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BIOMIMETIC SOLAR PROJECTS

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Abstract: This paper introduces a biomimetic methodology for the design and construction of photovoltaic plants in rural areas that minimizes environmental impacts and reduces costs. Unlike conventional solar layouts that impose orthogonal geometries onto natural landscapes, the biomimetic approach integrates hydrological and topographical data to align infrastructure with natural water flow and terrain features. By mimicking the branching patterns found in nature, such as river basins and trees, the methodology reduces the need for artificial drainage, minimizes erosion, and preserves soil and water bodies. Comparative studies conducted between 2020 and 2025 across five countries demonstrated that biomimetic projects not only enhance environmental performance but also can increase energy generation potential and reduce construction costs. The results position biomimetic solar design as a technically and economically viable alternative for sustainable solar development.

Key-Words – Biomimetics, Hydrology, Photovoltaic Solar Energy.

Resumo: Este artigo apresenta uma metodologia biomimética para o projeto e construção de usinas fotovoltaicas em áreas rurais que minimiza os impactos ambientais e reduz os custos. Diferente dos layouts solares convencionais, que impõem geometrias ortogonais sobre a paisagem natural, a abordagem biomimética integra dados hidrológicos e topográficos para alinhar as infraestruturas com o escoamento natural das águas e as características do relevo. Ao imitar os padrões ramificados encontrados na natureza, como bacias hidrográficas e árvores, a metodologia reduz a necessidade de drenagem artificial, minimiza a erosão e preserva o solo e os corpos de água. Estudos comparativos realizados entre 2020 e 2025 em cinco países demonstraram que os projetos biomiméticos não apenas melhoram o desempenho ambiental, mas também podem aumentar o potencial de geração de energia e reduzir os custos de construção. Os resultados posicionam o design solar biomimético como uma alternativa técnica e economicamente viável para o desenvolvimento solar sustentável.

Palavras-Chave – Biomimética, Hidrologia, Energia Solar Fotovoltaica.

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1. INTRODUCTION

Nowadays, engineering companies often show a conceptual inertia while developing photovoltaic projects, with a conflictive industrial approach, regarding their rural surroundings.

In order to maximize their exposure to sunlight, photovoltaic structures need to be oriented in a north-south direction. It is common, therefore, for internal streets of solar plants to be parallel or perpendicular to this direction, always depending on the electromechanical arrangements.

Conventional electromechanical arrangements, usually generated by automatic software, aim only to optimize the photovoltaic occupation of a given available area, without foreseeing any environmental impacts or construction difficulties for the resulting transversal accesses.

Going up and down, while crossing undulating terrain, those straight paths artificially concentrate the surface runoff of rain. The water, gaining speed in the concrete-lined protective drains, takes less time to concentrate at the outlets.

Meanwhile, during construction, the removal of vegetation cover reduces the retention and infiltration capacity of rainfall, increasing the volume of water runoff and the probability of erosion and sedimentation of exposed soil.

Due to those altered factors, the hydrogeological risk of solar projects increases substantially, easing the occurrences of erosion processes and contamination of watercourses, with negative impacts on local communities, flora and fauna, as well as other economic and legal problems.

Alternatively, the biomimetic methodology for solar projects states that, together with the electromechanical requirements, the infrastructure layout should incorporate the specific hydrography of the existing terrain. Thus, in an organic manner, electrical routes and internal roads must be designed to simultaneously enable efficient circulation and, whenever possible, avoid crossings with watercourses or aggressive alterations to natural surface runoff.

From 2020 to 2025, comparative studies were carried out between 12 conventional photovoltaic projects and their corresponding biomimetic versions, adding up to more than one gigawatt of generation power in projects developed in Brazil, Colombia, Chile, Spain and Italy.

According to the studies, the biomimetic versions presented lower environmental risks, mainly as a consequence of the reduction or even absence of structural drainage. Going further, natural designs of biomimetic projects often allowed for increased electrical generation capacity, reduction in the total length of internal roads and less interferences between networks.

The objective of this paper is, finally, to explain and disseminate the fundamentals of the biomimetic methodology, envisioning more environmentally integrated solar projects and, at the same time, offering competitive opportunities for the companies responsible for their implementation and operation.

