Design Optimization of Large-Scale Solar Plants with Terrain-Adapted Trackers

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Abstract: A methodology for optimizing ground-based single-axis tracker (SAT) solar power plants when terrain-adapted trackers are implemented is presented using simulation results from the PVGRAd™ grading optimization software. A sample project is analyzed in detail, and the suitability of terrain-adapted trackers is explored under multiple design options and scenarios. Finally, the optimal design point for the sample project is found for minimum construction cost.

Background

Ground-based utility-scale solar photovoltaic power plants are inherently land-intensive infrastructures. Minimizing the project earthwork is an essential design target for several beneficial reasons, including reducing construction costs and schedules, minimizing the environmental and hydrological impact of the project, and minimizing topsoil disturbance for rapid attenuation of erosion potential.

We define *minimum array grading design* 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. This design concept seeks to take advantage of the available tracker design installation limits so that the proposed terrain grading adapts as much as possible to their angular restrictions.

While there are infinite grading solutions that would satisfy the tracker's geometric restrictions for any given site -for example, grading the full project as a flat surface- finding the solution that provides the strict minimum earthwork is a mathematically complex problem, solvable only by means of optimization algorithms, as implemented in the PVGRAd™ simulation software. The results of the simulations not only provide the necessary information for the selection of the appropriate tracker for the project but also yield the corresponding detailed grading and pile foundation design.

Terrain-Adapted Solar Trackers

Providing single-axis trackers (SAT) with additional geometric flexibility to better adapt to the existing terrain is—by definition—a good strategy toward the goal of minimum grading design (Figure 1). Several solar tracker manufacturers offer terrain-adapted products based on non-straight-line axle designs by means of U-joints at the top-of-pile bearing locations, or simply by exploring the structural flexibility of the axle itself to adopt a certain elastic curve. The axle portions between two adjacent piles are herein called *segments*.

This additional feature qualifies as a new design geometric restriction, to be added to the earthwork minimization problem—namely, the maximum relative angle allowed between two adjacent segments of the axle (δ). This restriction is also included in the PVGRAd™ algorithms for analysis. (Note that if $\delta = 0$ degrees [deg], the tracker reduces to a traditional straight-line axle type as a particular case.)

The main project variables affected by the set of selected restrictions are (i) earthwork volume, (ii) foundation steel weight, and (iii) terrain disturbance area. This paper explores these project variables (and the trade-off between them) for multiple scenarios, with attention to the impact of segmented trackers in the overall variables. To best illustrate this process, we analyze a sample project in detail. In addition, we complete a sample cost analysis to identify the optimal design point that represents the minimum cost scenario.

