Model and analysis of solar thermal generators to reduce the intermittency of photovoltaic systems with the use of spectrum splitting

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ABSTRACT

In this paper we introduce an approach to damping intermittency in photovoltaic (PV) system output due to fluctuations in solar illumination generated by use of a hybrid PV-thermal electric (TE) generation system. We describe the necessary constrains of the PV-TE system based on its thermodynamic characteristics. The basis for the approach is that the thermal time constant for the TE device is much longer than that of a PV cell. When used in combination with an optimized thermal storage device short periods of intermittency (several minutes) in PV output due to passing clouds can be compensated. A comparison of different spectrum splitting systems to efficiently utilize the incident solar spectrum between the PV and TE converters are also examined. The time-dependent behavior of a hybrid PV-TE converter with a thermal storage element is computed with SMARTS modeled irradiance data and compared to real weather and irradiation conditions for Tucson, Arizona.

Key words: Solar energy, Spectrum Splitting, Thermo-Electric Device, Intermittence, concentrating photovoltaics

1. INTRODUCTION

Solar energy is an abundant energy resource that can be converted into electricity through two approaches: solar photovoltaics (PV) and thermoelectric devices (TED). Photovoltaic (PV) energy conversion is one of the most viable ways of harnessing solar energy due to its direct electrical energy conversion process, its potential for high conversion efficiency, and its ability to use it in both distributed and centralized configurations[1]. However in spite of significant development and investment in PV system they still do not provide a significant part of the energy supply. One of the main reasons for this is that PV cell response times are a function of charge carrier recombination time constants that are very short compared to intermittent obscuration due to clouds. This results in rapid power fluctuations in PV system output and makes them less reliable as a power source. Figure 1 shows a typical PV system output in Tucson Arizona as a function of time for July 7, 2013. Also shown is the expected power and energy available for the same day (calculated with the SMARTS[2] solar irradiance simulator). The energy lost due to intermittency and diffuse light conditions is approximately 8-9% of the total energy available on a clear day. While this loss is substantial a more important effect is the rapid loss of power which causes a significant loss in power reliability and would require back up by other sources of power generation.

In this paper the combined use of PV and thermal electrical devices (TED) is investigated for implementing a system that is more tolerant to fluctuations in solar illumination. The properties of thermal electric devices are first reviewed. This is followed by description for a hybrid PV-TE converter in combination with low cost thermal energy storage block. The system is then evaluated to determine the duration of intermittency that can be compensated under ideal and actual illumination conditions.

2. THERMAL ELECTRIC DEVICE CHARACTERISTICS

Thermal electric devices generate electricity through thermal generation and separation of charge carriers according to the Seebeck effect[3]. The TED can be modeled as a voltage source that depends on the temperature difference between the hot and cold surfaces of the device:

$$V_{TE} = S\Delta T, \qquad (1)$$

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where S is the Seebeck coefficient and ΔT is the temperature difference (K) between the two surfaces of the TED. Typical values for the Seebeck coefficient of commercially available devices range from 0.026-0.038V/K. The maximum electrical power that can be obtained from the TED is given by:

$$P_{TE,max} = \frac{1}{4}\frac{V_{TE}^2}{R_{int}}, \tag{2}$$

where R_i is the internal resistance of the device and is a function of the number of *p-n* couple between the hot and cold surfaces. Typical values for the internal resistance of commercially available devices are 1.2-2.1 Ω [4]. The efficiency of a TED can be expressed as[5]:

$$\eta_{TE} = \frac{T_H - T_C}{T_H}\frac{\sqrt{1+(Z_T)}-1}{\sqrt{1+(Z_T)}+T_C/T_H}, \tag{3}$$

where T_H and T_C are respectively the hot and cold junction temperatures, and Z_T is a dimensionless figure of merit

$$Z_T = \left(\frac{S^2\sigma}{k}\right)T, \tag{4}$$

where S is the Seebeck coefficient, σ the electrical conductivity, k the thermal conductivity, and T the average temperature. Under conditions of large ΔT (200 °C) and optimized material parameters TED conversion efficiencies greater than 8% are possible however more realistic values are in the range of 2-4%.