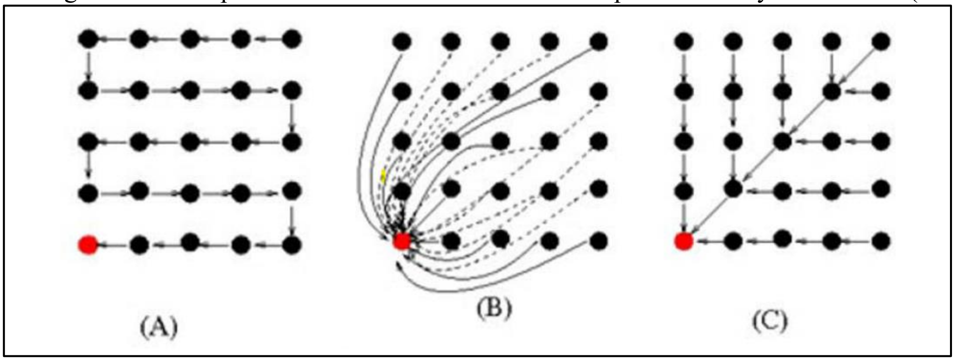
2. METHODOLOGY AND RESULTS

2.1 Orthogonal networks and dendritic networks

In nature, drainage networks present hierarchical dendritic structures, that is, smaller branches group together in collector branches and, cumulatively, create a shape similar to a tree, originated by the action of gravity guiding the water always along the steepest paths. Similarly, trees grow against gravity, with incremental diameters in their branches as the weight to be supported becomes greater.

Giacometti (2009) compared the transport efficiency of networks with grouped orthogonal paths (A), networks with individual direct paths (B), and networks with a tree structure (C) as represented in (Figure 1). Regarding the same figure, Giacometti comments: "*A tree-like structure is then an efficient structure (the most efficient, in fact!) for transporting matter (or energy) from an extended source (the black dots) to a single outlet (the red dot)*".

Figure 1 – Examples of structures with different transport efficiency. Giacometti (2000).



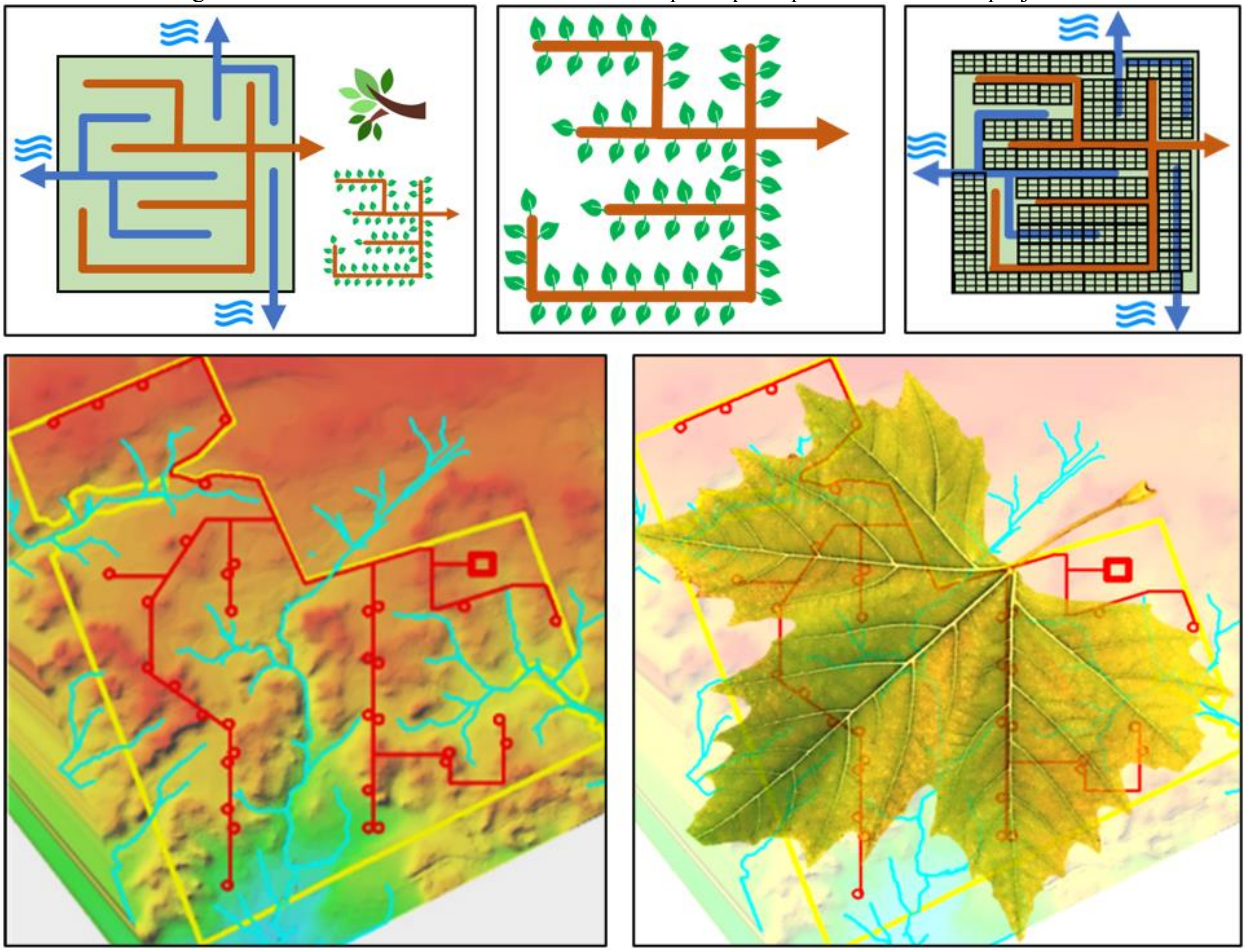
This statement inspires and supports the biomimetic approach to solar design, determining that, for energy transport, natural shapes can be more economical than purely industrial shapes (Figure 2).