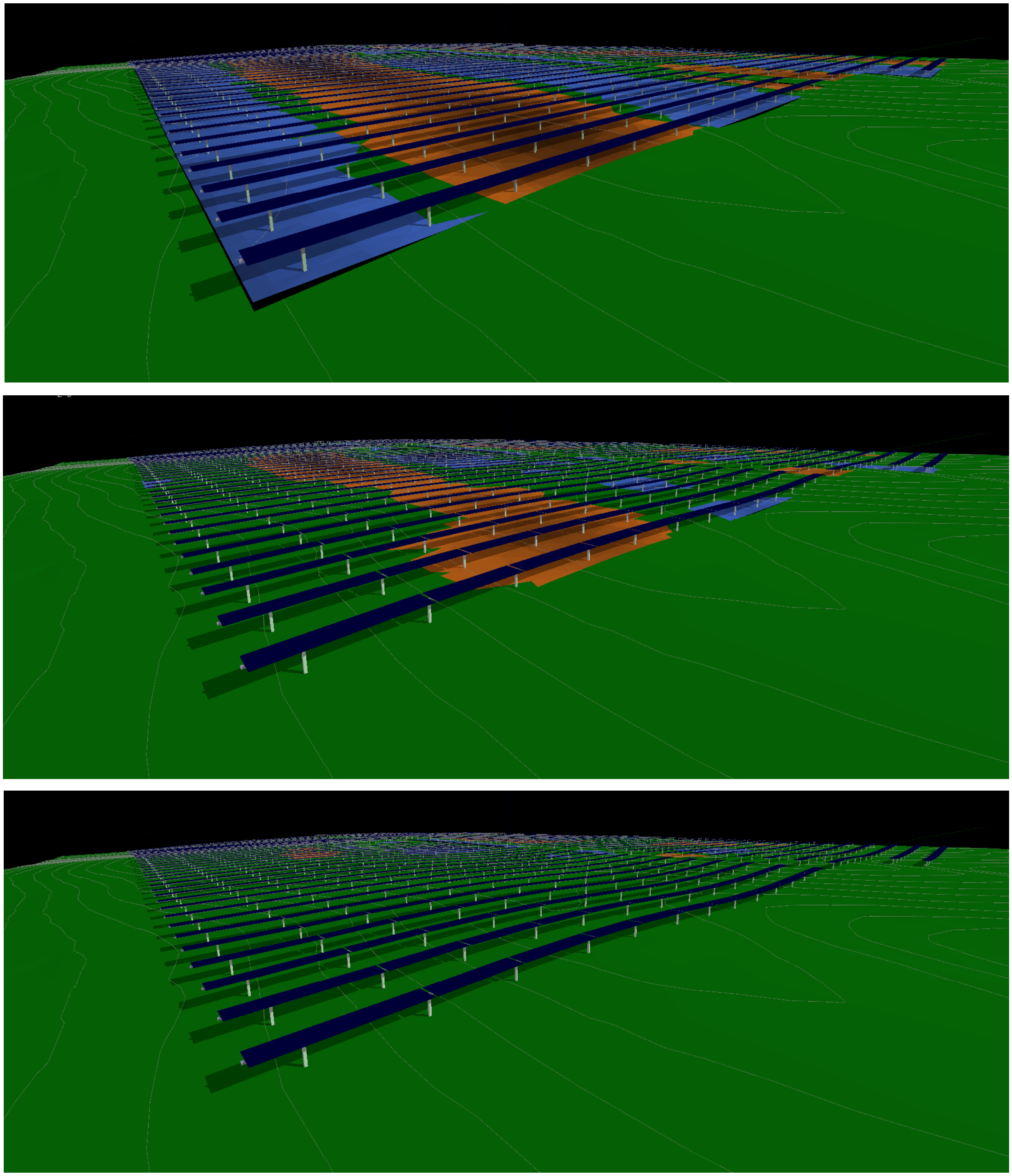

*Figure 1 – Comparison of local earthwork patterns for increasing δ angle. **Top image**: $\delta = 0$ deg (straight-line tracker). **Center image**: $\delta = 0.75$ deg (segmented tracker). **Bottom image**: $\delta = 1.5$ deg (segmented tracker). Earthwork intensity is reduced with increasing δ as the terrain adaptability of the axle improves (maroon = cut; blue = fill; green = undisturbed terrain).*

Case Study

To illustrate the effect of segmented trackers in the overall project variables, we analyze a sample project: a site with some relevant undulating hills on the U.S. East Coast. Figure 2 shows the reference scenario.

The first parameter to consider is the distribution of segmented trackers across the project layout. Designers may decide to locate segmented trackers only in areas with relevant terrain undulations, while saving other areas with smoother topography for straight-line axle trackers, because installing segmented trackers where no improvement in earthwork can be achieved over straight-line trackers would not be cost effective. PVGRAd™ automates this process with a built-in algorithm for automatic distribution of segmented trackers. The only user input needed is the percentage of segmented trackers to be distributed across the project; this additional restriction is called the *implementation intensity* (%).

The second parameter to consider is the *maximum δ angle* (deg) allowed by the tracker mechanical design, which depends on tracker manufacturer specifications.

Earthwork Volume

Simulations with different combinations of these two parameters yield different earthwork volume values for the sample project (Figure 3).

The results show a rapid decay in earthwork with small implementation intensities, up to 20%. The decay rate decreases with increasing implementation intensities, such that no substantial earthwork reduction is found for implementation intensities larger than 50%. This nonlinear relationship between earthwork and implementation intensity constitutes the core of the automatic selection process for the location of segmented trackers across the project layout; this process automatically optimizes where the segmented trackers would be more effective given the existing topography.

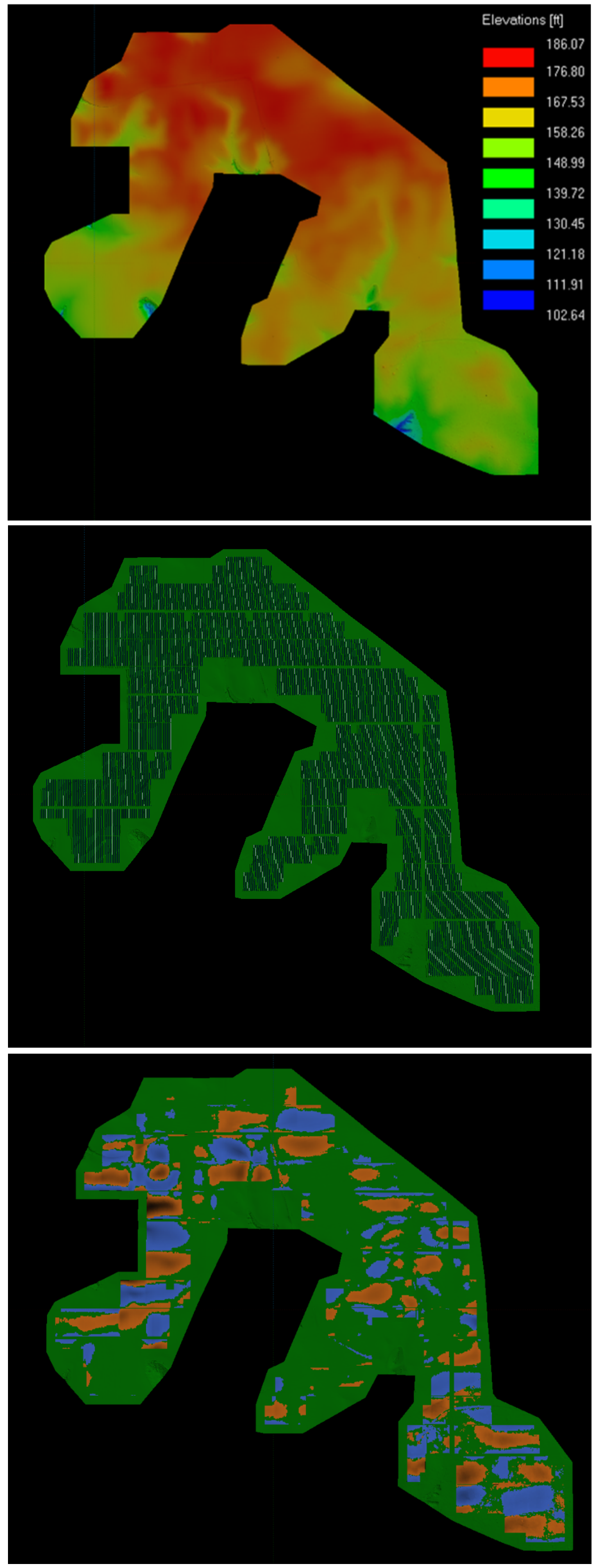

*Figure 2 – **Top**: Site-elevation heat map. **Center**: Plant layout. **Bottom**: Balanced earthwork pattern with straight-line trackers (δ = 0 deg, RW = 12″)*

Regarding δ angle selection, improved axle flexibility reduces earthwork volume dramatically. Figure 3 compares four δ angles—0.0, 0.75, 1.5, and 3.0 deg—for the sample project.

