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MODEL OF LOSS MECHANISMS FOR LOW OPTICAL CONCENTRATION ON SOLAR PHOTOVOLTAIC ARRAYS WITH PLANAR REFLECTORS

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ABSTRACT

The use of low optical concentration with planar reflectors represents a relatively simple method for improving solar photovoltaic (PV) specific efficiency. A coupled optical and thermal model was developed to determine the effects on yearly performance of a planar concentrator on array-scale solar PV installations. This model accounts for i) thermal, ii) angle of incidence, iii) reflectivity, and iv) string mismatch loss mechanisms in order to enable informed design of low optical concentration systems. A case study in Canada is presented using the model and the simulation results show that a planar reflector system installed on a traditional crystalline silicon-based PV farm can produce increases in electrical yield from 23-34% compared to a traditional optimized system and thus represents a potential method of achieving practical gains in PV system yield.

1 INTRODUCTION

Photovoltaic (PV) electricity production represents a sustainable form of electricity generation that has the potential to provide a significant portion of a sustainable energy mix (1). Installed costs have consistently declined and are predicted to continue into the future (2). Currently the PV industry is dominated by crystalline silicon (c-Si)-based PV technologies, where the cost of the modules accounts for half of the total installed cost of the system with the largest cost fraction is the c-Si cells in the module (3-4). Making the most efficient use of the PV modules is thus a clear method of decreasing the costs of generating electricity using PV. The primary metric of system efficiency is the specific efficiency, defined as produced energy (kWh) per installed rated power (kW). The baseline for comparison is a stationary solar array, which operates in a fixed orientation and trades a low

specific efficiency for low balance of systems (BOS) and low operational & maintenance (O&M) costs. Tracking systems increase the specific efficiency at the cost of moving parts, which increases both initial BOS costs and continuing O+M costs throughout the systems lifetime. Another methodology for improving the specific efficiency of a PV array is the use of optical concentration, where solar insolation falling in the area around a PV device is concentrated onto the device itself.

Low concentration methods increase incident insolation by <10X and include compound parabolic concentrators (CPC), V-trough concentrators or flat planer concentrators also known as boosters (5). Flat planar concentrators are reflecting surfaces which increase the collecting area and ultimately increase the energy yield of a PV array and have the advantages of being inexpensive compared to both V-trough and parabolic reflectors, while providing a constant illumination over a large area (e.g. an entire PV module). Planar concentrators have been studied extensively for solar thermal collectors and have been found to substantially increase the energy yield (6-8). In addition, there have been some studies into the performance of planar reflectors joined with PV systems (9-15). These studies have performed experimental or theoretical investigations into the effects of positioning a reflector with respect to a PV panel to maximize insolation, and have shown increases in performance of 20-30%. To date, work still must be completed to understand the loss mechanisms associated with reflector systems specifically when applied to a PV system, and how low concentration systems can be optimized to account for such losses. This paper will provide a theoretical model of the loss mechanisms.

A conventional PV array in the northern hemisphere

consists of multiple east-west rows containing southern facing PV panels. Depending on economic variables, the rows are spaced in the north-south direction by an amount to minimize row to row shading during periods of low solar altitude in the morning and night. However during times of high solar altitude the spaces between the array are illuminated, and at the time with the greatest solar potential (solar noon) the largest area between these panels is not utilized, flat planar concentrators allow this unused energy to be captured by the PV panels.

This study expands on previous work in planar concentrators, to create a model that more fully analyzes the loss mechanisms inherent in this concentration technique including i) thermal, ii) angle of incidence, iii) reflectivity, and iv) string mismatch loss mechanisms. This model is applied to a case study of a planar concentration PV system appropriate for use in Canada. Results are presented and discussed in order to provide a framework for the design and optimization of these systems.

2 THEORETICAL MODEL

Here a theoretical model is developed to predict the output of a low-level concentration system implemented at an array scale. Array scale refers to a plurality of rows of solar panels as would normally be arranged in a commercial or utility-scale PV system.

