Impact of Grading Intensity in the LCOE of Single Axis Tracker Utility-Scale Solar Photovoltaic Power Plants

Javier Damia-Levy, Energy Practice Lead,
Max Simon, Civil Project Engineer, Energy Practice,
AZTEC Engineering Group, Inc. (TYPSA Group)

Motivation

Ground-based utility-scale solar photovoltaic power plants are inherently land intensive infrastructures. With solar development activities migrating from the US Southwest to milder climates in the country, the grading optimization design problem is increasingly relevant, especially in sites with certain levels of topography.

Optimizing the project site grading intensity in large-scale solar plants is an iterative task involving (i) designing multiple grading solutions for the project and (ii) evaluating the corresponding energy yield simulation for each case through detailed calculation of the shading and orientation losses ('terrain loss'), so to account for the non-planar system geometry. The results are then combined into some financial model for comparison of scenarios and optimum design point determination for the trade-off.

The engineering effort involved in designing multiple grading solutions and corresponding terrain loss calculations at early project development stages is time consuming and unpractical for typically high paced projects. To overcome this difficulty, AZTEC Engineering has developed a specific 3D simulation software (*PVGRAD*) which automatically produces the minimum grading solution for single-axis tracker projects based on a limited set of geometric input parameters. By varying the input parameters, a sensitivity analysis can be done, and the optimum design point found for the project. This paper illustrates this process and provides conclusions for one sample project.

Grading of PV systems with Single Axis Trackers

Minimum grading design can be defined as the site topography alterations minimally needed to achieve compatibility with a set of imposed single-axis-tracker geometric restrictions for a given plant layout. In a high-level approach, the site topography can be analyzed based on two different length scales. Small scale terrain irregularities (or 'terrain roughness') are those with a characteristic length smaller than the tracker length. Large s scale terrain irregularities (or 'terrain orography') are topographic irregularities with a characteristic length scale larger than the tracker length. In general, terrain roughness irregularities can be absorbed by the difference between the imposed maximum and minimum tracker torque tube heights (TTH); i.e., the variation range the reveal length of the tracker foundation piles are given by design. This interval is defined as the *reveal window* (RW):

$$RW = TTH_{max} - TTH_{min} \qquad (1)$$

If for a certain tracker the terrain roughness scale is smaller than the specified RW, no grading would be needed under that tracker to locally smooth the terrain roughness. In practice, TTH_{min} is limited by the minimum clearance between ground and module frame when the tracker is fully deployed, and TTH_{max} is limited for project constructability reasons.

More relevant in evaluating the grading intensity is the large-scale terrain orography. The limits for which a certain terrain orography requires grading are given by the angular limitations the trackers are subjected to. These are (i) the maximum North-South tilt angle the torque tube is allowed, and (ii) the maximum East-West drop angle between two adjacent trackers. The second restriction accounts for the fact that excessive difference in the vertical elevation of two adjacent trackers would expose the higher tracker to full wind loads, thus increasing the structural costs, in addition to increased system shading losses.

A third geometric control parameter is the maximum transversal slope of the East-West corridors between tracker alignments. In some instances, these corridors are designed as internal roads for construction and O&M purposes. The slope limitations for the transversal section of these corridors have an essential role in grading design as they entail the conditions for geometric continuity of the full system.

Finally, a grading solution to be optimal requires grading balance. In practice, the cut/fill quantities are to be balanced considering shrinkage and compaction factors. Grading balance for the full project may require incorporating excess material from other on-site civil improvements (excavated basins, roads, etc.) into the array grading design.

In summary, the geometric restrictions defining the grading design parameters are the following:

- RW parameter, from foundation piles.
- North-South maximum tracker torque tube tilt angle (α).
- East-West maximum drop angle between adjacent trackers (β).
- Transversal slope limitations for East-West corridors between tracker alignments (γ).

For any given topography and plant layout, there are infinite possibilities for grading solutions which satisfy the set of restrictions. A trivial solution would be grading the full site as a single horizontal plane. It can however be proved that the minimum grading intensity is achieved if the site is graded by means of ruled surfaces. Finding the minimum grading solution for a given set of restrictions is a computationally intense process which can only be resolved by means of numerical methods and 3D simulation techniques. The details on the grading algorithms built in PVGRAD are beyond the scope of this paper.

