SHADING CALCULATIONS FOR THE BIG DISH

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Abstract

The Australian National University has re-engineered its Big Dish design for commercialisation and mass production [1], building the 'SG4' 500m^2 Big Dish solar paraboloidal concentrator for solar-thermal to electric energy conversion using direct-steam generation. The SG4 Dish implements two-axis tracking and may be incorporated into a dish-array for large-scale power production.

A program has been created for modelling the annual shading fraction in an array of two-axis tracking collectors. Annual shading on the SG4 dish included into an array of a specific shape with a pre-defined energy transport network was simulated for a site location of Canberra, Australia. Annual shading fraction was calculated in order to optimise dish spacing for reduction of the energy transport network pipe length. Results shows that dish separations can be altered to reduce pipe length by 11.6% for the proposed array without introducing further losses to the system.

1. Introduction

Array shapes have been proposed by Carden and Bansal [2] based on optimisations of energy transport networks (see [3]) for steam delivery to regularly-spaced point-focus distributed receivers (PFDR). Array costs were minimised with respect to optimal pipe dimensions and pipe insulation thickness that were determined subject to fluid friction and thermal energy losses from the steam medium. For a given energy transport network, these losses may be reduced by closely spacing collectors within the array.

Another form of loss arising in fields of PFDR's is shading from nearby collectors. Pons and Dugan [4] minimise annual shading fraction in a field of dish-Stirling systems for a given ground-cover ratio[1], *g*, as a function of NS and EW dish spacing for a 10×10 array of circular aperture dishes. Similarly, Igo [5] performs an economic analysis of a large dish-Stirling field by simulating a dish-field with separation determined as that of the Model Power Plant in Albuquerque, USA. Staggering of dish rows is simulated and it is found that an unstaggered layout is optimal, justifying exploration of dish spacing parameters constrained to the NS and EW directions. Carden and Bansal cited dish spacing to render shading loss as negligible, citing the work of Osborn (1980)[2] for spacing in the North-South (NS) and East-West (EW) directions, respectively. However, by further quantifying the shading losses for different dish separations within the given array shape, an optimisation of NS and EW dish separation can be tailored to minimise total pipe length in the predetermined energy transport network subject to an an admissible loss due to annual collector shading.

Edwards [7] presents an optimisation of dish spacing for a square array shape of collectors for distributed steam generation, with spacing parameters limited to a square lattice. Cited in this work is a direct radiation model used to evaluate insolation. Results are obtained for 20 equi-spaced days throughout the year. Optimal ground-cover ratio of the array is determined subject to shading and energy transport losses for the energy transport network presented by Williams [8]. The present work extends this parameter space to model independent NS and EW spacing. This allows minimisation of overall pipe length for a given energy transport network by accounting for the different occurrence of pipe segments in the respective directions

1 Ground-cover ratio is the ratio of collector aperture area to of total ground area covered by the array.

2 This reference was unable to be located. For a brief description of Osborn's shading algorithm, see Appendix G in the PhD Thesis by Fraser [6].

(see figure 2, where NS pipe segments outnumber EW segments by more than a factor of 6.)

In this study, a program for calculating the annual shading fraction of total insolation using sun-position algorithms or weather data has been created. It has been applied to the problem of minimising pipe length in the array proposed by Carden and Bansal by calculating the annual shading fraction of total insolation in Canberra, Australia on this array. NS and EW separation of collectors are altered and total shading and pipe length are determined for the array shape and energy transport network presented. The array in the simulations comprises PFDR's with the aperture shape of the ANU 'SG4' Big Dish. From the data simulated, NS and EW dish separation for minimisation of pipe length for a range of annual shading fractions is calculated, and it is found that total pipe length can be reduced without introducing further losses from shading.

2. The Shading Program

The program for simulation of annual shading was created using Python with matplotlib and numpy exensions for MATLAB-like matrix maths. It is capable of conducting annual shading calculations for a user defined dish-field shape and dish spacing. Modelling shading for general array shapes and general dish placements for regularly spaced arrays is also possible. Weather data may be parsed and used to determine solar azimuth angle, zenith angle, and direct normal insolation. In the absence of weather data, a sun-position algorithm presented by Grena [9] has also been included.

2.1 Program Limitations

This program performs calculations of annual shading fraction under the assumption that only shading from dishes directly adjacent to a given dish, or first-order neighbours, are significant. It has been demonstrated that higher-order neighbours account for shading of less than 2% of total intercepted energy [10]. This saves computation time by determining the combinations of first-order neighbours in the given array and the number of times each combination appears. The number of shading calculations required for a given time interval is then reduced to calculating the shading for each neighbourhood combination.