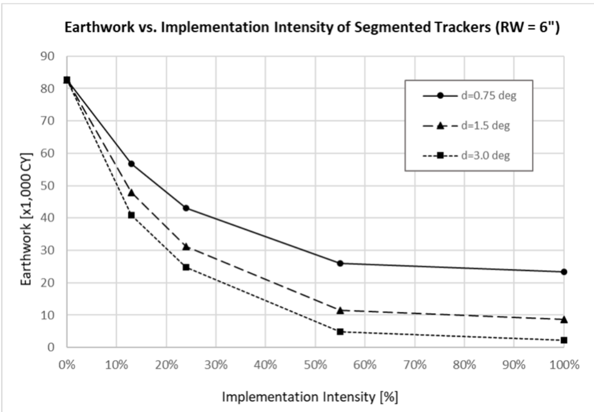

Figure 3 – Earthwork volume in function of implementation intensity for several δ angles. Pile RW = 6″. The $\delta = 0$ case is represented by the 0% implementation data point.

Reveal Window and Foundation Steel Weight

A third parameter is also relevant in the overall project variables: the *reveal window* (RW) of the tracker foundation piles. Although larger RWs are better able to absorb the small-scale terrain irregularities under the trackers and thus reduce the need for local terrain smoothing and grading, they require increased pile lengths and sections and, thus, overall steel weight.

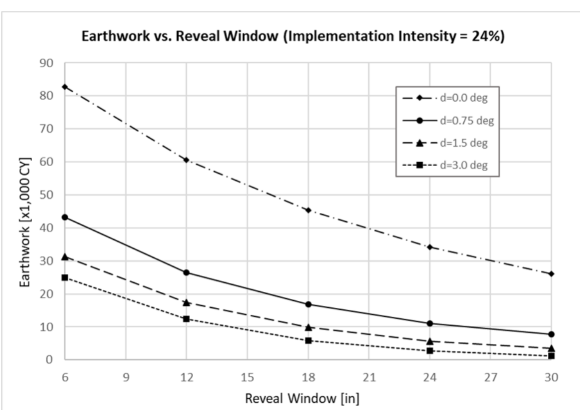

Figure 4 – Earthwork volume in function of RW for several δ angles. Implementation Intensity = 24%.

Figure 4 depicts the sample project's earthwork reduction with varying RWs for an implementation intensity of 24%.

PVGRAd™ includes structural calculation routines to determine the required embedded pile length and steel section for each pile based on top-of-pile loads, soil mechanical properties, and the reveal length —as obtained after the grading simulation. This provides the overall project foundation steel weight, as shown in Figure 5 for several implementation intensity levels. As expected, for a given δ angle, the overall steel weight increases as earthwork volume decreases.[1]

However, this correlation between earthwork and foundation steel weight is not valid when comparing values across different δ angles. For example, as shown in Figure 4, the sample project can be designed to 30,000 cubic yards (CY) of earthwork either by using straight-line trackers ($\delta = 0$ deg) with an RW = 27″ or by installing 24% of the trackers with $\delta = 1.5$ deg and RW = 6″. The total steel weight in the first option is $2{,}128 \times 10^3$ pounds (lb), while the second option is $1{,}955 \times 10^3$ lb. Therefore, the same earthwork volume does not imply the same steel weight. This is best illustrated with *pile reveal distribution curves*, which are obtained when the reveal length values of all piles are sorted from lower to higher. A typical pile reveal distribution curve is shown in Figure 6 (top).

In this curve, the shorter piles typically fall in areas where grading indicates "cut," while the larger ones fall in areas where grading indicates "fill." This is expected because grading is mostly used to adapt the existing terrain to the available RW. The portion of the reveal distribution curve between the extremes represents the pile population falling in undisturbed terrain. The difference between the maximum and minimum reveal lengths is obviously the selected RW value. As a check, Figure 6 (bottom) shows the heat map of pile reveals across the footprint of the

[1] *The pile structural calculations in this case study assume that the soil skin friction is sufficient to absorb the additional axial loads at top-of-pile bearings when forced by the axle's elastic curve, so no extra embedment length is required for this technology and site.*

sample project, which can be compared with the grading pattern in Figure 2.