Figure 2 – Visual and structural similarity between rivers, trees, leaves and electric lightning.

2.2 Biomimetic Fundamentals

The fundamental principle of biomimetic solar projects lies in the definition of branched electrical arrangements that grow with opposite directions to those of the adjacent water networks. In other words, designing accesses and electrical components locating them, whenever possible, on the safest areas regarding natural drainage (Figure 3).

Figure 3 – Tree structures based on terrain´s shape help to optimize rural solar projects.



By applying that biomimetic principle, the resulting electrical networks, embedded between the branches of the hydrographic networks, favor the coincidence of internal accesses with the watersheds (Figures 3, 4, 5 and 6). Thus, the need for structural drainage to protect accesses or watercourse crossings is drastically reduced.

Often, due to their pseudofractal geometry (Mandelbrot, 1982), biomimetic photovoltaic arrays are able to fit a greater quantity of equipment in the same implementation area as a conventional project, increasing the installed electrical generation capacity in those cases.

As well as avoiding interference and overlaps between networks, the simplification of roads and electrical trenches reduces civil works. Installation and maintenance activities are further favored by the quantitative drop of buried electrical conduits for crossings, which also reduces the incidence of rodents and insects.

Essentially, biomimetic solar projects fulfill their electromechanical demand with more natural and economical layouts based on the shape of existing waterways within the project area.

Figure 4 – Comparative images of a conventional solar layout (left) and its biomimetic version (right). The blue lines represent natural watercourses. In biomimetic projects, access roads, electrical cabins and medium voltage cables (red) are preferably located in elevated areas, protected from flooding and erosion.