The program is capable of performing calculations only for arrays situated on a flat surface.

Tracking error is not included in the program and may further introduce uncertainties into the simulations.

There is currently no model implemented for simulating direct normal insolation when calculating array shading based on the sun-position algorithm.

2.2 Shading Calculation Requirements

Each annual shading calculation requires:

- A polygon that is the shape of the collector silhouette.
- A data array defining the first-order neighbour combinations for the array shape.
- Two dimensional Cartesian coordinates defined for each of two dishes. This allows to span the full parameter space of possible two-dimensional collector lattices for regularly spaced arrays.
- Weather data comprising direct normal insolation and solar altitude and azimuth angles for each time step to be modelled. In the absence of weather data, the simulation start time, end time, sample interval, array latitude and array longitude must be provided for use of the sun-position algorithm implemented.

2.3 Setting up the Simulation

A polygon representing the dish silhouette shape is defined and shape algebra is then performed using the 'shapely' package for Python [11]. Its shape is defined by a 2-dimensional array of vertex coordinates. Desired dish spacing parameters are defined in a data array with each entry to be incremented through as input to the annual shading calculations. Coordinates for the collectors comprising the array shape of interest are input into an $N \times 2$ data array, where N is the total number of collectors in the array. These coordinates are examined to determine the number of unique first-order neighbour combinations in the dish array. A data array that defines these neighbour combinations is created for input into the annual shading calculation.

Weather data is parsed and direct normal insolation, solar azimuth angle and solar zenith angle are retrieved for input into the annual shading calculation.

2.4 Annual Shading Calculation

For each annual shading calculation, the year is divided into discrete time intervals defined by solar azimuth and elevation angles. The total shaded area over the collector apertures in the field are calculated for each time sample in the following way:

- The coordinates of the dishes defined by input dish separation in the full first-order neighbourhood combination are transformed to a sun-view coordinate system defined by the solar azimuth and zenith angles. This coordinate system is explained by Meller [10] and overlap of dish apertures and the central neighbourhood dish in this coordinate system indicates shading from dishes in front of it.
- Distance of each dish along the solar vector is used to determine which dishes are in front of the dish being investigated. Dishes behind the dish of interest are disregarded to save computation time.
- The remaining points are used as central points to which dish-aperture polygons are transposed. The polygons are objects of the 'polygon' class defined by the shapely package implemented in Python.
- The intersection polygon of each of the remaining polygons with the polygon of the central dish are saved along with their NC index (see figure 1). These polygons form the basis of calculations of shading for each NC for the current time increment.