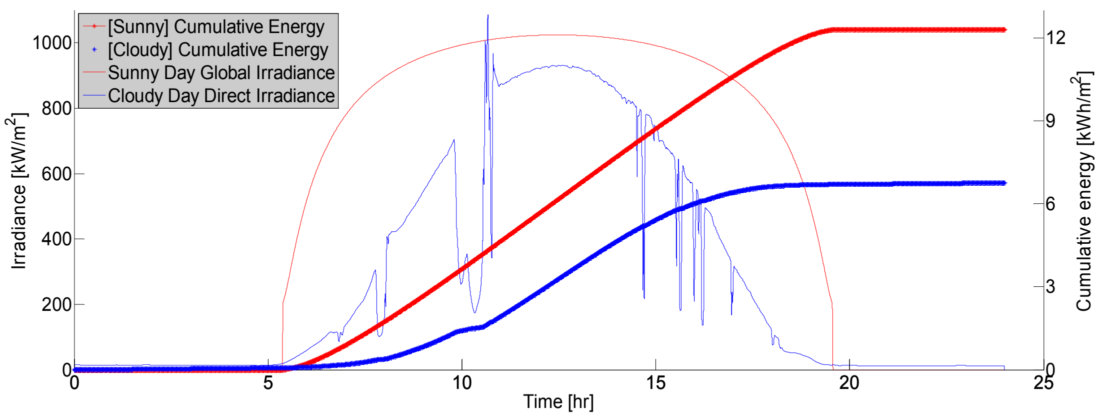

Figure 1. Cloudy day irradiance obtained from Tucson Electric Power (TEP) YARD for July 7, 2013; expected irradiance calculated with SMARTS.

3. SYSTEM DESIGN

3.1 Thermal Model

A simple model for the thermal storage and conversion system is shown in Figure 2. In this model a thermal storage medium (thermal block) absorbs solar radiation and is used to power a thermal electric device (TED) during periods of time when the sun is blocked and the PV output drops.

The incident solar irradiance powers the system and is given by:

$$P_{inc} = (1-R)\eta_{OE}E_S CRA_{T-srf} \tag{5}$$

where R is the power reflection (Fresnel) coefficient of the receiver surface, η_{OE} is the optical efficiency, E_s is the solar irradiance, CR is the concentration ratio, and $A_{T\text{-}srf}$ is the top surface area of the storage block.

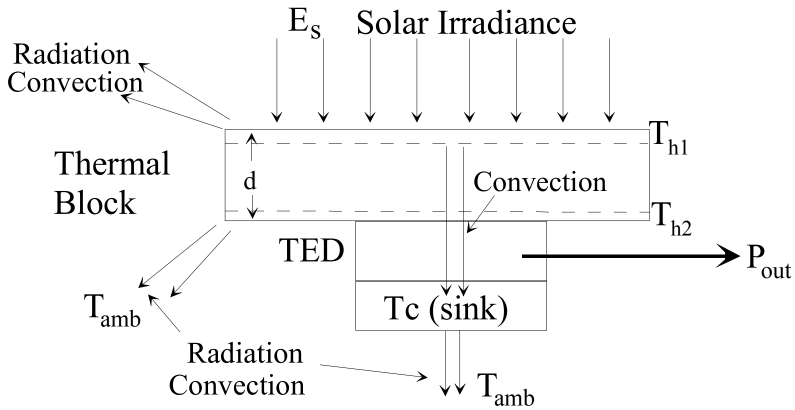

Figure 2. Detail of the input and output powers in a thermal block, with parameters affecting the heat transfer.

