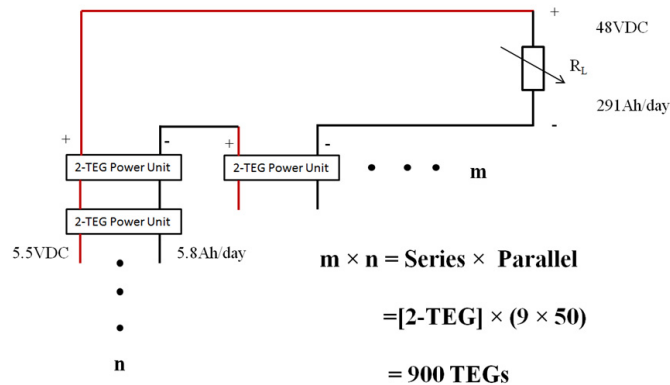

Fig. 3. Electrical circuit design and sizing of 2-TEG power units for determining the required number of CTEG-PCMTS systems for TE/Battery configuration.

As stated previously, the worst peak sunshine hour (PSH) value for Melbourne was 3.31 and the required PCMTS is sized according to the daily operation. The PCM used in the PCMTS is paraffin wax RT27 which has a melting temperature of 27 °C and latent heat of 184 kJ/kg. The total mass of PCM required for cooling the TEG power units at 130 suns solar concentration (under the operating conditions of 3.31 hours at 1000W/m^2 of incoming solar insolation) is 10,424 kg.

3. Results and discussion

The purpose of this comparative study is to give an overview through system sizing and cost breakdown of the TE/Battery configuration as a future RAPS system. By comparing it with the existing PV/Battery system, it is able to provide a feasibility analysis for implementing the CTEG-PCMTS system as the future TE/Battery RAPS. The sizing and cost breakdown of the PV/Battery and TE/battery configurations are shown in Table 1 and 2 respectively. It should be noted all the listed costs are expected to be increased in practice as labour and site costs are not included in the total cost. There are also minor component costs such as structural frames, wiring, system enclosure and installations which are not included in the overall system costing. Despite the fact that CTEG-PCMTS system is able to store thermal energy for latter domestic use, this benefit is not included in this comparison and is considered a bonus feature of utilising TE/Battery over PV/Battery.

Table 1: Sizing and cost breakdown of PV/Battery and TE/Battery configurations.

PV/Battery		**TE/Battery**	
Location:	*Melbourne*	*Location:*	*Melbourne*
No. of PV panels	34	No. of TEGs	900
(2 × 170 Wp in series)	(17 parallel strings)	No. of Fresnel lens concentrators	450
		Total Fresnel lens costs	
PV array cost	A$60,758		A$45,000
Total PV array cost	**A$60,758**	**Total solar concentrator cost**	**A$45,000**
Days of autonomy	7.5	(9 × 9.7Wp in series)	(50 parallel strings)
		CTEG array cost	**A$34,200**
No. of batteries	24	**Total CTEG array cost**	**A$79,200**
	(3 parallel strings)		
Cost. of batteries	A$26,400	Days of autonomy	7.5
Total battery bank cost	**A$79,200**	PCM mass	10,424kg
Inverter/charger	1	**(RT27 Paraffin wax)**	
		Total PCM cost	**A$83,390**
Inverter cost	A$6,600	No. of batteries	24
			(3 parallel strings)
Total inverter costs	**A$13,200**	Cost. of batteries	A$26,400
Total system cost	**A$153,158**	**Total battery bank cost**	**A$79,200**
		Inverter/charger	1
		Inverter cost	A$6,600
		Total inverter costs	**A$13,200**
		Total system cost	**A$254,990**

The total cost for the TE/Battery is 1.66 times higher than the PV/Battery configuration as sized by Richards and Conibeer [4]. From Table 2, the battery is the highest cost component for the PV/Battery system which is 51.7 % of the total system cost. For the TE/Battery configuration, the highest cost is the PCM (thermal storage) which is 32.7 % of the total system cost. The next highest cost component after the batteries is the Fresnel lens concentrators which are 17.6 % of the system cost. They are an essential component of the TE/Battery system for providing the heat source to the TEG power unit for thermoelectricity generation. Despite having higher system cost than the PV/battery system, there is a benefit of using the TE/Battery system which is that the stored heat in the PCMTS can be extracted and reused. The PCMTS is capable of storing large amounts of heat energy from cooling the TEG power units during the day. The estimated amount of heat energy stored during the day is ~5 GJ. Reusing the stored heat for other applications is able to improve the system efficiency and reduce the energy cost. However, this consideration is not included in this comparative study but it is noted as an additional benefit of using TE/Battery configuration. The amount PCM requires in the PCMTS is 10,424 kg (~10 tons of paraffin wax) for 7.5 days of anatomy based in Melbourne which is massive in terms of mass.

Table 2: Fractional costs breakdown.

Fractional cost of PV/Battery		*Fractional cost of TE/Battery*	
Inverter	8.6%	Inverter	5.2%
PV modules	39.7%	Solar concentrator (Fresnel lens)	17.6%
Batteries	51.7%	TEG modules	13.4%
		PCM	32.7%
		Batteries	31.1%

4. Conclusion

The RAPS sizing and cost breakdowns of using TE/battery and PV/battery system were compared and analysed. The sizing and cost analysis revealed that the TE/battery system is 1.66 times more expensive that the suggested PV/battery system by Richards and Conibeer. This is due to the high cost of the PCM which has dominated the overall system cost. The price of the PCM is expected to decrease as it is not presently in common use in solar-based applications. Also there is a major potential benefit in the TE/Battery configuration. The large amount of stored heat (~5 GJ per day) in the PCMTS can be reused for other applications where heat energy is required. This approach can improve the overall system efficiency and reduce the energy cost, especially in area where space heating is essential. Hence the CTEG-PCMTS system as TE/Battery RAPS has the potential for future sustainable power generator development.

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