To illustrate the results obtained with PVGRAD, a sample project site is analyzed. This project "A" has the following main characteristics:

Project "A"	
Location	Kentucky
TMY Data	NREL-Lexington Bluegrass AP
Peak power	116.10 MWp
Module type	M-Si 410Wp (72 cells)
Strings	10,488 x 27 mods
Nominal power	92 MWac
Inverter size	46x 2 MWac
ILR	1.262
SAT	x1 portrait / backtracking
SAT pitch E-W	26.25 ft [8 m]
GCR	25%

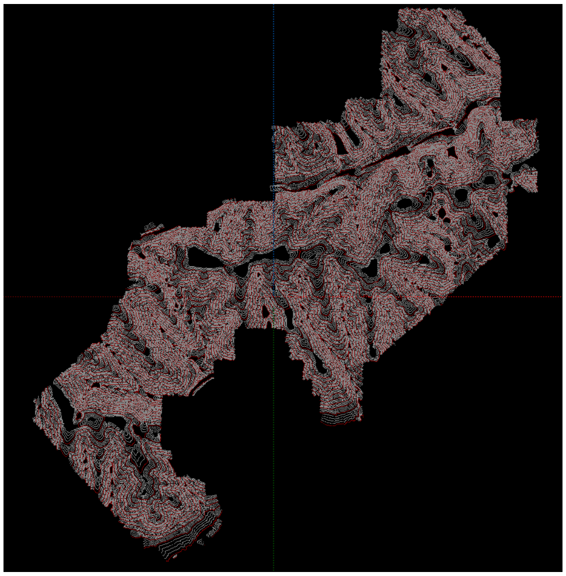
Table 1. *Reference project main parameters*

Figure 1 shows some 3D images of the site topography and contour lines; trackers' foundation pile distribution as obtained from the system layout; and the calculated minimum grading pattern under the following assumptions for the control parameters:

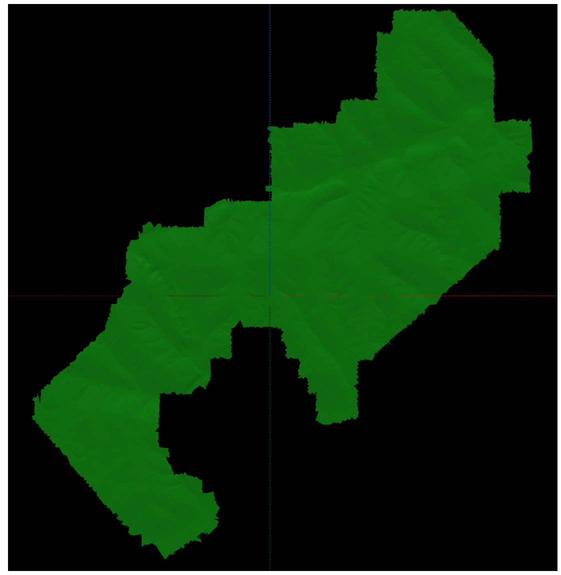
Reveal window (RW)	3.0 ft
Maximum N-S slope (facing North) $\alpha_{N,max}$	4°
Maximum N-S slope (facing South) $\alpha_{S,max}$	8°
Maximum E-W drop angle β	5°
Maximum internal road transv. Slope γ_R	1.87°
Maximum non-road transv. Slope γ_{NR}	14°