A power and energy balance occurs between the incident solar illumination and thermal losses. The balance occurs at a temperature T_H. Losses in the system occur through radiation and convection. The temperature at the back surface of the thermal storage block in general is determined by heat conduction. It is assumed that the back surface is in contact with the TED to produce power by the thermal converter. However for this analysis it is assumed that the storage medium is relatively thin and therefore the temperature at the top and bottom surfaces are equal. In addition to thermal losses the power removed from the storage block by the TED can also be considered a loss and is factored into the energy balance relation. Taking these factors into account the incremental change in energy stored in the thermal block can be expressed as:

$$Q_{i+1} = Q_i + [\alpha \cdot P_{inc} - \varepsilon\sigma(T_H^4 - T_{amb}^4)A_{str-F} - (P_{conv} + P_{TED})] \cdot \delta t, \tag{6}$$

where Q_i is the previous energy stored in the block, α is the absorption coefficient, P_{inc} the incident solar irradiance (eq. 5), ε the emissivity constant, T_H and T_{amb} are the storage temperature and ambient temperature respectively, P_{conv} is the power lost to convection, and P_{TED} is the power utilized by the TED.

The incident solar power that is absorbed and used to increase energy storage is $\alpha \cdot P_{inc}$. Power is radiated from the thermal storage block and to it from the surroundings at the ambient temperature T_{amb} according to:

$$P_{rad} = \varepsilon\sigma(T_H^4 - T_{amb}^4)A_{str-F}, \tag{7}$$

where A_{str-F} is the full area of the thermal storage volume, σ is the Stefan-Boltzmann constant, and ε is the emissivity of the storage medium. For efficient energy storage ε < α. Power is also lost through convection to air molecules surrounding the thermal block according to:

$$P_{conv} = h \cdot (T_H - T_{amb}) \cdot A_{str-F}, \tag{8}$$

where h is the heat transfer coefficient between the medium and air. (It is possible to enclose the storage medium in an evacuated chamber to eliminate this term but this was not done in this analysis.)

3.2 Proposed Hybrid PV-TE Solar converter

Three configurations for the hybrid PV-TE system were evaluated (Figure 3). Model 1 (M1) uses full spectrum on separated areas for the PV and TE conversion devices. The thermal system for each configuration uses a thermal storage block that is insulated on all sides except for the top illuminated surface. This reduces the overall surface area and reduces convection and radiation losses. The TE devices are placed on the bottom of the storage block. Natural convection going through heat sinks attached to the TE devices are assumed to keep the cold temperature of the TE device at the ambient temperature.

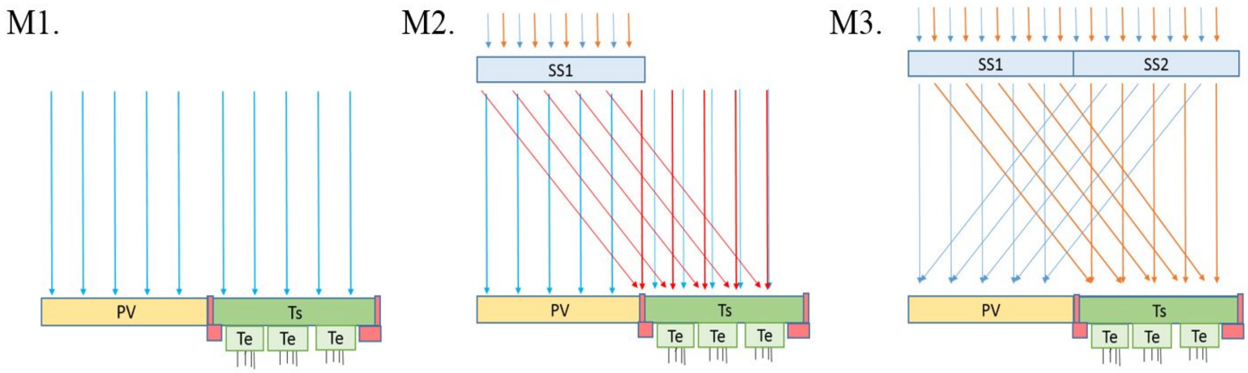

Figure 3. Three configurations for using the available solar illumination: Model 1 (M1) receives direct irradiance without spectral management, Model 2 (M2) uses partial spectrum splitting, and Model 3 (M3) uses full spectrum splitting.

Models 2 and 3 (M2 and M3) include a solar spectrum splitting system. For M2 it is assumed that an ideal spectral transmission filter is used above the PV cell that redirects wavelengths not efficiently converted by the PV cell to the TE device. M3 also has an ideal spectrum splitting filter above the TE device that redirects wavelengths that are more efficiently converted by the PV cell to that device.

