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IMPACT OF TOPOGRAPHY AND EARTHWORKS IN UTILITY-SCALE PHOTOVOLTAIC PROJECTS

IMPACTO DE LA TOPOGRAFÍA Y MOVIMIENTOS DE TIERRA EN PROYECTOS FOTOVOLTAICOS TIPO UTILITY

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Abstract:

In recent years, due to the increase in the number of PV projects worldwide, flat land for PV projects has become scarce. More and more projects are being built on steep terrain. The civil works associated with these topographies have a substantial weight in both the CAPEX and the schedule, and have numerous interactions with other facets of the project such as environmental impact, energy generation, irradiation on the modules, hydrology, etc. The objective of this thesis is to characterise and quantify these interactions in order to gain efficiency in the design and construction of this type of projects. Specifically, three dimensions are studied: the reduction of earth movement, the impact on energy generation and the impact on the environment. Firstly, work has been carried out on mathematical modelling at the structural level of the plant, with the aim of implementing an algorithm to optimise the position of the structures and reduce the associated earthworks in the early stages of the design. The results show that a reduction of the total amount is possible using a simple algorithm based on the mathematical model developed. In addition, work is currently underway to quantify the mismatch losses associated with different factors. For this purpose, real data from panels and structures have been taken and modelled under various conditions. It is hoped that knowledge will be gained to improve production estimates. Finally, a field study has been planned to investigate the importance of vegetation in plant hydrology, as well as methods to maintain this vegetation during dry periods. The intention is to see which methods are most suitable for preventing erosion and landslides and to see if they are feasible from a technical-economic point of view.

Key words: Geomatics, Modelling, Simulation, Mismatch, Civil works, Hidrology

Resumen:

En los últimos años, y debido al incremento de proyectos fotovoltaicos en todo el mundo, los terrenos llanos para este tipo de implantaciones han comenzado a escasear. Hay cada vez más proyectos que se construyen en terrenos escarpados. La obra civil asociada a estas topografías tiene un peso substancial tanto en el CAPEX como en el cronograma, y tiene numerosísimas interacciones con otras facetas del proyecto como el impacto medioambiental, la generación de energía, la irradiación sobre los módulos, hidrología etc. El objetivo de esta tesis es caracterizar y cuantificar estas interacciones para ganar eficiencia en el diseño y construcción de este tipo de proyectos. En concreto se estudian 3 dimensiones: la reducción del movimiento de tierras, el impacto en la generación energética y el impacto en el medio ambiente. Primeramente, se ha trabajado en un modelado matemático a nivel estructural de la planta, con el objetivo de implementar un algoritmo para optimizar la posición de las estructuras y reducir el movimiento de tierras asociado en fases tempranas del diseño. Los resultados muestran que es posible una reducción de la cantidad total mediante un algoritmo simple basado en el modelo matemático desarrollado. Además, se está trabajando actualmente en diversos estudios para cuantificar las pérdidas por *mismatch* asociadas a diferentes factores. Para ello se han tomado datos reales de paneles y estructuras y se han modelado en diversas condiciones. Se espera obtener conocimiento para la mejora de las estimaciones de producción. Finalmente se ha planteado un estudio de campo para investigar la importancia de la vegetación en la hidrología de la planta, así como métodos para mantener esta vegetación durante períodos secos. La intención es ver qué métodos son más idóneos para prevenir la erosión y el deslizamiento de tierras y ver si son viables desde un punto de visto técnico-económico.

Palabras clave: Geomática, Modelado, Simulación, Mismatch, Obra civil, Hidrología

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1. Introduction

The surging global demand for renewable energy has propelled photovoltaic (PV) technology to the forefront of sustainable energy initiatives, with a heightened focus on optimizing the deployment of solar structures (Bóraswski *et al.* 2023). As the PV industry matures, the intricacies of civil engineering within PV projects have gained prominence, emphasizing the need for efficiency in structural design (Al Garni and Awasthi 2018). The increasing scarcity of flat terrain suitable for PV installations has resulted in more projects being developed on steep or irregular land, where civil works acquire a critical role, not only in terms of cost and schedule but also in their environmental energetic consequences.

This growing complexity highlights the intersection between geomatics, civil engineering, and algorithmic development. Specifically, there is a pressing need for tools capable of optimizing the position of structures during the early stages of design, aiming to reduce earthworks, accelerate project development, and mitigate environmental impacts.