This model is based upon the basic assumptions that the entire reflector system can be modelled in two-dimensional space as shown in Fig. 1. (10) Because the concentration system is to be implemented on an array scale, rows are expected to be long in comparison to the width of the reflector, and it is assumed that at the edge of rows the reflective surface will be extended in order to eliminate uneven illumination at periods of high solar azimuth angles. The rays simulated in this algorithm therefore are the projection of solar rays incident on the reflector onto the plane normal to the reflector at a representative point in the mid-region of the array. Because the optical path length of the reflected rays is short, the effects of increased air mass on light attenuation are assumed to be negligible. In addition, at periods of highest insolation the solar azimuth angle is lowest, as it is symmetrical around solar noon, and therefore this abstraction is assumed to have a low impact on the performance of the algorithm.

In order to ensure that the performance of the model is independent of a specific PV technology or module, the actual electrical output of the modules in the system is not calculated and is left for future work. Instead, the effective insolation in the plane of the PV panel is calculated, taking into account all losses, which are described in this paper.

This insolation is compared to a stationary PV system oriented at the optimal angle for the region in which it is installed.

2.1 Design domain

The design domain for the system is shown in Fig. 1. In the proposed model, the absorber area is broken into two

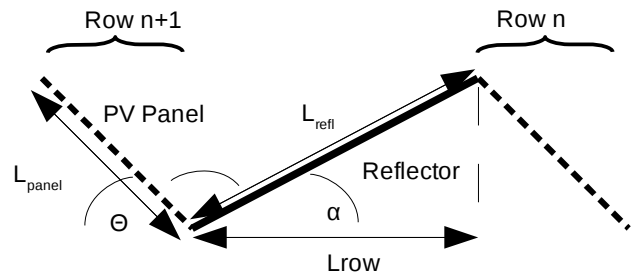


Fig. 1: Graphical representation of the design domain

separate zones as shown in Fig. 2, each representing an entire PV module. The entire model depends on the physical variables of θ_{panel} , the tilt angle of the PV panel array in relation to the horizontal, L_{row} , the spacing between adjacent rows, and L_{panel} , the total height of a stack of two modules. It is assumed that the reflector connects the top of the previous row to the base of the PV modules in the row being investigated. Thus, L_{refl} , the length of the reflector and α , the angle of the reflector with respect to the horizontal, are derived from the three main variables. It is acknowledged that a practical systems would have to allow for panel access, snow clearing, etc., however the current abstraction is assumed to be representative of a more complex and realistic system.

Other inputs of the model are the direct and diffuse insolation for the region. Here this model was applied to a specific case study in Kingston, Ontario and used experimental solar flux data obtained from the Solar Calorimetry Laboratory at Queen's University. This data was collected over the years of 2009 to 2010 using two Eppley PSP pyranometers, one of which is shaded with an adjustable shadow ring which was nominally adjusted weekly. There were some periods in the year where the shadow band was not properly adjusted, and data from the following year was substituted in these cases in order to ensure a proper prediction of beam radiation.

2.2 Logical Flow of theoretical model

The model was developed in Matlab 7.7-R2008b, and initially inputs and formats collected direct and diffuse irradiation for an entire year, and extracts date and time

values from the data set. These time values are used in conjunction with solar angle formulae obtained from Duffie et al. (16) and the latitude and longitude of the site to calculate the solar zenith and azimuth angles for each data point. Based on the angle of the reflector and solar zenith angle, the effective aperture is calculated as the area of the projection of the reflector plane onto the normal of the incident light rays at the top of the reflector, which determines the total power that can be reflected by a unit length of reflector. Only beam radiation is considered to be collected in this manner.

$$F_{PV-Refl} = \frac{R+1 - (R^2 + 1 - 2R \cos(\beta))^{\frac{1}{2}}}{2} \quad (1)$$

where β is the included angle between the two planes and R is the ratio of L_{refl} to L_{panel} .