Table 2. *Sample set of grading control parameters*

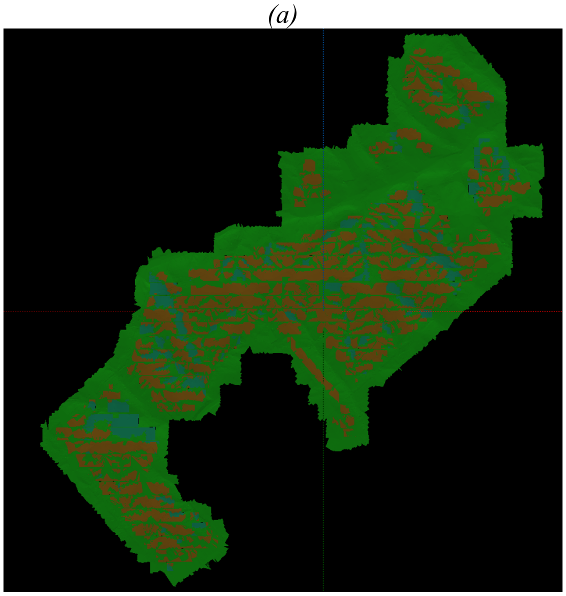
As shown in Table 2, the maximum North-South tilt angle for the trackers may have different values whether the tracker is facing North or South. The reason for this refinement is to limit the production losses for the north-facing trackers, while keeping the maximum possible south-facing angle for improved energy yield. In essence, there is no point in artificially limiting the maximum south-facing slope for the trackers as this would imply increasing grading costs for lower energy yield. The optimum grading design shall take the advantage of any south-facing terrain slopes within the limits of the tracker specifications and plant constructability.



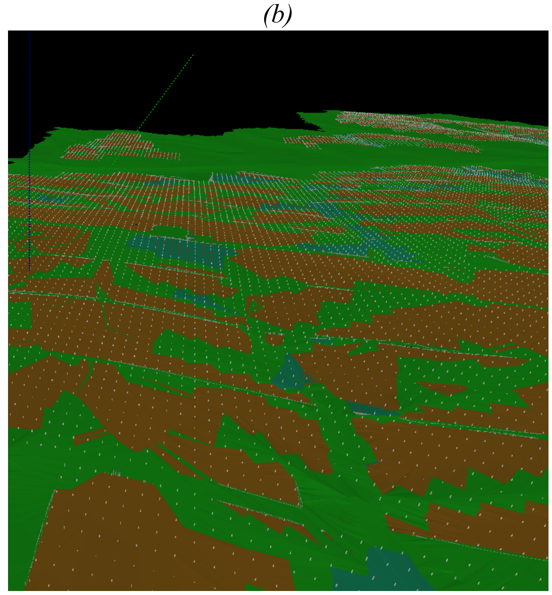
(a)



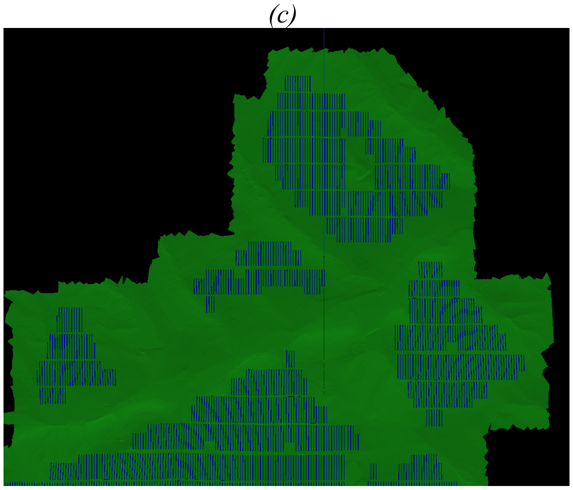
(b)



(c)



(d)



(e)

Figure 1.

(a) Contour lines for existing terrain.

(b) Digital terrain model for existing terrain

(c) Calculated grading per parameters in Table 2. Maroon = cut. Blue = fill.

(d) Grading detail with foundation piles. Note the ruled surface terrain adaptation in the pile distribution.

(e) Trackers' layout in the North area of the site

The calculated grading volumes for the exercise depicted in Figure 1 are: 260,020 cu.yd (cut) and 285,990 (fill). Grading balance is achieved for an overall shrinkage/compaction factor of 90%. These are the strict minimum possible grading volumes this project would require per the selected set of control parameters and within standard construction tolerances.

Tracker Foundations - Steel Quantities

As mentioned above, the allowed reveal length range for the tracker foundation piles' (RW) plays a relevant role in grading intensity. In fact, grading design and tracker foundation design are inherently coupled. As shown in the example in Figure 1 (d), once the grading design is completed, the reveal length for all piles in the system is also set. PVGRAD has a built-in structural calculation model for driven steel piles. This model evaluates the required steel section and embedded lengths for every pile based on resulting pile reveal length, pile loading data from tracker specifications, and site geotechnical data.