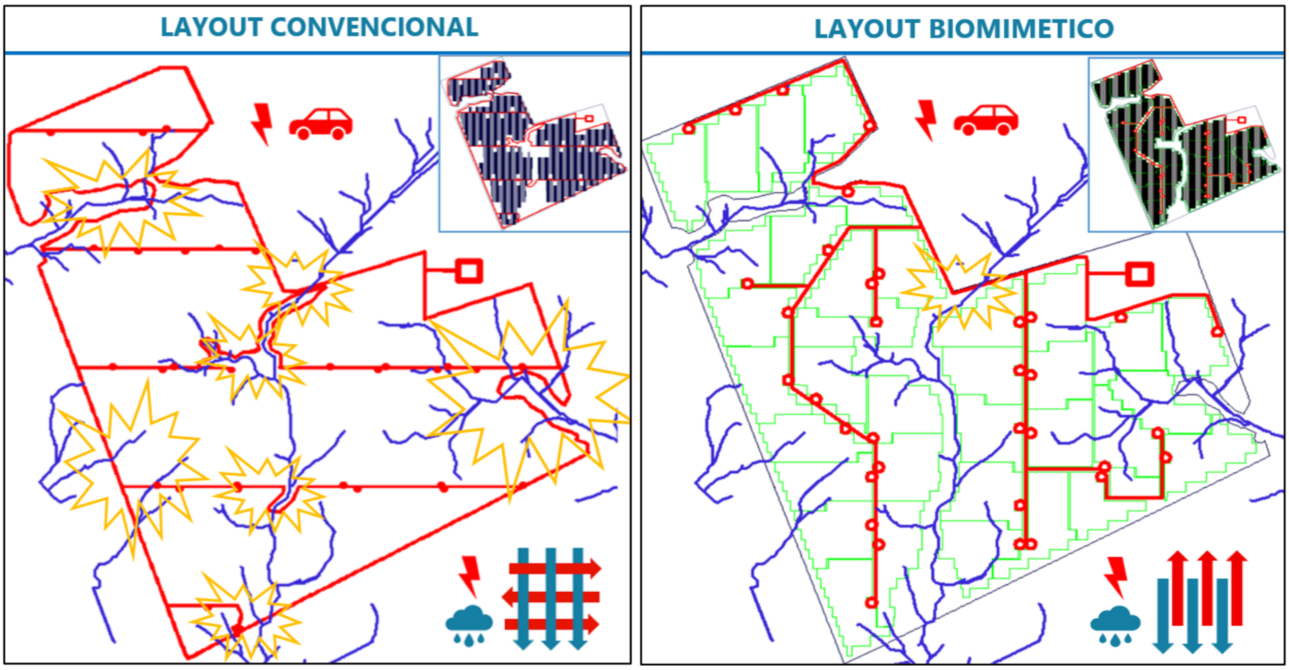


Figure 5 – Biomimetic layout with electromechanical arrangement (green) and accesses (orange/yellow) adapting to the local hydrography to optimize use of area, shorten routes and avoid interference with the natural runoff.