Once the total insolation useful for electrical production and thermal effects on the plane of the PV panel has been determined, thermal and AOI losses are applied as

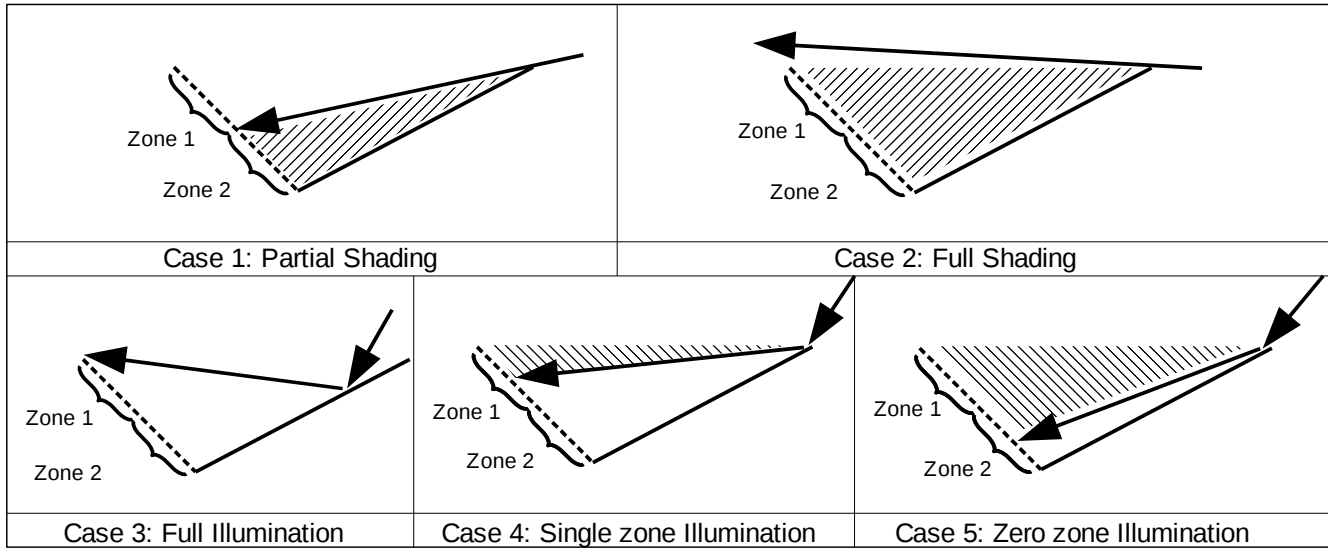


Fig. 2: Illumination cases utilized in the theoretical model

The zenith angle is then used in a geometric ray tracing algorithm developed for this purpose to locate the top edge of the reflected ray on the row of PV panels. In this model five illumination cases are utilized as seen in Fig. 2. In Case 1 the PV modules are partially shaded, but each individual module is not partially shaded, thus eliminating the need to calculate current mismatches. In Case 2 all of the PV modules are completely shaded by the reflector. If the ray lands within the row of panels (Case 4 and 5) string mismatch losses are applied as described later in this paper. If the top of the ray lands above the row of panels (Case 3), the fraction of reflected power is considered to be proportional to the fraction of the ray that is contained on the row of panels, multiplied by the reflectivity of the reflector.

Diffuse insolation on the plane of the reflector is calculated using the isotropic sky model (17). It is assumed that this radiation will be reflected diffusely onto the plane of the PV panels, and the view factor between the two planes is (19):

described in the following sections to determine the total effective power in the plane of the PV panels.

2.3 Factors effecting insolation on a PV panel

In order to effectively model and optimize the energy production of a PV module the following factors must be taken into account: i) the total insolation on the panel surface, ii) angle of incidence, iii) panel temperature, and iv) spectral distribution (20). In low concentration systems there is the additional effect of v) string mismatch and vi) reflection losses. The total insolation, AOI, reflection losses, string mismatch, and temperature effects are dealt with implicitly in the code via optics and the thermal effects of increased radiation, and spectral distribution is dealt with through the normalization of the data set, which is explained further in section 2.3.6. The goal of this methodology is to create a linear relationship between irradiation and panel performance, thus eliminating the need to limit the model to the response of a particular panel. These losses and their treatment are described fully in the sections below

2.3.1 Thermal losses

It has been shown that the open circuit voltage will decrease proportionally to optical concentration, due to the increase of cell temperature (21). As a result, increasing temperatures are known to decrease PV cell efficiency, and further, long-term degradation is seen for cells if temperature exceeds a certain limit (22).

Previous work has shown a temperature difference between operating panel temperature and ambient of 40-45°C and 50-55°C with concentrations of 1.6X and 2.2X respectively with no active cooling, compared with a temperature difference of 28-32°C for panels at 1X concentration (23). Reis et al. demonstrated that as long as a maximum ambient temperature of 40°C was not exceeded, it was possible to have 2X concentration without surpassing maximum cell temperatures of 80°C without cooling (24). Following these system designs, no cooling system was considered here.