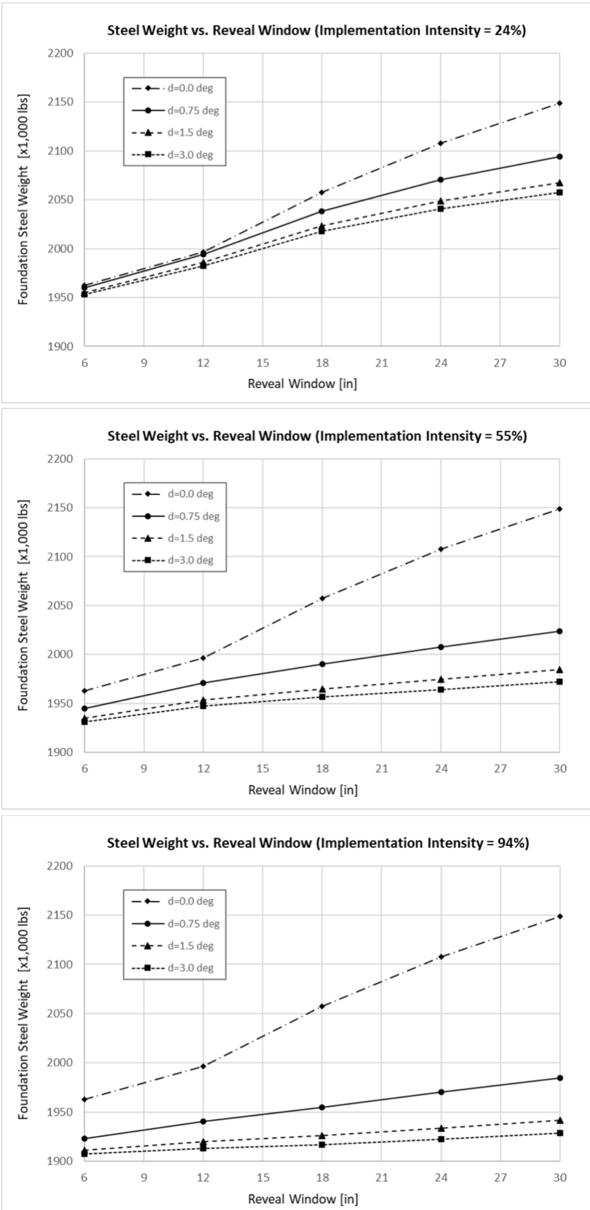

Figure 5 – Pile steel weight in function of RW for several δ angles and implementation levels. Note that the sample project's steel quantities show a maximum variability of only 13% across the different scenarios.

Increasing the RW value reduces the cut and fill bandwidths at the ends of the pile reveal distribution curve and thus extends the central band of piles sitting on undisturbed terrain. This defines the correlation between earthwork volume and RW for a given δ and implementation.

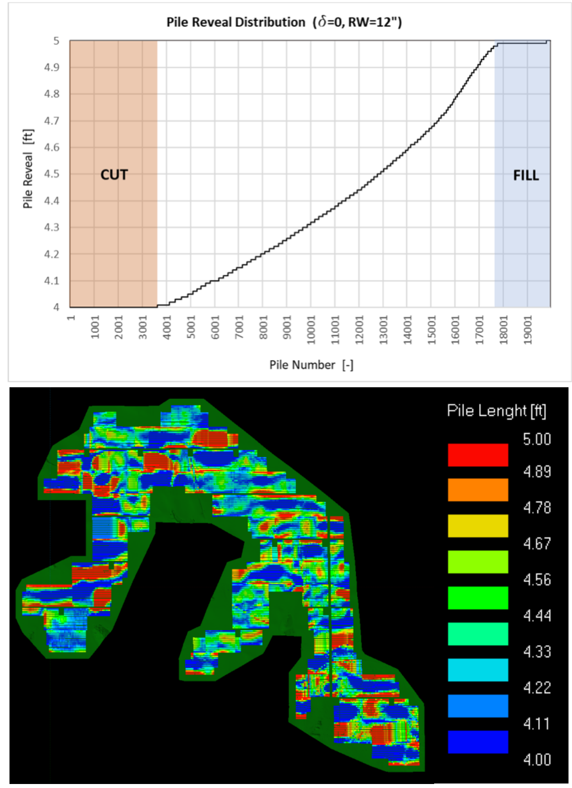

*Figure 6 – **Top**: Typical pile reveal distribution graph. **Bottom**: Pile-reveal heat map (compare with cut/fill footprint in Figure 2).*

Figure 7 plots the corresponding pile reveal distribution curves, with an RW = 12″ and implementation intensities of 24% and 94%, for varying δ angles. This graph shows that as δ increases, the number of piles requiring longer reveals reduces (pushing the frequency diagram to the right side of the graph), thereby confirming that the reduced steel weight is accurately quantified in this analysis.

This is another benefit of using segmented trackers: the improved terrain adaptability of the axle reduces the need for longer piles to locally absorb small-scale terrain irregularities, as it also happens with trackers having very short axle lengths and with fix-tilt structures in general.

Disturbed Terrain Area

Soil disturbance is a relevant variable in land-intensive solar projects. Reduced soil disturbance yields not only construction and maintenance savings related to temporary erosion-control best management practices but also schedule savings by promoting faster top-soil layer regeneration across the site, which, in turn, limits the project environmental impact during construction.

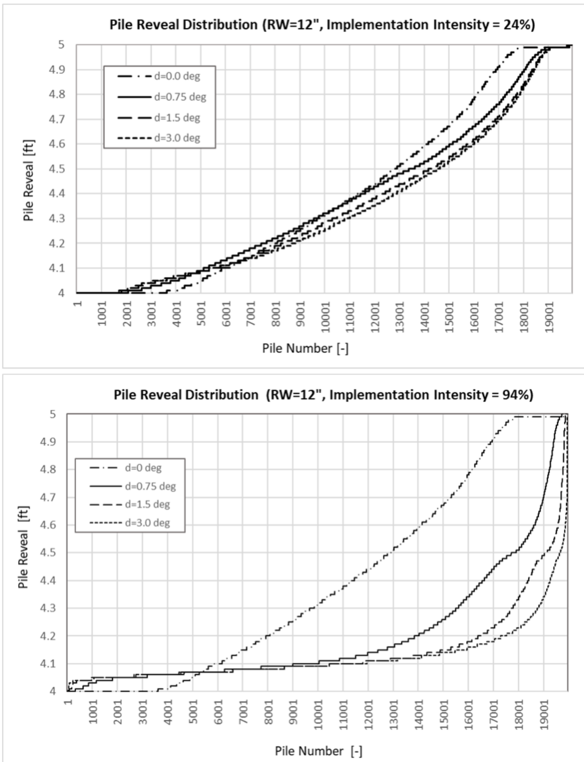

Figure 7 – Pile reveal distribution curves for varying δ angles.