It is straightforward that there is a trade-off between grading intensity and steel quantity. While this trade-off is mainly controlled through the RW parameter, it should be noted that once the terrain under a certain tracker is graded, the reveal lengths of the corresponding piles will be geometrically adapted to the tracker torque tube resulting orientation, regardless if the reason for local grading is terrain roughness smoothing or terrain orography adaptation. As shown later in this paper, the trade-off between grading and steel costs is of second order when compared to the main trade-off for grading cost vs. energy yield. Still, the tracker foundation cost is a variable in the overall cost equation and thus also captured in this optimization exercise.

Energy Yield Calculations – Terrain Losses

Energy yield simulations have been completed with the PVSyst software (www.pvsyst.com). As of the date of writing this paper, the most updated version of PVSyst (v.6.8.4) doesn't allow to model a multiplicity of horizontal single axis trackers with different orientations in the same run. This limitation has been circumvented with the following two-step process for an approximate estimation of the system energy yield:

(1) Simulating the plant with all trackers' axis in horizontal position (N-S tilt = 0) but locating each tracker vertically per their average topographical elevations after grading. With this approach, the mutual shading losses at low solar elevation angles can be approximated to the real geometry. In order to include the backtracking effect in the simulations, the trackers are grouped in pairs as independent 'tracking fields'. This methodology follows the strategy described in [1].
(2) Updating the energy yield values obtained in step (1) with a "N-S tilt correction factor". This correction factor is calculated by means of a weighted-average of the N-S tilt angle frequency distribution for the full project.

Both calculation steps require detailed spatial location data for the trackers, which are extracted directly from the 3D system model. PVGRAD automatically exports the required system geometry information in **.SHD* file format, suitable for PVSyst scene rendering and shading loss calculation purposes. Figure 2 shows screenshots of the sample project geometry created by PVGRAd once imported in PVSyst:

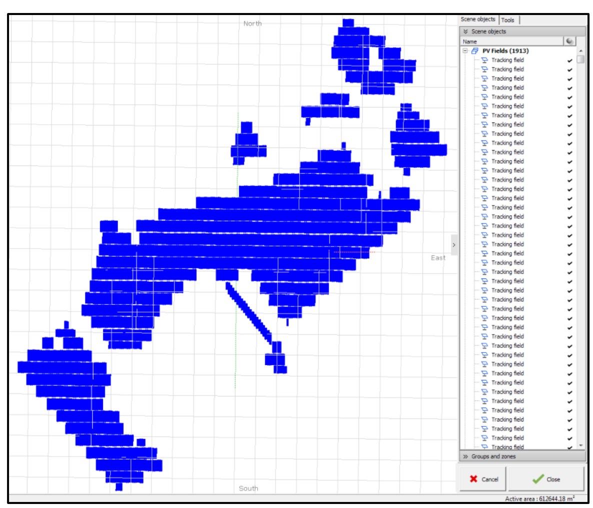


***Figure 2 (a)**. Project SHD file (general view)*

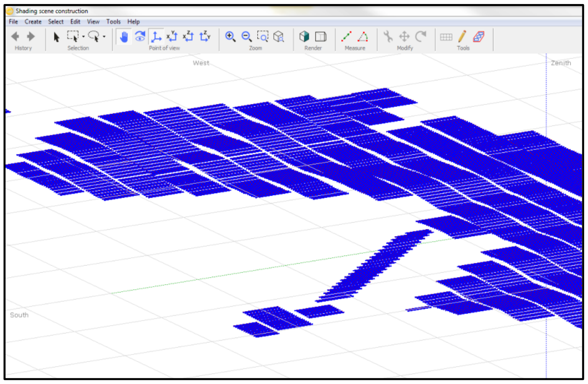


Figure 2 (b). *Project SHD file (detail)*

The calculated energy yield for Project "A" after simulation step (1) is

$$E_1 = \ 194{,}227\ MWh/yr$$

The set of data required for the N-S tilt angle correction in step (2) is obtained from PVGRAd as a frequency distribution chart. The result for the sample case is shown in Figure 3.