In this context, a lightweight optimization algorithm based on mathematical modeling of plant layouts has been developed, with particular emphasis on accessibility and usability during tender phases, where rapid and license-free solutions are highly valuable. The goal is to be able to estimate the amount of earthworks associated to a particular layout, in order to compare different options during the first steps of the design process.

Parallel to these efforts, optimizing energy performance in PV plants situated on complex terrains demands a detailed assessment of irradiance variability across the site. As PV plants increasingly incorporate bifacial modules and single-axis trackers, small differences in orientation, shading, or slope can generate significant mismatch losses, which traditional evaluation methods often fail to capture.

Furthermore, precise monitoring of solar irradiance is fundamental for operational performance evaluation and performance ratio (PR) assessment. Although pyranometers are standard for measuring plane-of-array (POA) irradiance, deploying them on every tracker is infeasible in utility-scale plants. Advances in geomatic simulation, including clear-sky modeling, hillshade analysis using digital elevation models (DEMs), and bifacial irradiance estimation, enable more sophisticated, optimization-based strategies for representative sensor placement, addressing a significant gap in current practices (Li *et al.* 2024a; Li *et al.* 2024b).

The main goal is to investigate if geometrically informed algorithms can be used for sensor placement without the need for a complex irradiation model.

Finally, the increasing frequency of extreme meteorological events, such as the floods observed in Valencia in October 2024 (El País 2024), underscores the critical role of hydrological management in PV plants. In a context of swift climate change, preparing for extreme weather events is of paramount importance (Aposporis 2023).

This research integrates geomatic modeling, civil engineering optimization, and environmental assessment to advance the design and construction of PV plants on complex terrains, fostering more efficient, resilient, and sustainable renewable energy systems.

2. State of the art

The challenges associated with the deployment of photovoltaic plants on complex terrains have driven a significant body of research addressing civil works, energy performance, and environmental impacts.

In the field of civil engineering, minimizing earth movement has emerged as a key objective due to its economic and ecological implications. Extensive land grading not only increases project costs but also generates severe environmental disturbances, including habitat loss, soil erosion, and hydrological alteration (Pimentel Da Silva and Branco 2018; Tawalbeh *et al.* 2021). These works, however, focus on land usage rather than in specific problems related to earthworks. Despite its importance, most current practices rely on empirical knowledge or simplistic geometric criteria without fully exploiting algorithmic optimization based on topographic data.

Several efforts have been made to develop tools for optimizing PV plant layouts, but these often require specific software licenses or considerable computational resources, limiting their practical applicability during tender phases. Recent developments, such as the weighted least-square optimization method (Cicala *et al.* 2023), show promise in balancing computational efficiency with solution robustness; however, they have not been widely adopted in industry practice. Moreover, this solution is based on large planes, which are often not optimal from the point of view of earthworks savings.

The monitoring of irradiance variability across large-scale PV plants is another area with substantial knowledge gaps. Pyranometers remain the standard for measuring Plane of the Array (POA) irradiance, but economic and logistical constraints preclude widespread deployment across thousands of trackers. Traditional heuristic approaches—such as installing sensors on central rows—fail to account for spatial and energetic heterogeneity. New simulation techniques, including clear-sky irradiance modeling, digital elevation model (DEM) based hillshade analysis, and bifacial irradiance estimation, allow for a more representative selection of sensor locations. However, systematic methodologies integrating these tools into sensor placement strategies are still emerging, with notable studies like those of (Alcañiz *et al.* 2025; Pau *et al.* 2014) providing important initial frameworks. These works, however, focuse in the case of rooftop facilities, leaving aside the case of bifacial panels with solar tracking, which is extended in utility scale projects.

Finally, the increased occurrence of extreme weather events linked to climate change has amplified the urgency of effective hydrological management in PV plants. Traditional soil conservation measures, particularly vegetation establishment, have been proposed as viable strategies to mitigate erosion and reduce runoff (Choi *et al.* 2020). Yet, there remains a lack of comprehensive field studies specifically tailored to PV environments, particularly those combining hydrological performance with technical-economic feasibility evaluations.

In summary, while significant advances have been made, critical gaps persist in optimizing the interplay between topography, civil works, energy performance, and environmental sustainability in PV plants. This research seeks to address these gaps through an integrated approach grounded in geomatics, simulation, and field validation.

3. Methods

This study addresses three complementary research lines: earthworks minimization, optimal placement of irradiance sensors, and hydrological resilience strategies in photovoltaic (PV) plants located on complex terrains.