The disturbed-area values for two implementation intensities are depicted in Figure 8 for the sample project.

As expected, implementing segmented trackers and/or longer RWs directly correlates with a reduced soil disturbance footprint.

Variable-Cost Analysis and Optimal Design Point

Selecting the sample project's optimal design point involves a minimum-cost analysis. While the number of different cost items to be considered in a detailed cost analysis is large, and may vary considerably across specific projects and circumstances, a basic comparative analysis with reasonable unit-cost estimates, together with the quantitative data obtained through the above simulations, yields useful results for decision makers to consider during the early stages of the project development phase.

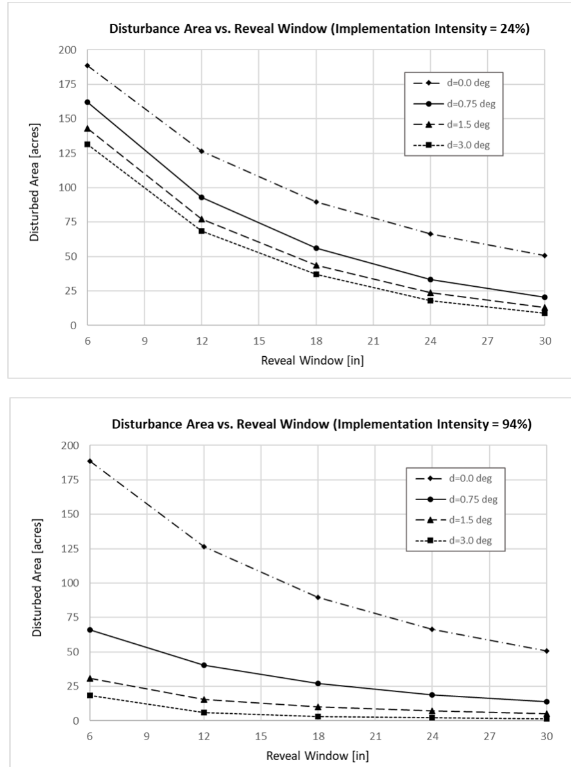

Figure 8 – Disturbance area with varying δ and RW.

To identify unit costs for each of the considered items in our analysis, we selected reasonable average industry-cost data points for the sample project that were applicable as of the date of this publication; therefore, these estimates should only be considered for illustrative and comparative purposes (Table 1). Later, we also analyze the sensitivity of these unit costs to evaluate the stability of the results.

Table 1 – Estimated unit cost data (for illustration and comparison only).

Item	Estimated Cost
Straight-axle tracker row	\$3,000/each
Segmented-axle tracker row	\$3,400/each
Earthwork	\$5/CY
Steel cost	\$0.7/lb
Soil disturbance variable cost	\$1,000/disturbed acre

Figure 9 depicts the total variable cost quantities (for comparative purposes only) when applying the unit-cost estimates from Table 1 to the quantities obtained through the simulations.

The most notable outcome is that the minimum cost point is found at low implementation intensities (between 10% and 30%) for all

δ angles and RWs. The left side of the curves shows a decay driven by the excellent reduction in earthwork achieved with segmented trackers; however, this is only cost effective when installed on the few areas where the topographic irregularities are significant. The right side of the curves reveals a monotonically increasing overall variable cost with implementation intensity driven by the extra cost of the additional segmented trackers, which overrides the savings they provide in earthwork, foundation steel weight, and soil disturbance. When comparing the different curves, it is apparent that increasing δ angles yield better results, although the tracker's unit cost variation with δ (if any) has not been captured in this sample analysis.

The effect of the RW in the cost curves is worth separate exploration. Increasing RW has a double effect: (i) it displaces the minimum cost point toward decreasing implementation intensities, and (ii) it consistently drives the cost curves downward. Figure 10 shows the monotonic cost reduction with increased RW for the minimum cost points extracted from the optimal design curve (δ = 3.0 deg).

The extra cost of increased reveal lengths for the piles (and associated step-up in steel sections) is worth the investment because of the earthwork and soil disturbance savings achieved when the remaining large population of straight-line trackers are given the flexibility of the increased RW to absorb shallow terrain irregularities, as shown in Figures 4 and 8 for the curves where $\delta = 0$ deg. In essence, a cost-effective design considers that deep grading is reduced with segmented trackers, while shallow grading is absorbed with increased RW.

Although the cost effectiveness of increased RWs can be easily demonstrated for any solar project, not all tracker manufacturers offer a convenient RW range, hence curtailing the optimization window to the left side of the curve in Figure 10.