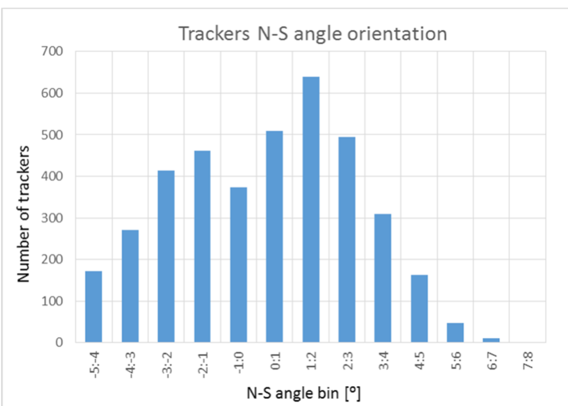


Figure 3. *Tracker angle frequency distribution chart. Positive angles: oriented South. Maximum North facing tilt angle set to 4 ^{o} in this run.*

Inspection of data in Figure 3 reveals that 43.7% of the trackers are facing North in this sample case. Also, the fact that 171 trackers have a North facing angle of $\alpha_{N,max} = 4^{o}$ implies that this is an active restriction in the proposed grading pattern. The heat map representation of N-S tracker angles is depicted in Figure 4 for the central area of the project.

The correction factor for the N-S tilt angle distribution is computed by simulating in PVSyst a typical array as a perfectly flat plane, with varying N-S tilt angles and otherwise identical system parameters. The energy yield vs. N-S tilt angle calculated points are then fitted to a quadratic function, which is then applied to each N-S angle bin in the frequency distribution chart to obtain a weighted average N-S correction factor. For the sample project, the correction function is shown in Figure 5.

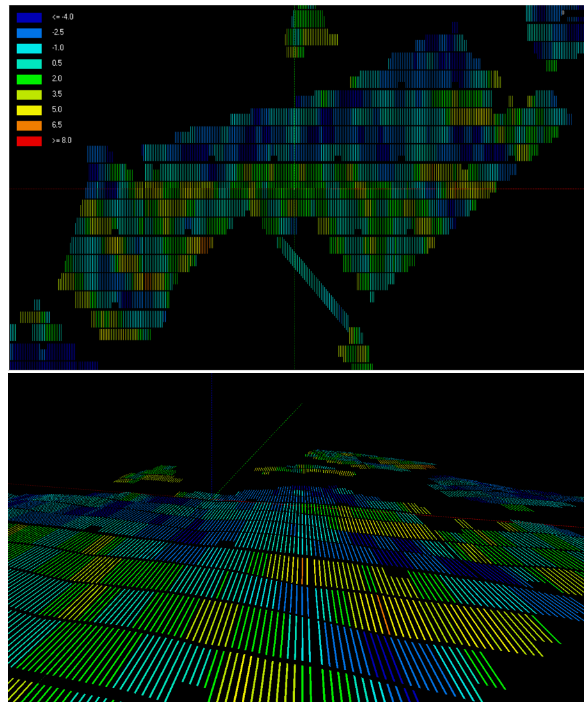


Figure 4. *Trackers' N-S tilt angle heat maps.*

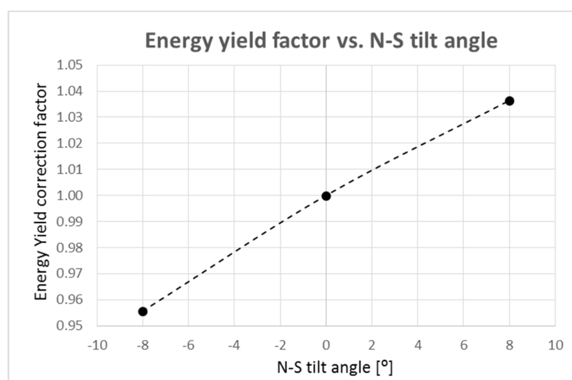


Figure 5. *Energy yield correction factor for N-S tilt angles for Project "A".*

$$f(\alpha) = -6.2149\ 10^{-5}\ \alpha^2 + 5.0597\ 10^{-3}\ \alpha + 1 \qquad (2)$$

Once applied to the frequency distribution table, the calculated weighted average energy yield correction factor is **1.0009** (0.09% increase) with respect to the perfectly flat horizontal case (Table 3).