The metric used for PV cell performance is the spectral conversion efficiency (SCE)[5,6] given by:

$$SCE(\lambda) = V_{oc} FF\, SR(\lambda), \tag{12}$$

where SR(λ) is the spectral responsivity, Voc is the open circuit voltage, and FF is the fill factor of a particular PV cell. SCE specifies the optical to electrical conversion efficiency as a function of wavelength of a solar cell. The conversion efficiency of a PV cell in a spectrum splitting system can then be computed as:

$$\eta_{pv} = \frac{1}{P_{AM1.5}} \int T(\lambda) \cdot E_{AM1.5}\,(\lambda) \cdot SCE(\lambda) \cdot d\lambda, \tag{13}$$

where T(λ) is the spectral transmittance of the filter incident, $P_{A1.5}$ is the total solar irradiance over all wavelengths for the Air Mass 1.5 solar illumination spectrum, and $E_{AM1.5}(\lambda)$ is the spectral irradiance with AM 1.5 illumination.

The output power required by the thermal electric device to offset the loss in power by the PV system is given by:

$$P_{TE} = \frac{E_S \cdot A_{PV} \cdot \eta_{PV}}{\eta_{TED}} \cdot F_C,$$

where E_s is the solar irradiance, A_{PV} is the area of the PV system, η_{PV} is the efficiency of the PV system, F_C is the fraction of the intermittency that is offset by the TE system, and η_{TE} is the efficiency of the TE device. An $F_C = 1$ implies that the full intermittency power loss is offset by the TE device.

4. MODELING AND SIMULATION RESULTS

Table 1 indicates the different types of materials that were considered for the thermal energy storage medium. A thermal storage volume with 1 m^2 top and bottom surface areas and thickness of 0.1 m was simulated using the different materials given in Table 1.

The thermal energy from the thermal storage block without the TED in Figure 4(a) shows that a block, at an initial temperature of 100 ˚C will decrease to ambient temperature (25^{o}C) in 2.56 hours if there are no external energy inputs and no thermal insulation of the block. Convection losses represent 95% of the losses. Figure 4(b) shows the temperature of the thermal storage block with different materials when illuminated with SMARTS2 data for January 1st, 2014. It can be seen that the temperature increases until equilibrium is reached between the incident illumination and convection and radiation losses.

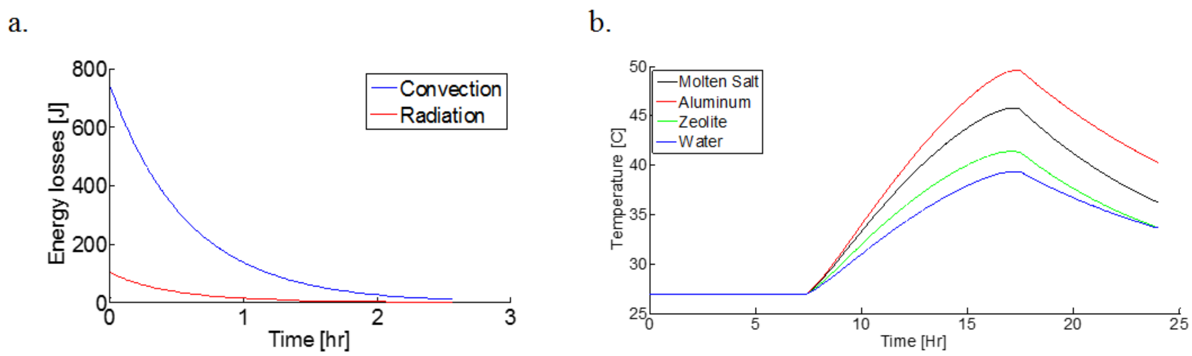

Figure 4. (a) Thermal storage energy decay due to convection and radiation. With no input of energy, a $0.1m^3$ block of aluminum of $0.1m^3$ takes 2.56 hours to go from 100 ˚C to 25 ˚C. (b) Maximum temperature for the same size thermal storage with standard solar irradiance, for different materials.