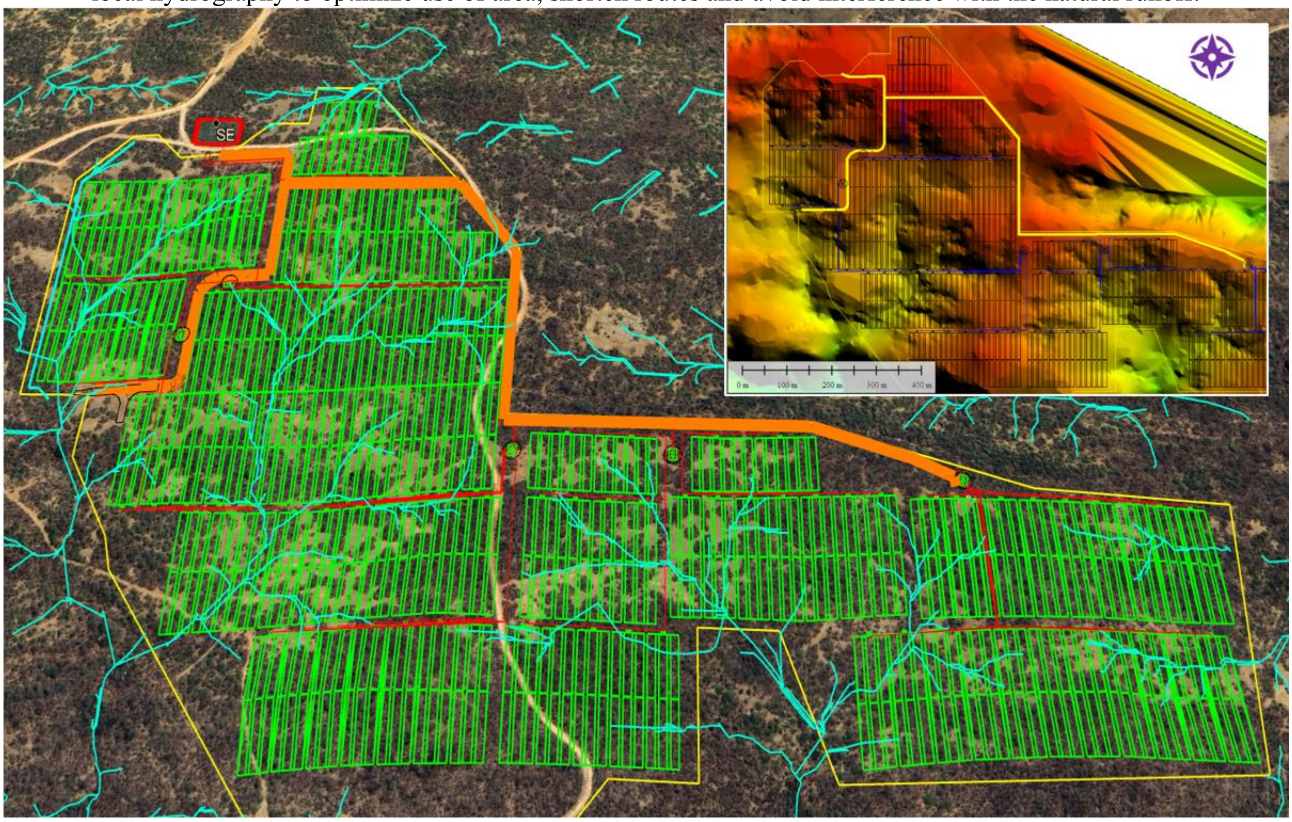
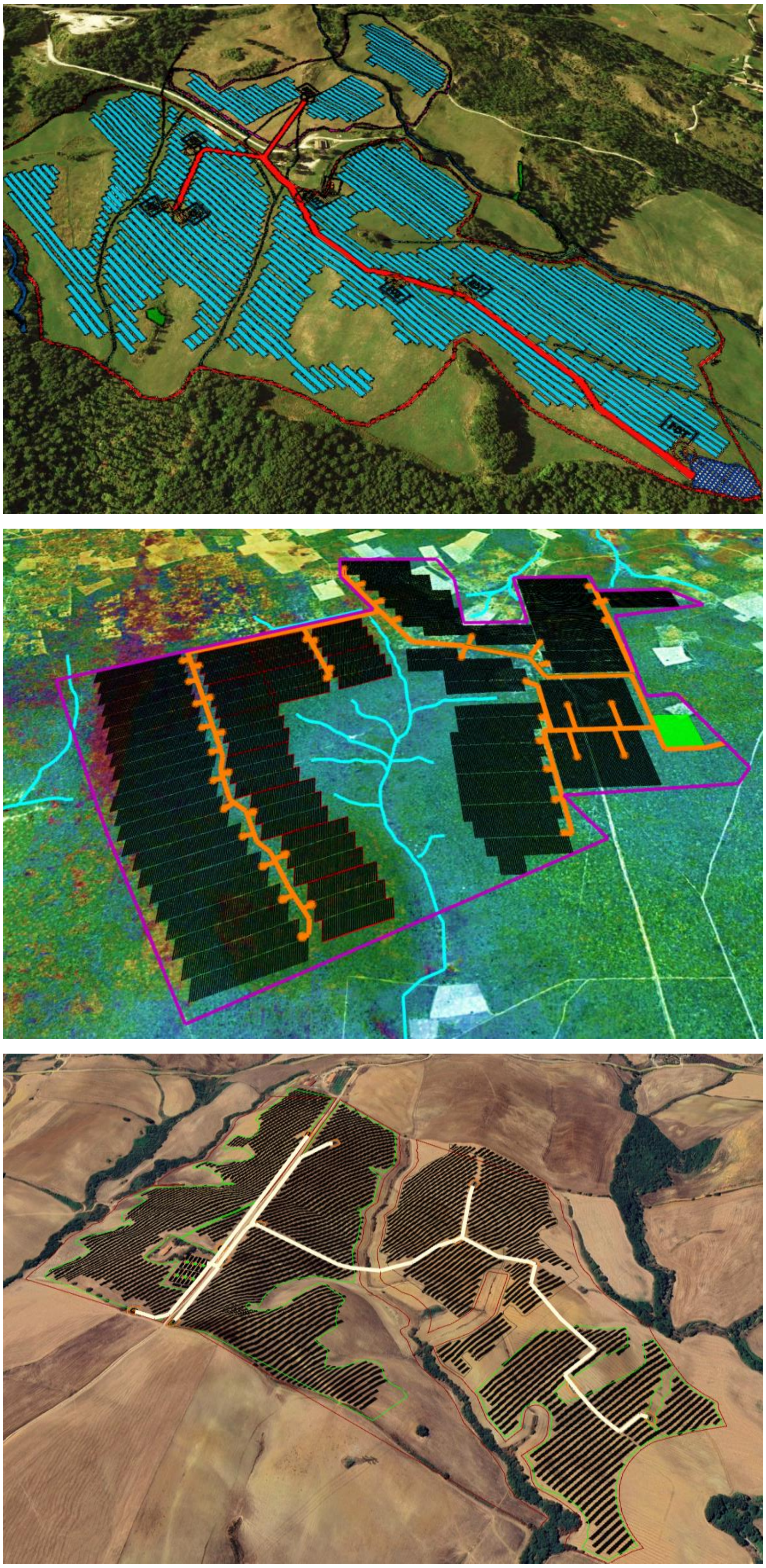