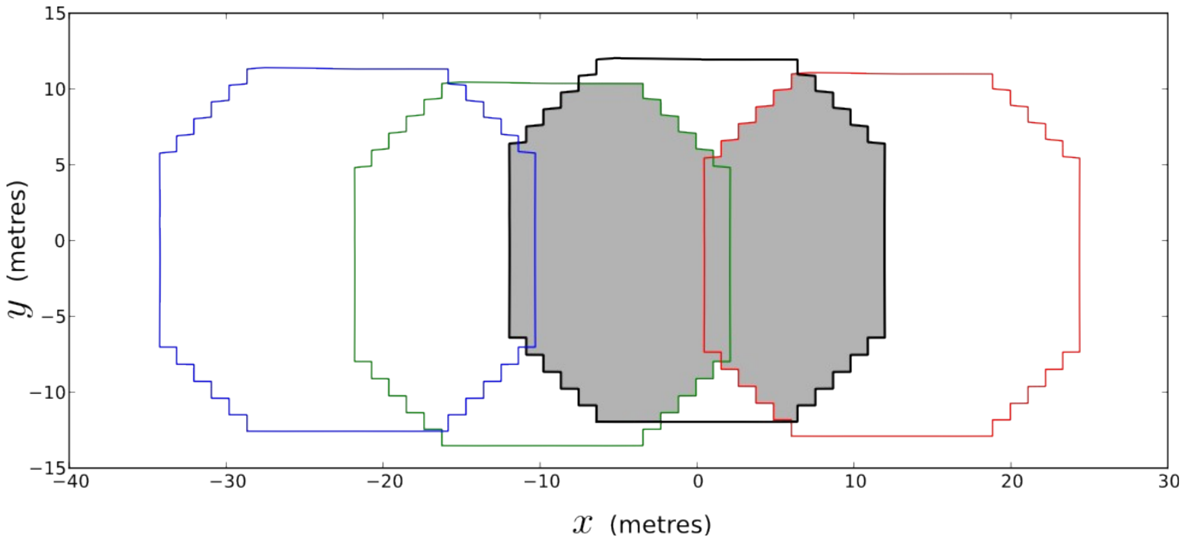

Figure 1. Graphical representation of polygon overlap in the sun-view coordinate system for a discrete time sample. Overall shading is the area of the union of shade polygons that are determined by calculating the intersection of each polygon with the central polygon.

- For each neighbourhood combination, each shading polygon is checked to determine which, out of those that have not been eliminated subject to the conditions already specified, will be included in the calculation. The area of the union of the relevant polygons is taken in order to quantify shading for the given neighbour combination.
- Shading for each neighbour combination is multiplied by the number of times it occurs within the array and total intercepted energy for the time increment is calculated based on time sampling interval and direct normal insolation data.

The intercepted energy calculated for all time steps is summed in order to determine total annual intercepted energy. This is compared to the expected total annual intercepted energy in the absence of shading in order to quantify annualshading fraction for given dish separations.

3. Shade Simulations

A polygon representing the aperture shape of the ANU 'SG4' Big Dish collector, as shown in Figure 1, is used for all simulations performed in this study. For these simulations, TMY2 data for one year for Canberra, Australia[3] is used that comprises data at a time increment of one hour. These data contain integer solar coordinate data that introduces an uncertainty ±0.5% in each coordinate. The parameter space has been limited to altering north-south and east-west spacing of dishes arranged in a rectangular lattice in order to reduce computation time and stay within the scope of the investigation.

3.1 Array Shape

The dish configuration simulated with the program is that by Carden and Bansal[2]. It is a tree-like structure that is optimised for minimisation of array transport costs (figure 2). This array has 2002 dishes with 32 neighbour combinations.