For the minimization of earthworks, a mathematical model (G-WLS) based on a Weighted Least Squares (WLS) approach was developed. The model represents the spatial configuration of single-axis tracker structures and adjusts the pile elevations to minimize earth movement while respecting constraints on maximum allowable slopes in both north-south (NS) and east-west (EW) directions, as well as continuity requirements between adjacent trackers. Design parameters such as tracker pitch, cantilever lengths, and maximum slope tolerances were explicitly incorporated. (García-Salinas *et al.* in review). In Figure 1 a depiction of the main variable can be found.

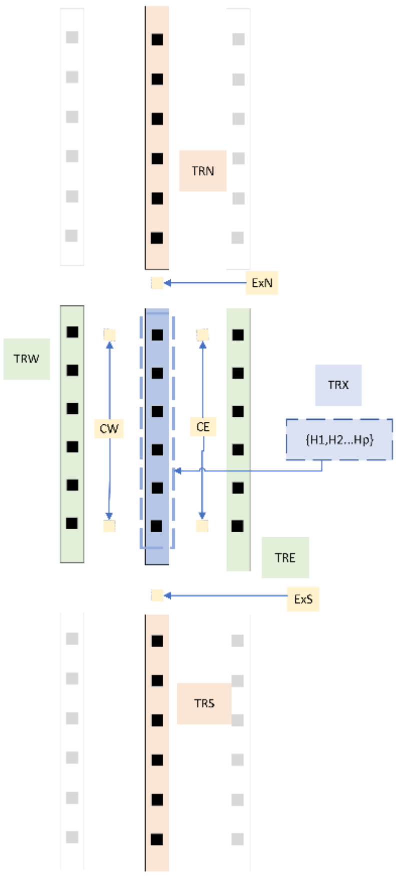

Figure 1: G-WLS model of PV plant. For each tracker TRX (blue), its neighbors in North-south direction (orange) and east-west direction (green) are considered to calculate slopes. Then external points ExN and EXs and central points CW and CE are used to pose additional constraints to ensure smooth solution.

The modelization was applied to a real plant and the earthworks were calculated and compared with a traditional solution based on planes. The mathematical minimization problem was in Eq. (1):

$$F = \sum_{x=1}^{x=n}\left[\left(\sum_{s=1}^{s=p_{TRx}}\left(\left|V_{Hs,TRx}\right| * FVol_s\right)\right)\right] \quad (1)$$

where

F = earthworks quantities.

$V_{Hs,TRx}$ = volume associated with each pile of the tracker.

$FVol_s$ = Function that varies with the sign of the difference of altitude of each pile. Being -1 for computing cut and 1 for computing fill.

For the optimization of pyranometer locations, seven algorithms were implemented and compared. These included heuristic methods such as K-means clustering and maximum spatial dispersion, as well as metaheuristic optimization techniques like Simulated Annealing, and multiobjective NSGA-II. These geometrically informed algorithms were compared against Multiobjective irradiance-informed algorithm to discover if they can provide good results in optimizing sensor placement.

Input data consisted of geometric coordinates, terrain elevation, and proximity to comunication boxes.

For the Multiobjective irradiance-informed algorithm, an irradiation model was developed by simulated effective irradiance using PVLib library for irrdadiance in the front side of the module and PVfactors library for the rear side of the bifacial panel (Anderson *et al.* 2023). Irradiance was calculated considering the tilt of the trackers and solar tracking at hourly resolution.

Terrain-induced shading was modeled via hillshade analyses from digital elevation models (DEMs) using GRASS (GRASS 2024). Particularly, shading was modelled with a time step of 3 hours and then interpolated to obtain shading at hourly resolution as can be seen in Figure 2.

The irradiation model was first compared with pyranometers located in one of the plants of study and validated. Then, the effectiveness of each method was evaluated using metrics such as Relative mean error (RME) and Coefficient of Determination (R^2). A total of 3 projects were assessed, all of them located in the south of Spain.

4. Results

The application of the developed methodologies yielded promising results across the research lines.

For earthworks minimization study, the G-WLS algorithm achieved a significant reduction in the volume of earth movements compared to commercial civil engineering software. Specifically, the G-WLS method reduced total earthworks by approximately 30% while ensuring compliance with slope and continuity constraints, demonstrating its potential to improve both environmental outcomes and project costs. Moreover, the computation time was drastically lower, with the G-WLS model completing optimizations in approximately 4 minutes, compared to over 2 hours required by traditional software, thus offering clear advantages during the tender phase of project development.