Thermal effects are modelled utilizing the Sandia thermal model, which is a simplified and robust methodology for calculating the relationship between insolation and panel temperature rise, and has been shown to have an accuracy of $\pm 5^\circ\text{C}$ (20). The model has been modified from its original form to yield the rise in temperature that can be attributed to added insolation from the reflector.

$$\Delta T = E_{refl} \{e^{a+b \cdot ws}\} \quad (2)$$

Where a and b are empirical constants determined by Sandia; for a c-Si PV panel in an open rack configuration the values of a and b are -3.56 and -0.075 respectively. The value for ws is the yearly average wind speed. For the case study in Kingston, Ontario, $ws=5.4$ m/s.

The value of ΔT represents the increase in panel temperature above the operational cell temperature for a PV module with no concentration due to reflected insolation. Thus, to determine the effective decrease in panel output, this value of ΔT is multiplied by the temperature coefficient of the panel being modelled. In this case study the module is a standard c-Si module with a temperature coefficient of -0.5%/°C.

2.3.2 Reflectivity losses

Sheets of anodized aluminium were chosen as reflectors for the initial test of this model. These reflectors have good mechanical properties, relatively low costs, high specularly, and provide a solar reflectance of approximately 90% (25).

2.3.3 Angle Of Incidence losses

There is often a substantial difference between normal incidence (assumed at standard test conditions) and the

actual angle of incidence of solar radiation in the field (IEC 904-1 International standard). Therefore, in some cases substantial reflective losses can occur. An analytical model for determining AOI losses, applied to 10 different European sites has been developed (26). Based on testing performed on commercial modules at Sandia laboratories (20), the effects of AOI are relatively low at angles below 55 degrees, however they increase dramatically beyond this point. The relationship was modelled by a sixth degree polynomial based on information provided in (20), and is displayed graphically in Fig. 3

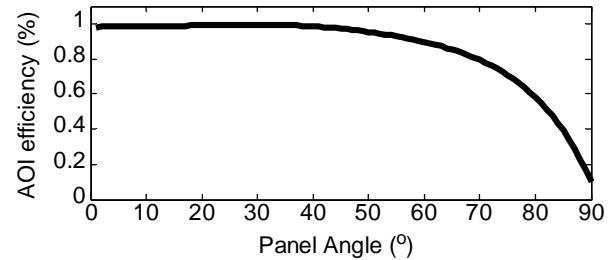


Fig. 3: AOI efficiency measured from commercial panels (20)

2.3.4 String mismatch losses

Non uniform cell insolation causes mismatch losses in solar PV arrays, and can occur due to manufacturer's tolerances in cell characteristics, environmental stresses, and shadowing (27). In the case of shadowing, the percentage power loss is much greater than the percentage of the array area that is shadowed (27). A shadowed cell in a series connection not only affects the power output of the array by blocking the current flow, but it tends to become reverse biased. Reverse bias can cause heat dissipated from the shadowed cells to damage the encapsulation or crack the cell, ultimately leading to module failure. Bypass diodes across individual cells or groups of cells are used to reduce these problems.

Therefore, string mismatch losses can have a significant effect on the performance of a PV module under uneven illumination. In the proposed model, the absorber area is broken into two separate zones as shown in Fig. 2, each representing an entire PV module. The conservative assumption made is that if the entire face of a panel is not uniformly illuminated by the reflected insolation, it will not register any increase in insolation. Thus, until the top of the reflected ray passes the top of the module, the increase due to performance is not registered.

For the purposes of the thermal model the reflected insolation is still considered to reach the panel, thus in the case where a module is only partially illuminated, thermal losses will be incurred due to the increase in panel temperature, while no electrical performance increases will be recorded.

2.3.5 Planar insolation

The Perez et al. model is utilized as the standard methodology of irradiation translation onto the tilted plane of the PV module (28). This model has been previously validated to have a high accuracy in a wide variety of applications, and requires the available inputs of direct and diffuse irradiation. When determining the planar insolation on the reflector, the albedo term is dropped from the model and replaced by the low concentration model.