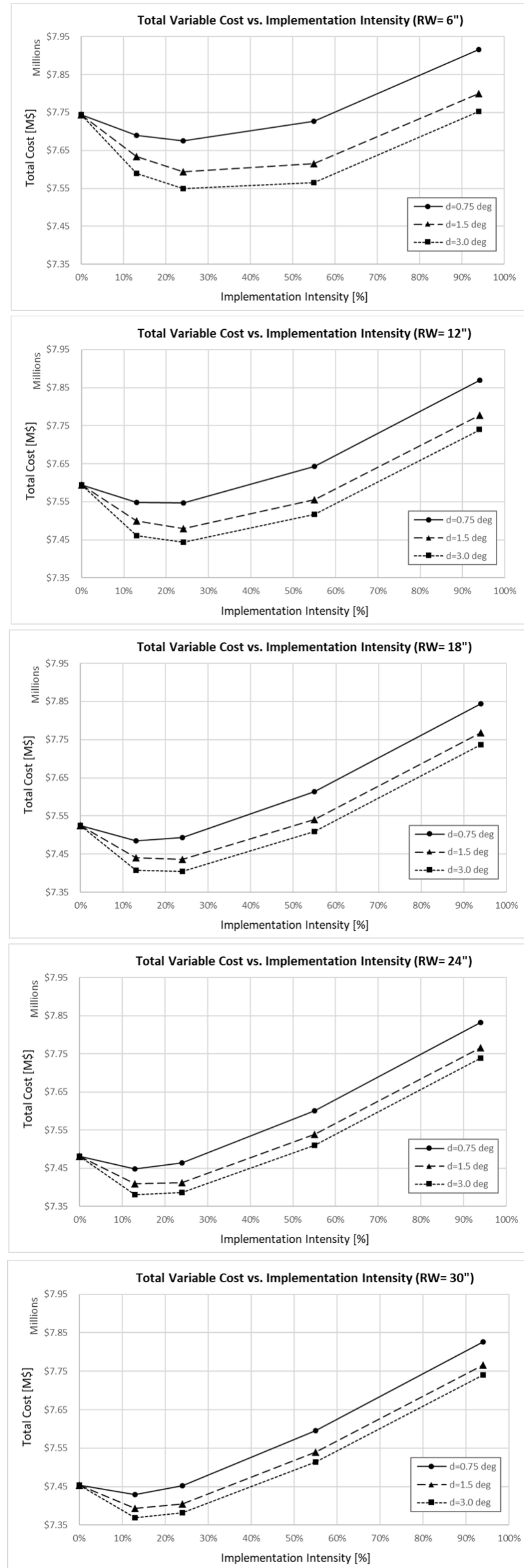

Figure 9 – Total cost variation with implementation intensity and δ, for all RWs.

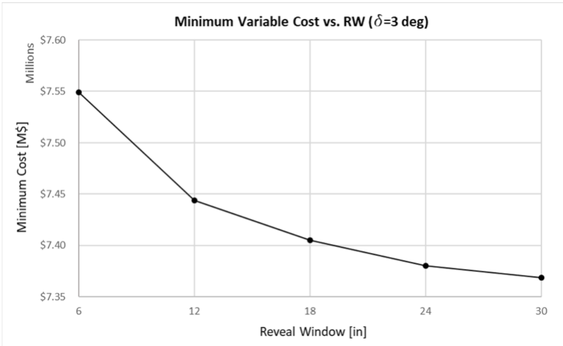

Figure 10 – Total minimum cost point variability with RW.

In summary, the optimal design point for the sample project is found with the following parameter values:

Implementation intensity = 13%

Segmented tracker technology angle (δ) = 3.0 deg

RW = 30″

The resulting optimal design for the project is depicted in Figures 11 and 12, with the following results:

Number of trackers = 1,648 [-]

Number of segmented trackers = 214 [-]

Cut total volume = -4,400 CY

Fill total volume = 4,400 CY

Disturbed area = 108,498 SY

Number of piles = 19,956 [-]

Total steel weight = 2,100,600 lbs

Note that the array grading has been set to balance through the simulations. Often, the excess material from other civil improvements (permanent basins, project roads, drainage features, etc.) needs to be incorporated into the array grading, thus altering the cut/fill ratio restriction input. In those cases, the implementation potential of segmented trackers is impaired because the imported dirt is allocated where the segmented trackers could otherwise prove to be more effective.

The optimal-design pile reveal distribution curve in Figure 11 (bottom) shows that even if the maximum RW for the optimal design is set to 30″, only 20% of the foundation pile population actually requires an RW > 12″.

