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How impervious are solar arrays? On the need for geomorphic assessment of energy transition technologies

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Abstract

Staying within manageable global temperature rise scenarios (i.e., 1.5° C) requires rapid decarbonization of energy sources. Research on the energy transition typically focuses on engineering, socioeconomic, and political challenges related to implementation of renewable energy technologies. Yet many facets of the energy transition are intricately intertwined with earth surface processes. Projects that advance the energy transition affect surface hydrology, sediment transport, and landscape evolution. Geomorphic processes likewise set the feasibility of energy transition projects. Here I use the lens of a recent policy debate to examine a case study that illustrates the key role of surface processes in determining the geomorphic impact and feasibility of the energy transition: the potential for conversion of agricultural land to photovoltaic arrays to drive soil erosion and water quality degradation. I point to open research questions that will result in both basic science advances and improved policy outcomes arising from effective geomorphic assessment of potential solar development. Zooming out from this case study, I suggest that there are significant environmental benefits to be gained by integrating earth surface processes research into planning for – and realizing – the transition to sustainable energy.

KEYWORDS
climate change, decarbonization, energy transition, environmental engineering, soil erosion, water resources

George Perkins Marsh's *Man and Nature* (Marsh, 1864) catalyzed the conservation movement by documenting the large-scale, human-caused geomorphic change that accompanied the industrial revolution as the first great energy transition – from wood to fossil fuels (e.g., Solomon & Krishna, 2011) – drew to a close. Now a new energy transition is underway. In an effort to avoid catastrophic global warming, we have begun the process of transforming our energy system away from fossil fuels and towards renewables. For the best chance of keeping within the still-livable warming scenario of 1.5°C, the transition to zero net carbon emissions must occur by the year 2055 at the latest, entailing a rapid rethinking of the ways that we generate, store, and consume energy (Rogelj et al., 2018).

The infrastructure required for the energy transition is being rapidly built across the globe, but interacts with Earth's surface in ways that are currently poorly understood. Any piece of energy transition infrastructure, such as a large solar array, can be judged based on its geomorphic feasibility (Is it possible and economical to build given landscape constraints?) and its geomorphic impact (How do its effects alter surface dynamics, potentially helping or harming the surrounding environment?). We seek technologies that have high geomorphic feasibility but minimize negative geomorphic impacts. We can maximize the speed and efficiency of the energy transition by building projects that, for example, are not plagued by expensive natural disasters (e.g., Mills et al., 2007) and do not meaningfully disturb the flow of water, sediment, solutes, and biota through landscapes. Quantitative analysis of the interactions between energy transition technologies and surface processes can help inform the choices that must be – and are already being – made with respect to what gets built and where, driving a more rapid and successful transition with fewer negative environmental side-effects.

There are large knowledge gaps, though, when it comes to understanding how surface processes govern the geomorphic feasibility and impact of energy transition technologies. Some of these gaps are large enough to affect policymakers making decisions under unenviable levels of uncertainty.

Consider solar arrays in the state of Virginia, USA, which provide an instructive case study in the interaction of energy transition technologies, earth surface processes, and public policy. Virginia was the fourth ranked state in the United States for solar installations in 2020 and 2021 (Solar Energy Industries Association, 2022). Solar developers are in most cases required to assess how the changes they make to the land surface will affect runoff dynamics and stormwater discharge, and to implement stormwater management techniques to minimize development impacts. Prior to March 2022, the Virginia Department of Environmental Quality (DEQ) considered only the foundations of solar installations to be impervious surfaces (Figure 1a), and ignored the panels themselves, when calculating stormwater discharges from new arrays (*Virginia Mercury*, April 18, 2022). In March 2022, the DEQ abruptly announced that the panels themselves would be reclassified as impervious surfaces, a move that exponentially increased the area of a given array considered impervious given that most arrays have panels that cover up to about half of their total land area (Figure 1b). The rule change would require many solar developers to dramatically enhance their stormwater management efforts at significant cost (*Virginia Mercury*, April 18, 2022). This sudden policy about-face reflects a lack of consensus among regulators on the extent to which solar arrays must be counted as impervious surfaces for stormwater management calculations; regulations vary widely across different localities, regions, and nations (e.g., Great Plains Institute, 2021).

The arguments between solar developers and the DEQ that followed Virginia's policy change provide an example of a debate over the geomorphic impacts of a key energy transition technology: To what extent do solar panels, which are themselves impervious but do not render the ground beneath them impervious (Figure 1), function to generate and concentrate overland flow and drive soil erosion? Understanding the impacts is necessary to determine the feasibility of the project in both economic and regulatory terms. Virginia has a legal obligation to reduce sediment-laden runoff to the ecologically critical Chesapeake Bay (US Environmental Protection Agency, 2018; Hood et al., 2021). Policymakers must therefore balance the need to build solar installations with potential soil erosion and water quality impacts – even though such considerations could dangerously slow the renewable energy transition. Similar tensions are becoming increasingly prevalent worldwide as land previously allocated to agriculture or grazing is re-purposed for solar power generation.