The duration of intermittency in the solar illumination that can be offset by the thermal electric system or dampening time is estimated according to:

$$\tau_D = \frac{Q_{stored}}{P_{out}},$$

where Q_{stored} is the total energy stored in the thermal block after some period of time and P_{out} is the power required by the PV system. The result in the following section illustrates values for Δt that can be obtained under different illumination and PV output power requirements. Also shown is the effect of using spectrum splitting between the PV and thermal conversion systems for improving intermittency compensation.

Table 1. Properties for materials modeled.

	$\boldsymbol{\rho}$ Density [Kg/m3]	C_p Heat capacity [J/Kg C]	$\boldsymbol{\varepsilon}$ Emissivity coef.
Water	1000	4190	0.95
Al	2700	920	0.08
Molten salt	1680	1560	0.44
Zeolite (Clioptilolite)	1120	3000.8	0.92

Table 2. Thermal storage properties for the different models and materials.

Systems	SMARTS2 Irradiance			Real Irradiance		
	Q_{MAX} [MJ]	τ_{MAX} [C]	$T_{D\text{-}MAX}$ [min]	Q_{MAX} [MJ]	T_{MAX} [C]]	$\tau_{D\text{-}MAX}$ [min]
M1 – Molten Salt	13.54	78.66	15.3	15.37	66.43	9.2
M1 - Aluminum	15.29	89.93	20.75	16.84	75.49	12.72
M1 - Zeolite	13.32	66.64	11.8	15.71	54.83	6.03
M2 – Molten Salt	15.84	87.42	20.48	-	-	-
M2 - Aluminum	17.98	101.01	28.02	-	-	-
M2 - Zeolite	15.56	73.29	15.8	-	-	-
M3 – Molten Salt	04.91	45.77	2.08	-	-	-
M3 - Aluminum	5.5	49.64	2.97	-	-	-
M3 - Zeolite	4.85	41.4384	1.73	-	-	-

Table 2 is a summary of the maximum energy stored per day and corresponding maximum temperature of the block when illuminated without concentration. Standardized illumination using SMARTS2 spectral irradiance values as well as measured data from a field test system in Tucson Arizona for January 1st, 2014. Also shown is the maximum dampening time ($\tau_{D\text{-}MAX}$) that the thermal storage block can compensate a 200W PV module (or indicate how this dampening time is defined).