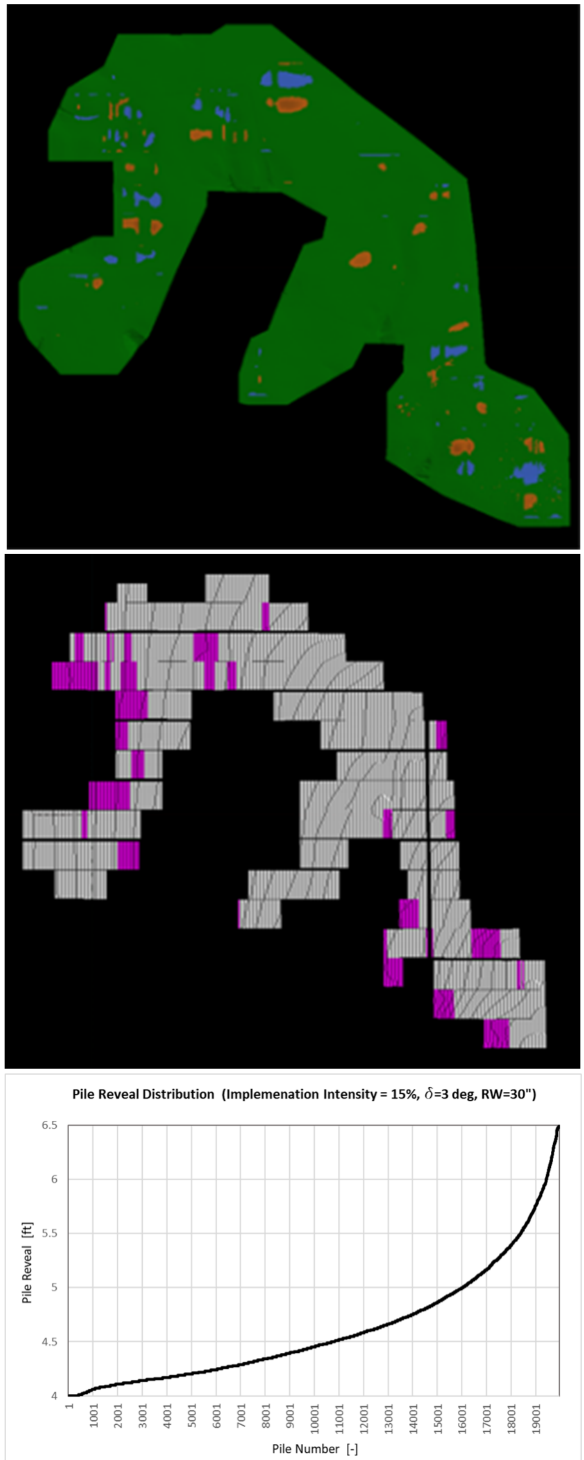

Figure 11 – Optimal design for the project. ***Top****: Grading pattern.* ***Center****: Optimized location of segmented trackers (in magenta).* ***Bottom****: Pile reveal distribution curve.*

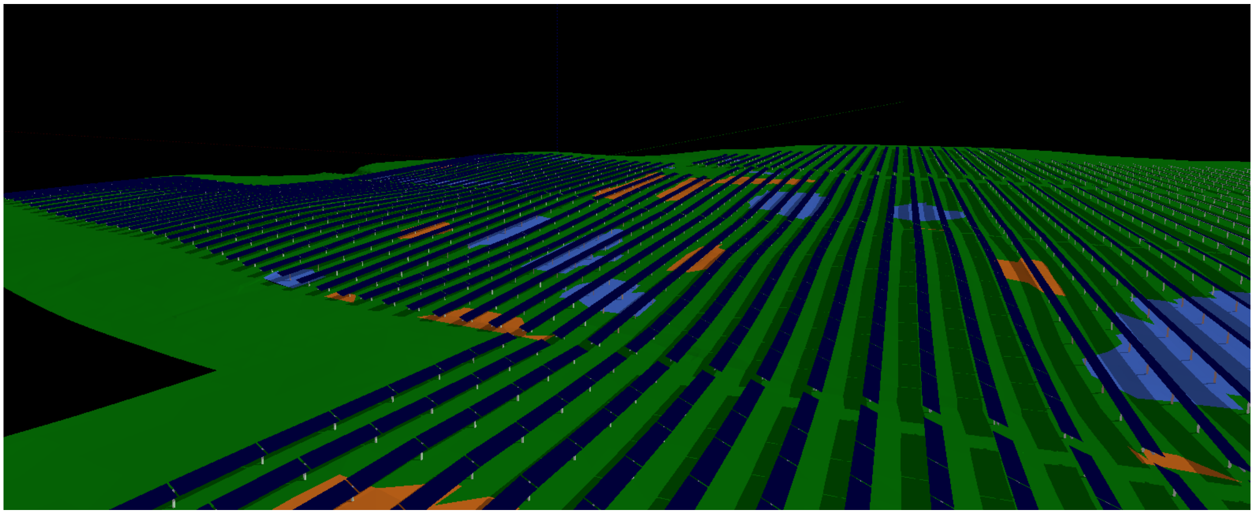

Figure 12 – Project general view, with relevant terrain undulations being absorbed by selectively located segmented trackers.

The cost structure for the selected optimal design point is depicted in Figure 13.

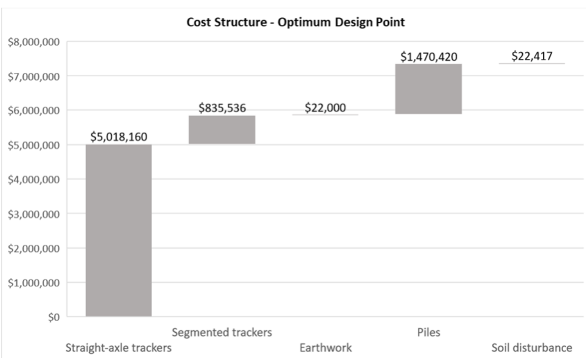

Figure 13 – Cost structure for the selected optimal design. Note that these represent the analyzed variable costs only.

Sensitivity Analysis

The robustness of the optimal design point selection is affected by the accuracy of the unit costs set in the cost analysis above, which may vary considerably for many reasons, from project to project or within a given project's development schedule.

As demonstrated in the previous analysis, the most relevant variable when determining the optimal implementation intensity is the difference in unit costs between straight-line-axle and segmented-axle trackers—which, in our sample project, we estimate as a $400/each difference. Figure 14 explores the overall cost curve adjustments when this cost difference varies. As the difference reduces, the optimal implementation intensity increases, which is an expected result. With a difference of only $100/each between tracker types, the optimal implementation intensity would be 55%; however, the right side of the cost curve becomes nearly horizontal, and thus, any implementation between 20% and 90% yields essentially the same overall variable cost.