Figure 6 – Illustrative examples of solar projects developed using the biomimetic methodology



2.3 Biomimetic accesses for soil conservation

Along with the strategic use of watersheds, the biomimetic methodology includes the incorporation of curves into the layout of solar projects. Terracing based on contour lines is a traditional agricultural practice for soil conservation. Configurations that apply this technique can be particularly beneficial for large plants on nearly plain or gently undulating terrains.

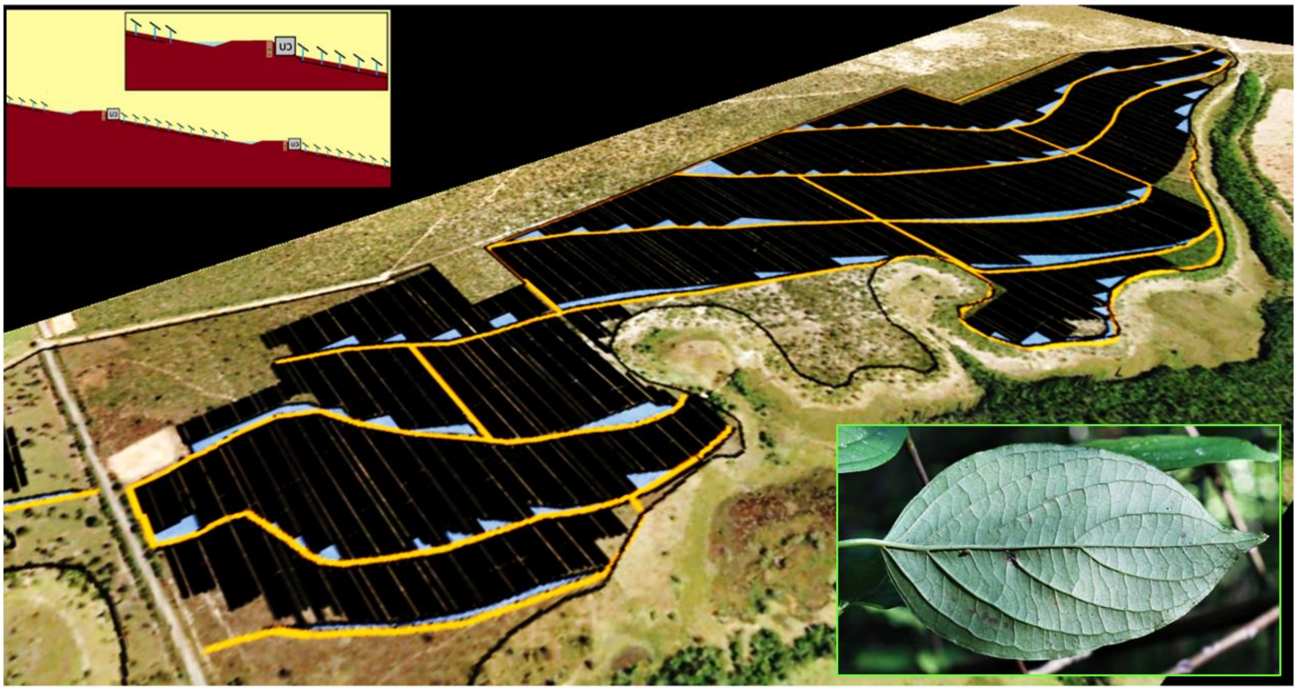
By implementing the main accesses as agricultural terraces (Figure 7), it is possible to subdivide the areas regularly and control the behavior of rainwater, also making it possible to dispense with concrete linings along the drainage routes.