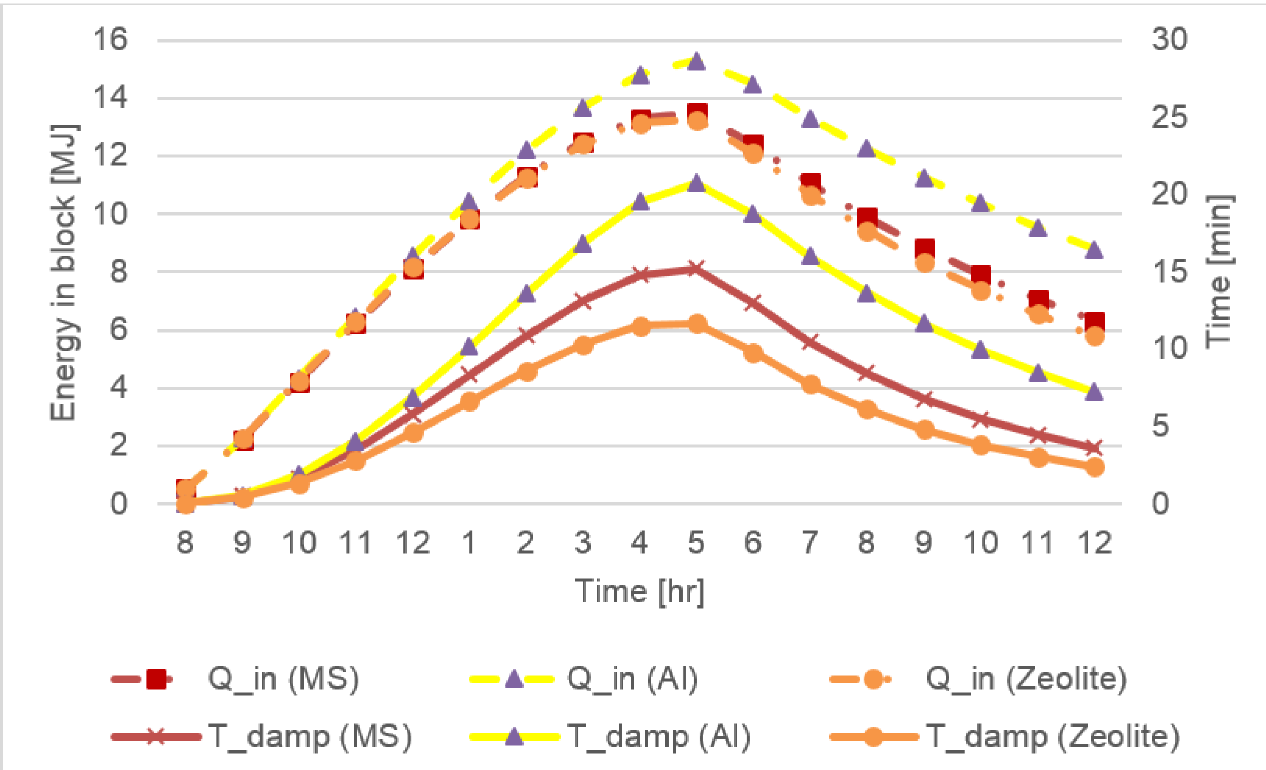

Figure 5. Energy available in the thermal storage at different hours throughout the day (M1). Different materials in a block of 1m^2 of surface area and 0.1m of thickness where simulated. The secondary axis shows the time an intermittency could be offset by the available energy.

The different models receive different amount of irradiance, which affects the energy stored as seen on Table 2. Figure 5 shows the energy stored in the block for different materials, and the time it would be able to match the PV system expected output to cover for any occurring intermittencies. Of the materials simulated, aluminum had the best properties due to its low emissivity values, reaching a maximum temperature of 89.9 ˚C which can provide a dampening time of 20.75 minutes.

In Figure 6 an intermittency of 8 minutes was assumed to occur at noon for a 200W PV module (20% efficiency for 1m^2). The power output drops immediately for the PV system, but it is operating in parallel with a M1 TE system with a 1.0m^2 X 0.1m aluminum storage block. The storage block can provide 6.2 minutes of energy when illuminated until 12 noon offsetting effectively 77% of the intermittency. The power drain depletes the stored thermal energy but with continued illumination the storage block temperature and stored energy increases again although not to the level achieved during the initial illumination period as shown in Figure 6 (a). In the example provided, if there were no clouds the panel output would be of 1809.5 Wh, but with clouds it is only 1780.22Wh; the TED could provide 22.7 Wh of this 29.2 Wh that are lost during the cloud coverage, improving the system output during clouds by 1.25%. More importantly the intermittency is reduced by 77%.