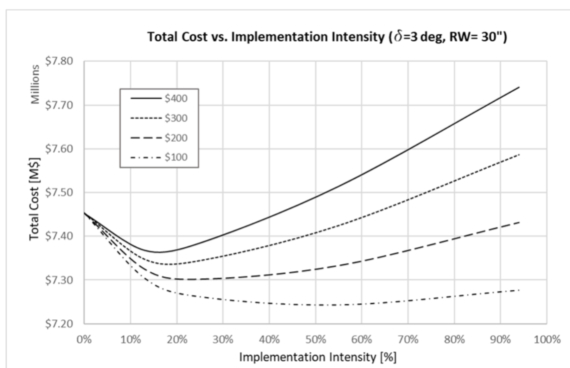

Figure 14 – Cost curve variability with reduced difference of unit cost between tracker typologies.

If the unit cost of earthwork increases from the sample estimate of $5/CY, the overall cost curves are displaced upward for implementation intensities below 50%, with the optimal implementation intensity point around 15% remaining stable (Figure 15). The impact in overall variable cost close to the minimum is small because the earthwork volume is marginal.

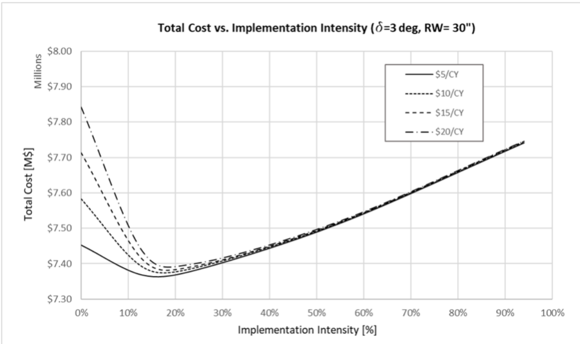

Figure 15 – Cost curve variability with increasing earthwork unit cost.

When evaluating the sensitivity to variable steel unit costs, we should consider that this affects not only the cost of foundation piles but also the material cost of the trackers. For our sample project, we assumed that the cost of steel in the trackers is 50% of their total cost. The sensitivity results for the overall variable-cost curves are depicted in Figure 16.

While the impact in cost is very important (as it can be predicted from the data in Figure 13), the optimal design point also remains stable around the selected 15% implementation intensity mark.

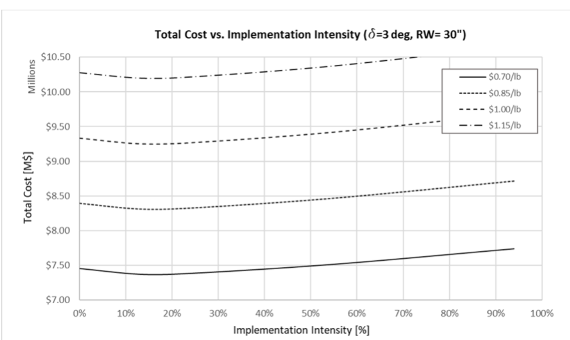

Figure 16 – Cost curve variability with increasing steel unit cost.

Finally, Figure 17 depicts the cost curves for variable soil disturbance unit costs, which are similar to those for variable earthwork unit costs.

The results shown in Figures 14 through 17 indicate that the determined optimal design point is sufficiently stable versus unit-cost volatility. Therefore, the proposed methodology is robustly designed for both the project development process and the cost estimation process during the later engineering, procurement, and construction (EPC) bidding phase. Provided that these sample unit costs are reasonable estimates when a cost analysis is conducted for a given project, the overall project design parameters would remain stable around the optimal design point, even under volatile market circumstances.

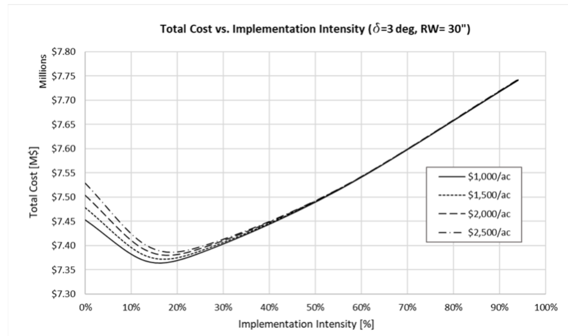

Figure 17 – Cost curve variability with increasing soil disturbance unit cost.

Conclusion

This paper illustrates the methodology for project optimization when implementing terrain-adapted SAT, by means of the PVGRAd™ simulation software capabilities. To illustrate this process, a sample project was analyzed in detail under multiple scenarios for the relevant design variables, and the optimal design point was found for cost minimization.

This analysis demonstrates that terrain-adapted trackers are an excellent option to drastically reduce earthwork and soil disturbance, because they are effective in those localized areas of projects where orography is relevant. Also, their inherent geometric flexibility requires less foundation steel.

When normalizing the improvements in overall earthwork volume, foundation steel weight, and disturbed terrain area through a standard cost analysis, it becomes clear that small implementation intensities of terrain-adapted trackers are more cost effective than full implementation schemes—especially when similar beneficial effects obtained with increased RWs for the foundation piles are appropriately weighted in the cost equation.

Finally, a cost sensitivity analysis to test the stability of the proposed design under varying scenarios demonstrated that the optimized design is reasonably stable under market fluctuations; therefore, it can be confidently defined during early project development stages.

Although the results may be extrapolated to projects with similar orography, each project has its own particularities and thus requires optimization analysis based on assumptions specific to that project

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.