In addition, the Perez model is used with the albedo term included to determine the theoretical maximum insolation on a PV array with no concentration, oriented at the optimal tilt angle for the case study in Kingston of 37 degrees. This insolation is used as the base to which the low concentration data set is normalized to determine the theoretical performance boost.

2.3.6 Spectral effects

The solar spectrum varies based on the solar Air Mass (AM) and presence and optical thickness of cloud cover (29-30). The irradiation values used were measured from an thermopile pyranometer ,which integrates the irradiation received evenly over wavelengths from (200nm to 3600nm) (30). However, the spectral response of c-Si panels is variable over the range of (300nm to 1100nm) due to a band gap of 1.1 eV (31), therefore as the solar spectrum changes there is not a constant relationship between measured integrated irradiation and PV module output. Recent work has shown this can create large errors in estimated output even for the response of PV to albedo (32). In order to account for this, normalized performance values are utilized in this comparison, assuming that the spectrum of incident and reflected light are equivalent. Therefore, when the predicted reflected insolation is normalized by the insolation calculated for the base case of an optimal static PV system at any given data point, any losses due to spectral mismatch will be eliminated. This allows a direct relationship between insolation and panel output when used in a normalized comparison.

2.4 Relating insolation to panel output

All the previous loss effects are applied directly to the module insolation and not electrical output. According to the Sandia performance model, the relationship between insolation and PV output is linear at a constant spectral distribution, temperature and AOI. Thus, a shift in module insolation due to temperature and AOI loss factors will cause a proportional shift in PV output, assuming that spectral effects are removed through normalization. Using this technique removes any dependance on a specific module beyond its temperature degradation coefficient.

3 RESULTS AND DISCUSSION

This model was implemented and a sensitivity analysis was performed in order to determine the largest possible output from a low concentration planar reflector system. The module height was considered to be fixed at 2000mm, representing two c-Si modules stacked in a landscape orientation. Initially, the row spacing was fixed at 1.75 times the panel height, and a series of tilt angles from 20 to 90 degrees were simulated. These simulations demonstrated the sensitivity of output ratio to the panel tilt angle, and the results are shown in Fig. 4.

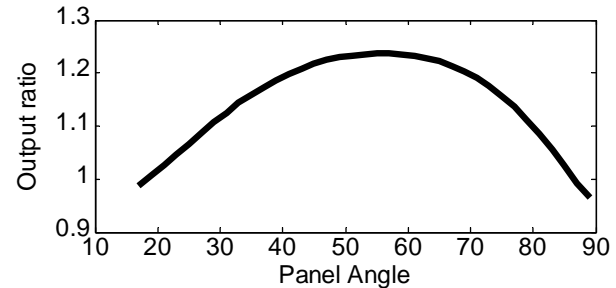


Fig. 4: Output ratio of a reflector system with a $L_{row}=3500$ mm

Fig. 4 demonstrates that for this row spacing, the maximum output ratio is achieved at 57 degrees. This panel angle was then taken to be fixed, and the row spacing was varied from 1000mm to 5000mm, and the sensitivity of output ratio was again determined and can be seen in Fig. 5.

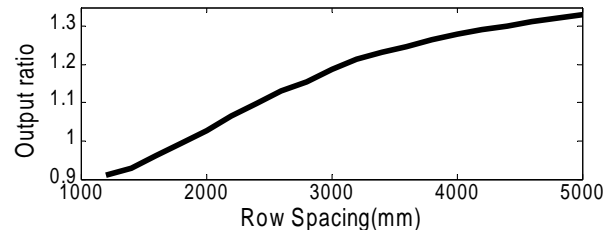


Fig. 5: Output ratio of an array with $\theta=57$ as L_{row} varies

Fig. 5 shows that there are diminishing returns for increasing row spacing above 3500mm, however it can be seen that increasing row spacing can continue to increase output. The final selection of row spacing would depend on an economic analysis of reflector and support costs and required packing factor versus increase in boost. For this study 3500mm was chosen as the row spacing. Future work is needed to do a full 3D optimization of the system.

The weighted average of output ratio, defined as the ratio of predicted in-plane and reflected insolation to the insolation on the base case of a system oriented at 37 degrees in Kingston, Ontario is shown as it varies throughout a representative year for a system with panel angle of 57

degrees and row spacing of 3500mm in Fig. 6.