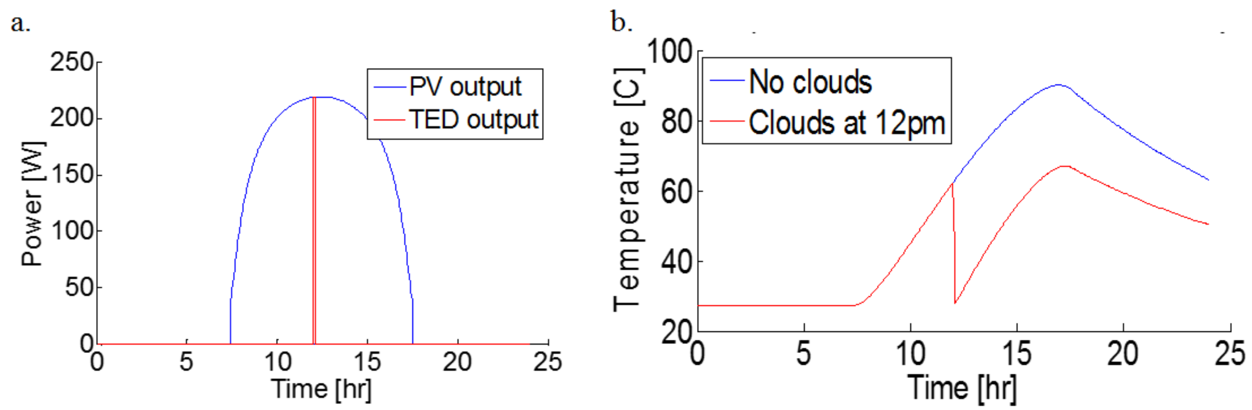

Figure 6. Behavior of a PV-TE system (M1), during an intermittency lasting 8 minutes that occurs at noon on 01/01/2014. (a) Shows the output power contributions by the PV and the TED. (b) Shows the temperature evolution of the Thermal storage, which decays during the intermittency by the TED using its stored energy.

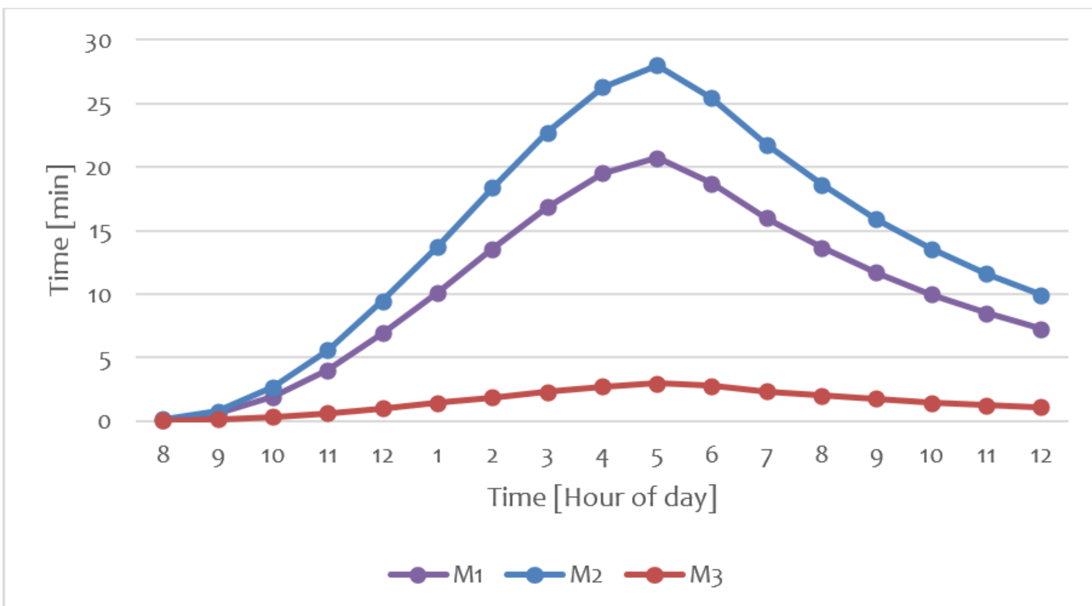

Figure 7. Dampening times provided by different illumination configurations.

The dampening times for the different illumination configurations illustrated in Figure 3 were computed in combination with a hybrid PV-TE system (200W PV with an aluminum storage block $1m^2$ X 0.1m) and shown in Figure 7. A spectral filter cut-off wavelength for the spectrum splitting systems was set at 900 nm. The longest dampening times occur for system M2 which redirects the part of the spectrum below the PV cell bandgap to the TE device. The significantly shorter dampening times of system M3 results from the higher efficiency and output power of the PV module and less power being used to store energy in the thermal block.

5. CONCLUSION

A hybrid PV-TE system with a thermal storage block was evaluated for use in offsetting intermittency in PV system output. It was found that intermittency dampening times of up to 20 minutes can be obtained under ideal thermal storage and TE device operation. The disadvantage of the system is that it requires a charging time, and depending on the time of day the intermittency occurs the fraction of the intermittency that can be covered is significantly reduced. However it is still possible to offset several minutes of intermittency. It was also found that partial spectrum splitting provides the most benefit for the hybrid system. In addition although aluminum showed the most benefit as a storage medium due to its low emissivity, molten salt and zeolite also provide significant thermal storage and hybrid system dampening times and would provide a more cost effective storage medium.

6. ACKNOWLEDGEMENTS

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