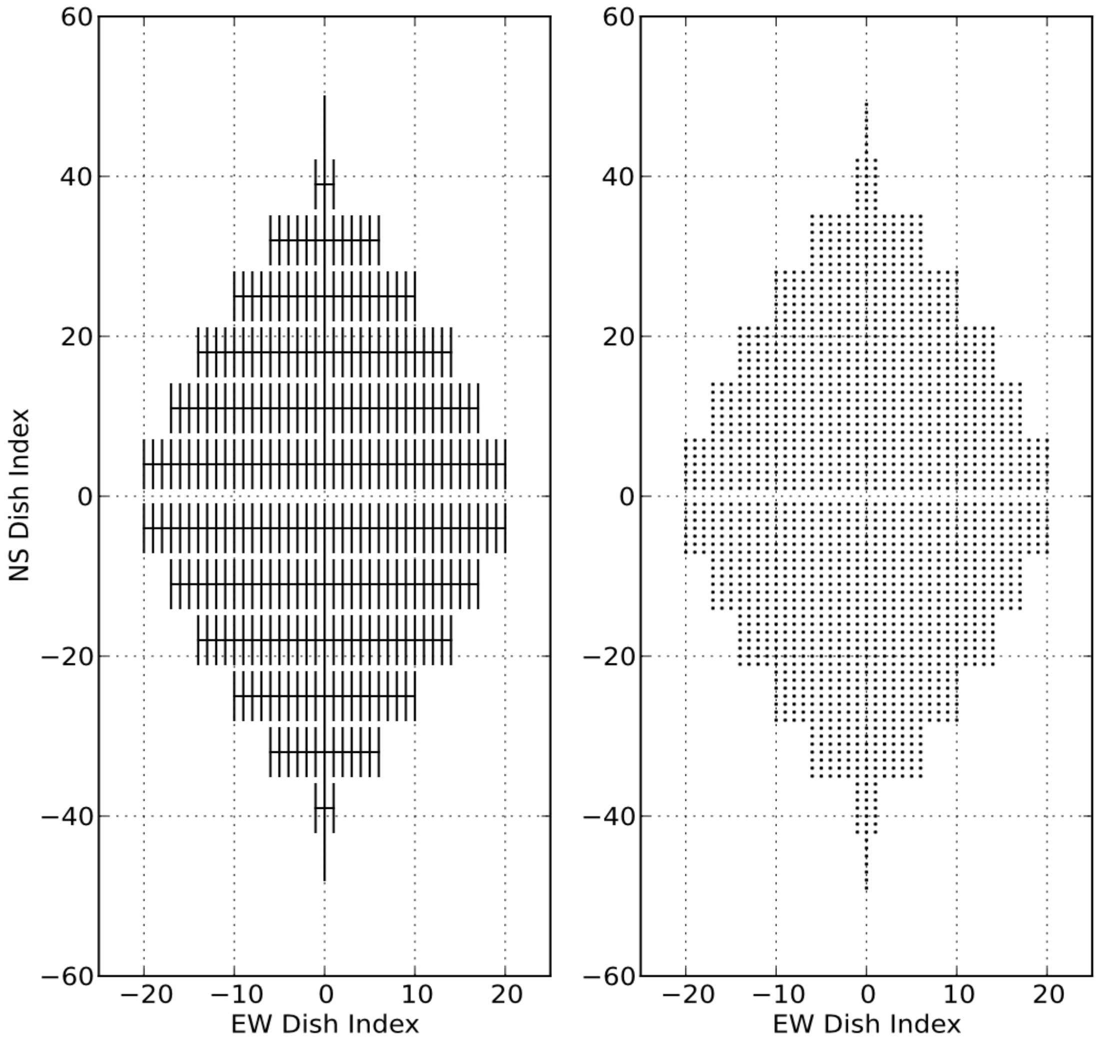

Figure 2. The array presented by Carden and Bansal [2]. (a) Left is the piping network determined as part of the optimisation and on the (b) right is the corresponding array shape.

3 Weather data collected by the Australian Bureau of Meteorology. http://www.bom.gov.au

Proposed for this array is an EW and NS separation of the dishes of $3D_0$ and $2D_0$, respectively, where D_0 is the diameter of the dish aperture. For the ANU Big dish, $D_0 \sim 24$m, though distances for the rest of this paper will be referred to in units of dish diameter. The number of pipe links in the EW direction is 272 and the number of pipe links in the NS direction is 1730, for a total of 2002 pipe links, with NS pipes outnumbering EW pipes by more than a factor of 6. Given the proposed array and dish separation, the total pipe length, $L = 3(272D_0) + 2(1730D_0) = 4276D_0$. Shading simulations were conducted to determine whether the pipe length could be reduced without introducing further losses from shading.

3.2 Shading as a Function of Dish Separation

A shading simulation was conducted to investigate shading with NS and EW dish spacing as free variables. A contour plot of the results of this simulation is presented in Figure 3. Lines of constant pipe length traverse shading minima, indicating the existence of a NS and EW dish spacing corresponding to minimum shading for a given pipe length. The dot-dashed line marks the parameter space corresponding to the pipe length of the array proposed by Carden and Bansal; the cross represents the dish separations proposed. The contour tolerance is set to 0.25% total annual shading. Remaining within this contour, pipe length can be reduced for the simulated array in the first instance by moving through the parameter space along the direction of the arrow with no increase in annual shading fraction.