Figure 7 – Layout and operation of agricultural terraces on contour lines.

By blocking and laterally diverting rain runoff, accesses on contour lines protect the electrical main components, installed on the side opposite to the water (Figure 8). For the same reason, a soil conservation effect is gained and shorter and safer routes are provided.

With no space for installations, the small remaining areas can be graded and used as micro-basins for rainwater retention, infiltration and evaporation, avoiding channeling the runoff towards bodies of water and, usually, building large basins and buffer systems for their protection.

Figure 8 – Illustrative image of a biomimetic solar project with internal accesses along contour lines.



2.4 Biomimetic vegetal suppression

The implementation of solar projects usually begins with vegetation removal, the purpose of which is to enable topographical works, leveling and installation of structures. Careful planning at this stage is crucial to prevent environmental impacts during and after construction.

Often, unaware of their importance, auxiliary accesses for vegetal suppression tend to enclose rectangular areas, intuitively starting from the limits of the property or from the project's internal roads alignments, without taking into account the slope of the terrain.

During operations, these temporary accesses are constantly scraped and compacted by the passing of machinery. Later, these degraded roads, under the actions of rain and terrain's slope, can unexpectedly concentrate runoff and initiate erosion processes and sediment dragging.

Regardless of the type of project, whether conventional or biomimetic, it is essential that the auxiliary accesses in the vegetation removal phase are topographically marked to follow the contour lines of the natural terrain. Thus, the swaths of vegetation and topsoil, running parallel to the accesses, will define new horizontal trails for their loading (Figure 9).

By applying this technique, the tire tracks and rills left passively by the machinery behave as micro agricultural terraces, retaining and distributing water laterally, favoring evaporation and infiltration and preventing the formation of erosion grooves that cause soil loss (Figure 9).

In addition to a lower environmental impact, vegetal suppression with auxiliary accesses on contour lines allows for well-spread and levelled routes, increasing the efficiency and safety of transport and siteworks, in line with the biomimetic approach.

Figure 9 – Vegetal suppression carried out correctly using auxiliary accesses on contour lines.

It is worth noting that plant mass and organic soils removed during the suppression are, in themselves, valuable resources for the construction site and for the environment. Logs, branches and topsoil are noble materials that, whenever possible, should be reused as protective elements in the plans for the recovery of degraded areas, especially when risks of affecting water bodies and natural ecosystems are identified.

3. CONCLUSIONS

It is commonly understood that any construction project tends to become more expensive and complicated when undertaking designs other than those commonly used. In the case of solar projects, it is almost counterintuitive to think of a simpler and more economical solution than designing and building rectangular areas and transversal accesses for modular industrial installations.

However, technical arguments and comparative studies have shown that several advantages emerge when the geometries of electrical and civil projects adapt themselves to the shapes of the local terrain and its hydrography.

Among those advantages, soil conservation and the preservation of water bodies and ecosystems are invaluable environmental benefits that are immediately provided.

The geometric efficiency of access and cable routes, together with the reduction of concrete linings, result in shorter construction time and costs. A more efficient transportation of smaller quantities of industrial materials also generates savings and leads to a significant reduction in direct and indirect greenhouse gas emissions.

Vegetation removal should be carried out leaving auxiliary paths and waste stockpiles aligned with the contour lines. Planning and controlling this process is essential to preserve the soil and avoid affecting watercourses, right from the start of construction.

Biomimetic solar projects are a holistic solution, technically and economically viable as an alternative to conventional projects. The author believes that the methodology hereby presented leaves a path to follow by solar designers, leading to a better integration of solar projects into the environment.

Due to their socio-environmental and economic benefits, biomimetic solar projects offer competitive strategies for sustainable solar development.

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