Min α	Max α	Ave. α	# Trackers	Factor
-5	-4	-4.5	171	0.0432
-4	-3	-3.5	270	0.0686
-3	-2	-2.5	414	0.1057
-2	-1	-1.5	461	0.1184
-1	0	-0.5	373	0.0963
0	1	0.5	509	0.1320
1	2	1.5	640	0.1668
2	3	2.5	495	0.1296
3	4	3.5	309	0.0813
4	5	4.5	163	0.0431
5	6	5.5	47	0.0125
6	7	6.5	11	0.0029
7	8	7.5	2	0.0005
Total			**3685**	**1.0009**

Table 3*. Weighted average energy yield correction factor for N-S tilt angle distribution, for a maximum North facing tilt angle of 4 ^{0}.*

Therefore, the approximate energy yield for this sample case is given by

$$E_2 = 1.0009\, E_1 = 194{,}402\ MWh/yr$$

which compares to the perfectly flat horizontal system energy yield figure of 196,604 MWh/yr. This 1.12% difference between both values represents the overall *terrain losses* for this site per the selected set of grading control parameters.

Simulation Results and Discussion

The described process is repeated for a number of different combinations of grading control parameters for relative comparison and evaluation:

RW = 3.0 ft constant

$\alpha_{N,max} \in [-1^0, -6^0]$ variable max. North tilt

$\alpha_{S,max} = 8^0$ constant max. South tilt

$\beta_{max} \in [1^0, 5^0]$ variable max. E-W drop angle

$\gamma_{max} = 14^0$ constant max. non-internal road

$\gamma_{max} = 1.72^0$ constant max. internal road

The results of interest are plotted for a total of 30 combinations of maximum North oriented tilt angle ($\alpha_{N,max}$) and maximum E-W slope (β) limitations (Figure 6).

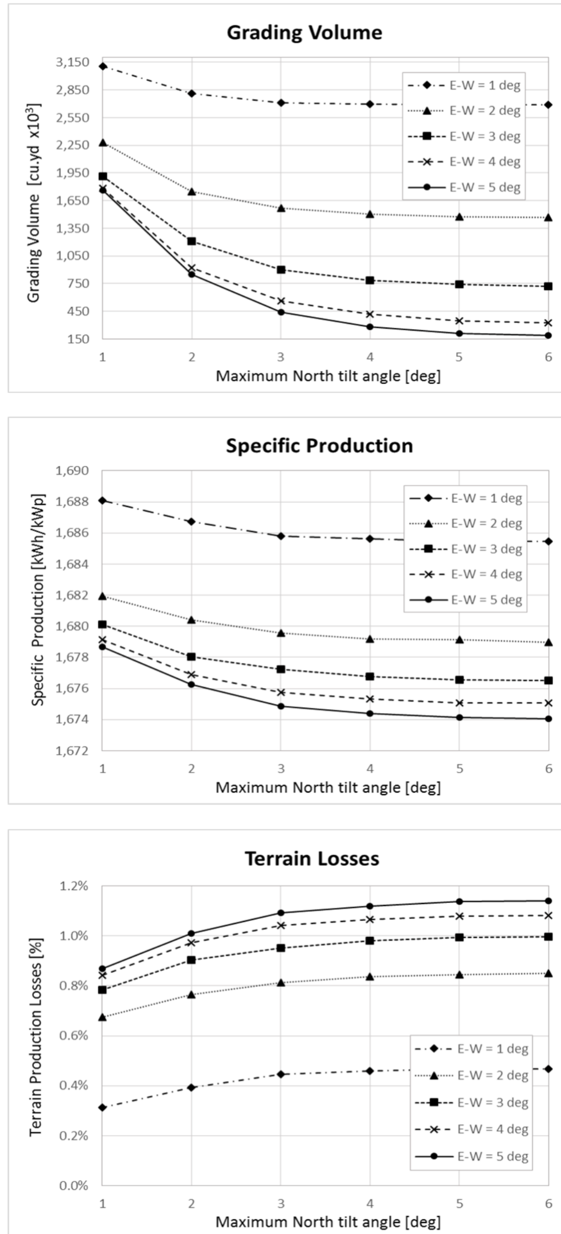


Figure 6. *Simulation results for project "A". From top to bottom: Grading volume. Specific production. Terrain losses.*

The first relevant result is the high variability of total grading volume with design assumptions. Building a nearly flat horizontal surface for the project requires more than 3 million cu.yd. of earthwork. This number reduces to 150,000 cu.yd (20 times less) by allowing a maximum North facing tilt angle of the trackers of $\alpha_{N,max} = 6^o$ and a maximum E-W drop angle of $\beta = 5^o$.