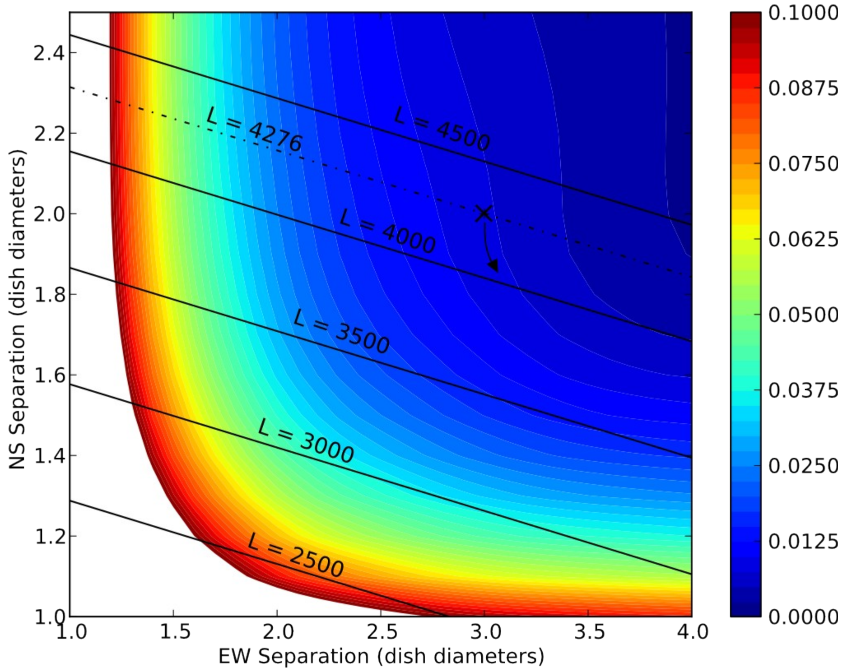

Figure 3. Investigation of shading for range of NS and EW dish separations. Black lines of constant pipe length, *L*, are overlaid on the shadow contour. The separation proposed by Carden and Bansal is marked with a black cross (×) and the pipe length for the proposed array is plotted as a dashed line. The arrow points in the direction of less pipe length for same annual shading fraction.

3.3 Shading as a function of Pipe Length

Simulations of annual shading fraction were then performed for a range of dish-field total pipe lengths with separation in the EW dimension as a free-variable. With total pipe-length as a constraint for each data point, the corresponding NS separation was calculated for input into the simulation. From Figure 4, the minimum pipe-length and corresponding EW and NS dish separation for a given annual shading fraction can be viewed. The loci of points that represent the minimisation of pipe length for a given shading fraction are plotted as black dots over the contour plot. The annual-shading fraction corresponding to these points is plotted as a function of NS and EW separation in figure 5 and as a function of pipe-length in figure 6. From this, the separation corresponding to minimum pipe length in each dimension for a given shading fraction is displayed explicitly. This allows minimisation of array pipe length for an admissible shading loss and this data may be incorporated into an optimisation algorithm that calculates the losses due to the energy transport infrastructure such as that presented by Carden and Bansal [2].

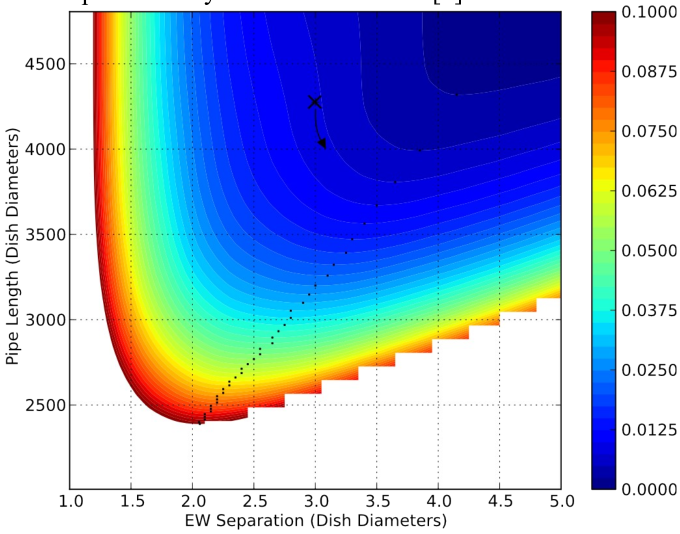

Figure 4. EW dish separation as a function of pipe length. Contours show areas of constant shading. The cross (×) marks the parameters suggested by Carden and Bansal. The arrow points in the direction of less pipe length for the same annual shading fraction. Black dots indicate the minimum pipe length and EW dish separation for a given annual shading fraction.

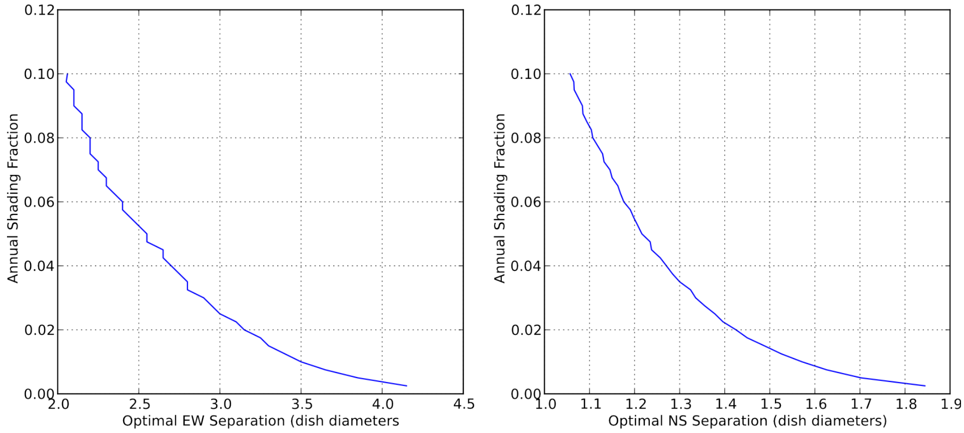

Figure 5. Annual shading fraction as a function of EW and NS dish separation for minimisation of pipe length for the simulated array, location and collector aperture.