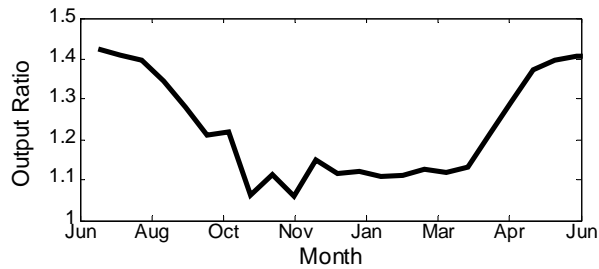


Fig. 6: Yearly output ratio for array with $\theta=57$, $L_{row}=3500$ mm

Fig. 6 shows that the maximum output ratios occur during the summer months. This distribution allows the concentrator to take advantage of the higher beam ratios that exist during these times of the year.

It can be seen from the results that a planar low concentration system at 57 degrees and row spacing of 3500mm can be expected to produce up to 23% more output than an optimal non-concentrating system located in Kingston, ON, Canada. Further, it is possible to produce increases of up to 34% by increasing the spacing between rows.

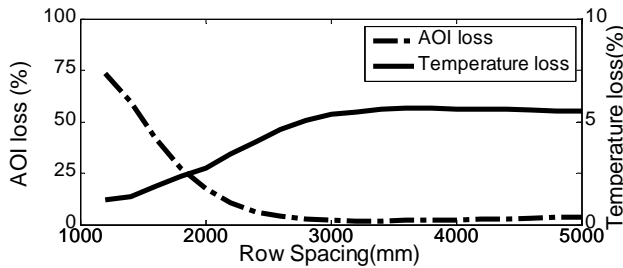


Fig. 7: Variation of AOI and temperature losses with increasing L_{row} for $\theta=57$

It is important to understand how the mechanisms that produce losses in this system are effected by changing design parameters. Fig. 7 and Fig. 8 show the response of AOI and thermal losses to changes in row spacing and panel angle respectively. These figures will be discussed in the following sub-sections in detail.

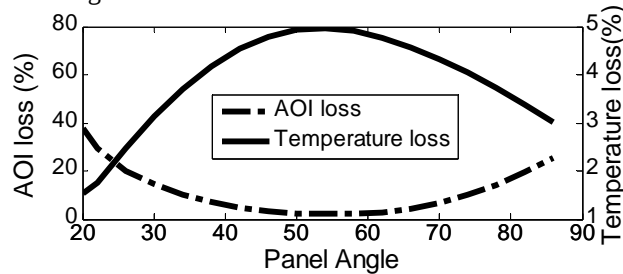


Fig. 8: Variation of AOI and temperature loss with increasing panel angle(θ) for $L_{row}=3500$

3.1 AOI losses

It can be seen that the AOI loss mechanism responds similarly to changes in panel angle and row spacing. In the case of row spacing, a low row spacing represents a very steep reflector angle, causing reflected rays to impact the panel at high angles. As the row spacing is increased, the reflector angle decreases causing the angle of incidence of the rays to decrease as well. Because of the asymptotic nature of AOI losses as described in section 2.3.3, the AOI losses decrease quickly as the row spacing is increased until around 3000mm, after which row spacing has relatively little effect on AOI losses. It should be noted, however that AOI losses begin to increase slightly after a row spacing of 4000mm, this is due to a low reflector angle being able to accept light at higher zenith angles, which in turn will impact the panel at a high AOI.

As the panel angle increases, because of the definition of the design domain, the reflector angle also increases according to sine of the angle. As the panel angle increases up to 60 degrees, the angle of incidence between reflected rays and the panel decreases, however after this point the angle of the reflector is effected to a greater extent and the AOI loss again begins to increase.

3.2 Thermal losses

The thermal losses in the PV panel in this array are dependant on the intensity of the reflected irradiation on the face of the PV modules. Fig. 9 shows the distribution of maximum increase in temperature and associated thermal losses for a c-Si PV module at 57 degrees from horizontal and 3500mm row spacing.