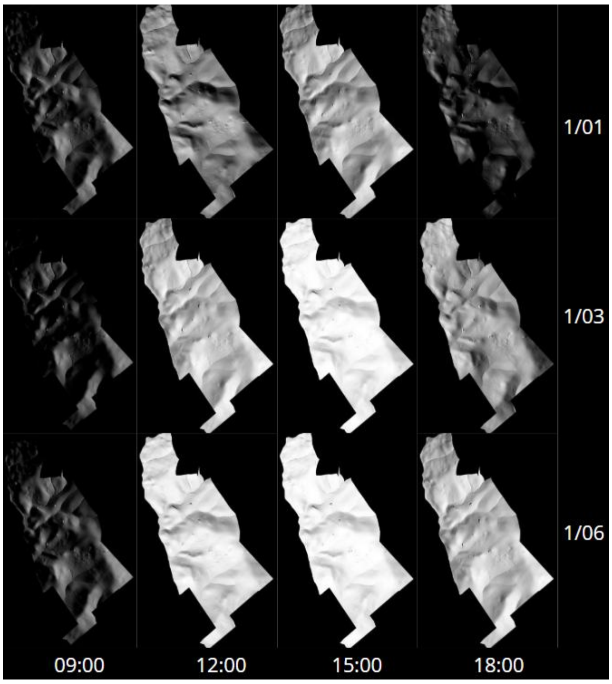

Figure 2: Shading analysis computed at a 3 hours timestep.

In the irradiance sensor placement study, the evaluation of eight different selection algorithms revealed that multiobjective optimization methods, particularly those incorporating energetic simulation variables, consistently outperformed purely geometric approaches. The irradiance-informed multiobjective method achieved the lowest Mean Absolute Error (MAE) and the highest Coefficient of Determination (R^2), indicating a superior ability to represent the temporal and spatial variability of effective irradiance across the plant. Multiobjective optimization based solely on geometrical data performed close to it. Heuristic methods such as K-Means clustering showed higher errors, particularly in sites with strong topographic variation, confirming the importance of incorporating energetic and topographic modeling into sensor deployment strategies. Figure 3 shows the comparative of RME between methods.

5. Conclusions and future works

Overall, the results demonstrate that data-driven, geomatics-integrated approaches can substantially improve the design, monitoring, and resilience of PV plants on complex terrains, offering both environmental and economic benefits.

For the case of earthworks calculation, an improvement in time of calculation and earthworks required is obtained, making it a useful tool for early stages of the project. Moreover, the fact that this approach can be implemented without the use of costly software licenses enhances its applicability to research centers and companies. Since the model only considers trackers leaving roads, platforms and other elements, more research is required to be incorporated into the calculations for a precise estimation.

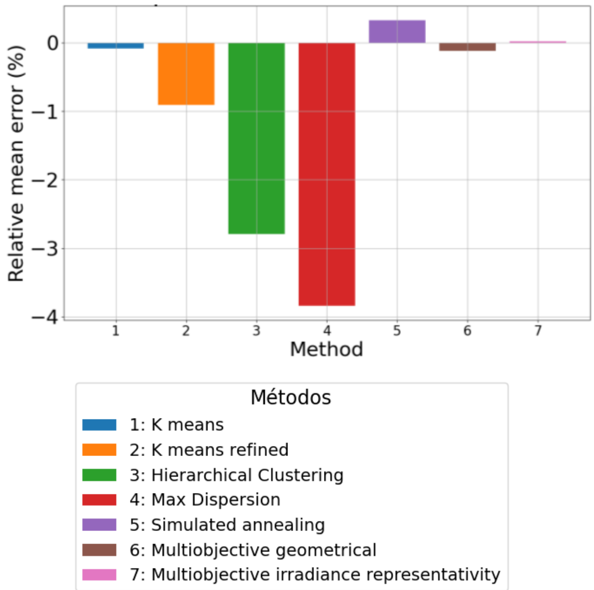

Figure 3: Representation of RME of different methods for sensor placement in project 1

Regarding sensor placement, good representativity is achieved by means of multiobjective algorithms, validating the use of geometrically informed algorithms for sensor ubication in large PV plants with bifacial modules and solar tracking. Future works will intend to improve the irradiation model to improve the capturing of rear side irradiation.