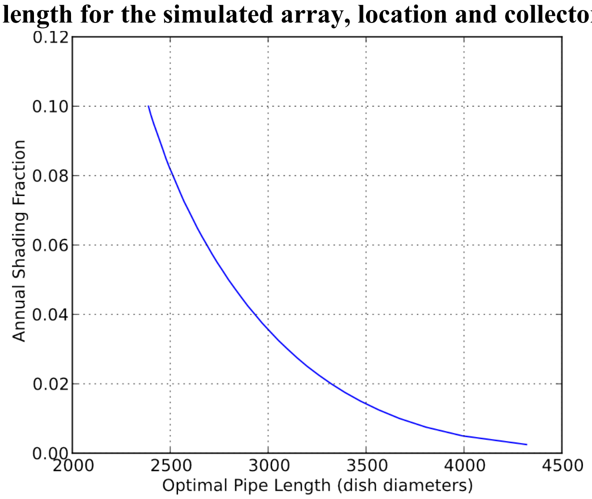

Figure 6. Annual shading fraction as a function of minimum pipe length for the simulated array, location and collector aperture.

3.4 Minimisation of Pipe Length Using Shading Data

The simulated shading data indicate that pipe length can be reduced without increasing the annual shading fraction. The NS collector separation of $2D_0$ and EW collector separation of $3D_0$ proposed by Carden and Bansal corresponds to an annual shading fraction of 0.79% of total insolation for the array shape and energy transport network specified, and the site location of Canberra, Australia. Figure 7 shows the contour of constant annual shading loss as a function of pipe length and EW separation. The EW separation corresponding to a minimum pipe length of $3780D_0$ is $3.65D_0$. This corresponds to a NS separation of $1.61D_0$. The reduction in pipe length for the array simulated is $496D_0$, or 11.6% of the proposed pipe length at no cost to annual system performance.

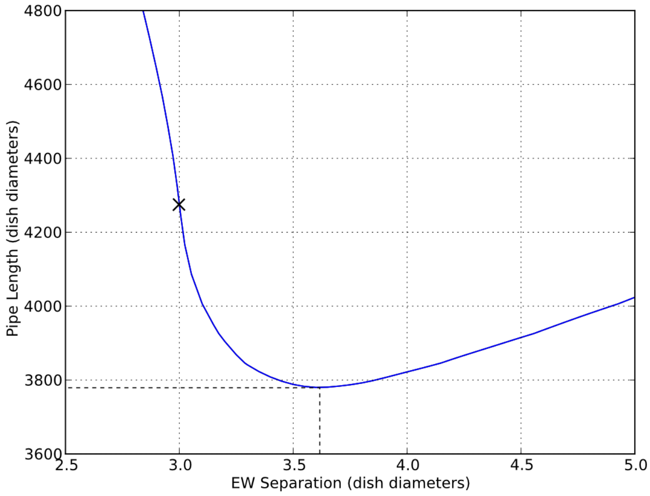

Figure 7. Pipe length as a function fo EW dish separation for the annual shading loss of the simulated array. The cross (×) marks the parameters suggested by Carden and Bansal. The pipe length minimum is shown graphically by the dotted line.

4. Conclusion

A program for simulating the annual shading fraction on a PFDR array was created. This program is capable of modelling annual shading losses for general array shapes, inter-array dish spacings and aperture shapes using available weather data or a sun-position algorithm.

This program was used to simulate annual shading fraction on ANU's 'SG4' Big Dish, incorporated as the collector in an array that was proposed in a study by Carden and Bansal for minimising energy loss in a steam transport network. Data exhibiting the relationship between minimum pipe length as a function of annual shading fraction were generated for the site location of Canberra, Australia using TMY2 weather data for solar azimuth angle, zenith angle, and insolation. Shading calculations found that for the specific dish spacing corresponding to 0.79% annual shading loss calculated for the proposed array, the pipe length may be reduced by 11.6% without further introduction of annual losses due to shading. The general shading data generated for the site may be incorporated into a system optimisation algorithm subject to the constraints of annual shading fraction and losses along with those of the energy transport network already investigated.

References

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