The savings in construction costs associated with increased geometric flexibility are offset by higher production losses. The specific production of this project reduces from 1,688 kWh/kWp to 1,674 kWh/kWp (0.83% production loss).

It should be noted that there is a reasonable correlation between grading intensity and energy yield. This intuitive idea is numerically demonstrated in the graph in Figure 7.

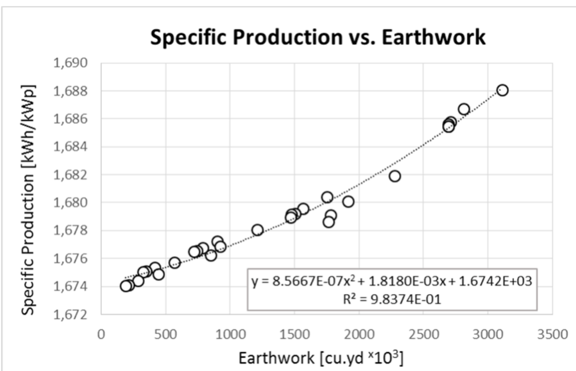


Figure 7. *Grading volume vs. specific production quadratic correlation for project "A".*

In order to determine the optimum-design point a relative LCOE analysis is completed with the above data (Figure 8). The LCOE calculations have been performed with the NREL software "*Solar Advisor Model* (SAM)" [2] per the following main assumptions:

EPC cost (except grading and foundations) = $0.816/Wp
Cost of grading = $5/cu.yd
Cost of steel = $0.7/lb
Analysis period = 30 yr
Debt fraction = 40% @ 18 years
Interest rate = 6.5%/yr
WACC = 6.95%
Inflation rate = 2.5%
Real discount rate = 6.3%
O&M costs = $15/kW-yr

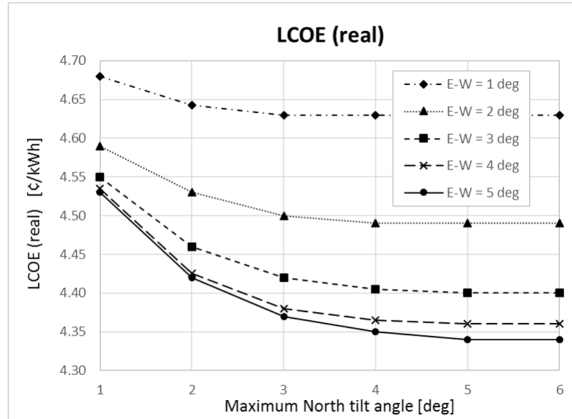


Figure 8. *LCOE sensitivity analysis for project "A".*

The conclusions of the LCOE analysis are straight forward for project "A", as there is a monotonic decrease of LCOE with decreasing earthwork. Because grading volume is ultimately related to the tracker's angular restrictions and "δ", it is apparent that selecting trackers with built-in installation flexibility in their design is key in improving life-cycle project financials. The ideal tracker design should allow for a large N-S tilt angle installation range and the ability to select the maximum and minimum foundation reveal lengths as appropriate for the project, so that the grading restrictions can be alleviated as much as possible per project constructability limitations.

About PVGRAd™

In 2018, AZTEC Engineering Group developed the three-dimensional simulation software PVGRAd™ for automated optimization of grading and steel design for single-axis tracker (SAT) solar plants; it is the first advanced earthwork and steel optimization technology for this purpose. Its numerical algorithms are registered under US Patent No. 11,301,790 and are constantly being improved by our solar engineering professionals.

PVGRAd™ was awarded the 2019 METIS Sustainable Infrastructure Award by Arizona State University and, in 2020, was included as Best Practice to Achieve the Sustainable Development Goals for Affordable and Clean Energy by the United Nations' Global Compact Organization. To date, the results of PVGRAd™ simulations have been used to optimize more than 8 gigawatts of solar plants worldwide by TYPSA Group's solar engineering teams in our Madrid, Phoenix, and Mexico DF offices.

For inquiries about PVGRAd™, please contact us at pvgradsoftware@aztec.us.