Regarding the hydrology component, preliminary planning activities have outlined the methodology for a future field study focused on vegetation-based erosion control. Although no experimental results are yet available, the study is designed to compare various vegetation management techniques under different rainfall intensities and soil types. The objective is to determine the most effective, low-maintenance strategies for enhancing hydrological stability in PV plants affected by heavy rainfall events.

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References

AL GARNI, H.Z., and AWASTHI, A. 2018. Chapter 2 - Solar PV Power Plants Site Selection: A Review. *In Advances in Renewable Energies and Power Technologies (Vol. 1).*

ALCAÑIZ, A., VAN KOUWEN, M.I., ISABELLA, O., and ZIAR, H., 2025. Wide-area sky view factor analysis and Fourier-based decomposition model for optimizing irradiance sensors allocation in European solar photovoltaic farms: A software tool. *Solar Energy*, **286**, 113139. DOI: 10.1016/J.SOLENER.2024.113139

ANDERSON, K.S., HANSEN, C.W., HOLMGREN, W.F., JENSEN, A.R., MIKOFSKI, M.A., and DRIESSE, A., 2023. pvlib python: 2023 project update. *Journal of Open Source Software*, **8**(92). DOI: 10.21105/joss.05994

APOSPORIS H., 2023. Floods in Greece drown hundreds of photovoltaic plants. Available: https://balkangreenenergynews.com/floods-in-greece-drown-hundreds-of-photovoltaic-plants/ [6/30, 2025].

BÓRAWSKI, P., HOLDEN, L., and BEŁDYCKA-BÓRAWSKA, A., 2023. Perspectives of photovoltaic energy market development in the european union. *Energy*, **270**. DOI: 10.1016/j.energy.2023.126804

CHOI, C.S., CAGLE, A.E., MACKNICK, J., BLOOM, D. E., CAPLAN, J.S., and RAVI, S., 2020. Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Frontiers in Environmental Science*, **8**. DOI: 10.3389/fenvs.2020.00140

CICALA, F.P., VALLEJO M. and RIONEGRO, M.T., 2022. Topography Analysis Methodology: Methodology for topography analysis, installation of PV mounting structrues and earthworks calculation. RatedPower. Available: https://go.ratedpower.com/hubfs/RatedPower-pvDesign-Topography-Analysis-Methodology%20(1).pdf [6/30, 2025].

GARCIA-SALINAS, C. MARTÍN-FURONES, A.E. ANQUELA JULIAN, A.B., ALEIX MORENO, J., In review. Novel approach to earthworks estimation in utility scale PV solar plants: G-WLS algorithm. Submitted to*: Applied Geomatics*

GRASS, 2024. GRASS - Bringing advanced geospatial technologies to the world. Available: https://grass.osgeo.org/ [6/30, 2025].

EL PAÍS, 2024. Las imágenes del paso de la dana en Valencia: la búsqueda de víctimas mortales | Fotos | España | EL PAÍS. Available: https://elpais.com/espana/2024-11-02/las-imagenes-del-paso-de-la-dana-en-valencia-la-busqueda-de-victimas-mortales.html [6/30, 2025].

LI, C., ZHANG, W., LIU, F., LI, X., WANG, J., and LI, C., 2024a. Multi-Objective Optimization of Bifacial Photovoltaic Sunshade: Towards Better Optical, Electrical and Economical Performance. *Sustainability*, **16**(14), 5977. DOI: 10.3390/SU16145977

LI, M., LI, Y., and DIAO, Y., 2024b. A precise and efficient K-means-ELM model to improve ultra-short-term solar irradiance forecasting. *Renewable Energy Focus*, **51**, 100645. DOI: 10.1016/J.REF.2024.100645

PAU, M., LOCCI, N., and MUSCAS, C., 2014. A tool to define the position and the number of irradiance sensors in large PV plants. *ENERGYCON 2014 - IEEE International Energy Conference*. DOI: 10.1109/ENERGYCON.2014.6850454

PIMENTEL DA SILVA, G.D., and BRANCO, D.A.C., 2018. Is floating photovoltaic better than conventional photovoltaic? Assessing environmental impacts. *Impact Assessment and Project Appraisal*, **36**(5), pp. 390-400.

TAWALBEH, M., AL-OTHMAN, A., KAFIAH, F., ABDELSALAM, E., ALMOMANI, F. and ALKASRAWI, M., 2021. Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook. *Science of the total environment*, **759**, 143528.