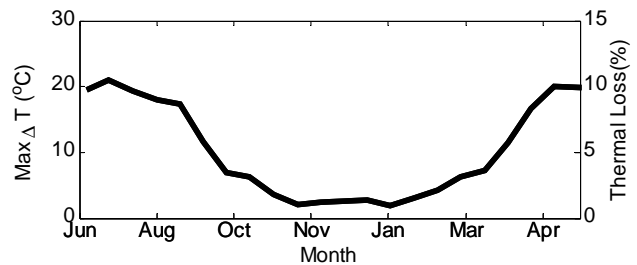


Fig. 9: Yearly maximum temperature increase due to reflected radiation and associate thermal losses

Because thermal losses are dependant on the light absorbed by the surface of the cell, thermal losses show an inverse trend to the AOI losses, as AOI losses represent insolation that is reflected from the surface of the module. In the case of increasing row spacing, it can be seen that the thermal losses increase in proportion to the AOI losses, but then plateau at around 3500mm even though the output ratio after this point is increasing, indicating that the amount of useful insolation is increasing on the module. This effect is

due to string mismatch losses; as the reflector length is increased, there is a larger window of time where the entire row of panels will be illuminated, reducing string mismatch losses and increasing electrical output. Because these gains are not related to an increase in solar insolation on the plane of the module, but to the electrical characteristics of the panel, ΔT remains relatively constant. After a certain point, the thermal losses begin again to decrease, and this is due to the increase in AOI losses at the larger row spacings.

In the case of the angle sensitivity, the temperature losses can be seen to be inversely proportional to the AOI losses.

3.3 String mismatch losses

String mismatch losses have been seen to interact with both the AOI and thermal losses in the model. The effect of string mismatch losses is to favour reflector geometry that ensures complete illumination of the modules for a large portion of the day. This can be achieved both through a larger row spacing, which produces a wider reflected ray, or through a decreased panel tilt angle. However, as previously discussed decreasing the panel tilt angle will also increase AOI losses. Therefore, generally the inclusion of string mismatch losses will favour larger row spacing.

It should be noted that these losses could be reduced by increasing number of stacked modules, which would increase the resolution of the segmentation. Also, the use of amorphous silicon based solar modules, with cells located perpendicular to the horizontal would reduce these losses by producing output proportional to the fraction of light on the panel. In addition, low voltage independent string modules would decrease this loss. However, two modules were chosen because this is the most likely layout for a commercial farm, as increasing to three module stacks would require a 9m row spacing and ~10m reflector. Here a system design was modelled which reduces these losses in a practical implementation of the system without requiring specialized modules.

The Queen's Applied Sustainability Lab aims to conduct further experimental work, with low concentration on the array scale. Confirming the model shown here as well as analyzing further methods to decrease the losses discussed in this paper. Ultimately, the aim is to combine knowledge of low concentration, snow effects on PV and the application of different technologies that minimize array scale losses, to determine an optimal array setup, maximizing efficiency and widespread PV commercialization.

4 CONCLUSIONS

This study has shown the theoretical framework for

modelling a planar concentrator on an array scale PV installation. This model thoroughly accounts for loss mechanisms in this system including thermal, angle of incidence, reflectivity and string mismatch in order to allow for informed design of low concentration PV systems.

A case study in Canada was performed with this model and the simulation results show that a planar reflector system installed on a traditional c-Si PV farm can produce increases in electrical yield from 23%-34%. Because of the simplicity of this system compared to tracking and parabolic concentration techniques it is predicted to be an effective method of achieving practical gains in specific efficiency and energy yield in Canada.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the Natural Sciences and Engineering Research Council of Canada.

6 NOMENCLATURE

A	Angle of reflector to horizontal (°)
θ_{panel}	Angle of PV panel to horizontal (°)
L_{row}	Length between rows (mm)
L_{panel}	Length of the PV panel (mm)
L_{refl}	Length of the reflector (mm)
$F_{\text{PV-Ref}}$	View factor of PV panel to reflector plane
β	Included angle between PV panel and reflector plane (°)
E_{refl}	Power reflected onto the plane of the PV panel (W)
a	empirical constant for sandia temperature model
b	empirical constant for sandia temperature model
ws	Wind speed (m/s)
AOI	Angle of Incidence (°)
ΔT	Increase in temperature (°C)

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