The lack of standardized and science-based regulations governing solar array stormwater runoff and erosion management stems, in part, from a severe lack of data. Despite the rapid proliferation of solar facilities globally, there has been little study of changes to surface water and groundwater hydrology, overland flow, and sediment transport caused by replacing predominantly agricultural and grazing land with solar panels (Bajehbaj et al., 2022). Solar development is superimposed on the existing geomorphology of a site, such that post-development hydrology and soil erosion depend on interactions between natural land-surface properties and array design choices (Figure 2). These interactions generate a complex parameter space with many contingencies, in which any natural or human-determined variable might gain or lose importance as other variables change.

The susceptibility of a site to soil erosion, in the absence of human infrastructure, is set by its climate (storm frequency, intensity, and duration; Istanbulluoglu & Bras, 2006) and land-surface properties (Figure 2). These include morphometric properties like aspect, slope,

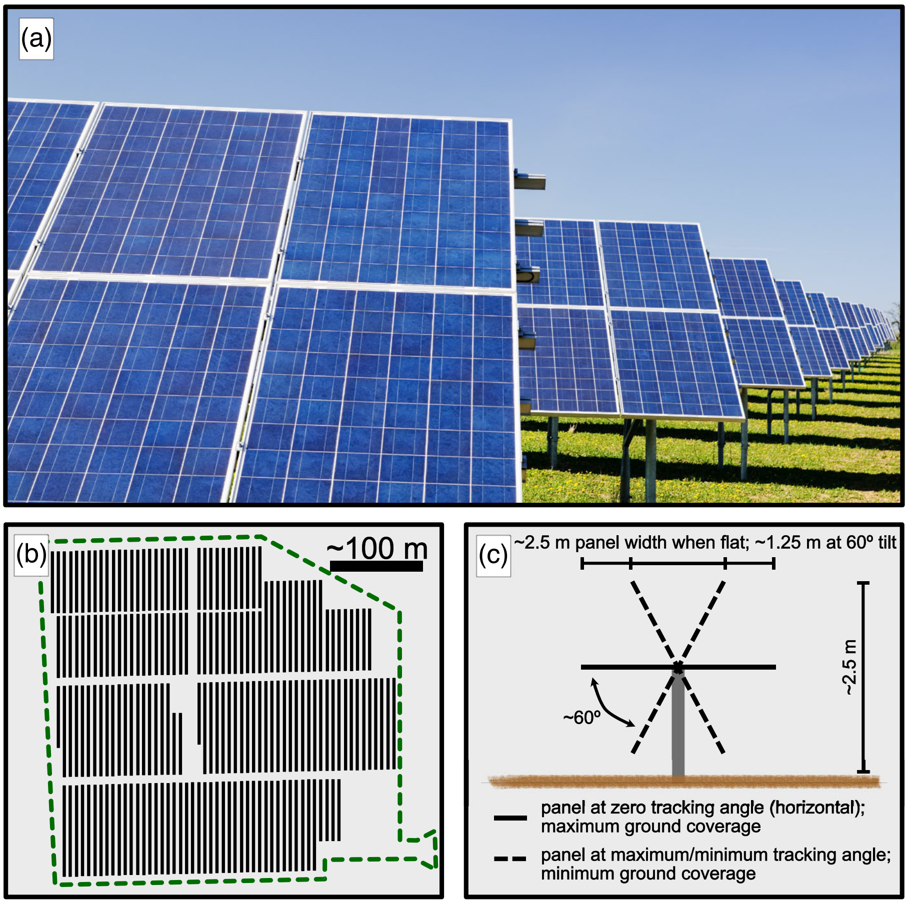

FIGURE 1 (a) Panels in a typical solar array. Panels have large surface areas and steep angles, but the sub-panel area remains pervious with the exception of small support pillars. (b) Planview schematic of a 5-MW (powers ~1000 American homes) solar array with panels in black and the extent of the project in green. Arrays can have ground coverage ratios – the ratio of panel area to total array area – up to about 50%. In this array, the longest panels are supported by 13 small posts, leaving the rest of the sub-panel area as pervious, though shielded, ground. (c) Schematic of rotation capabilities of tracking arrays (those that rotate to follow the sun) viewed from along the axis of rotation, illustrating how the direction, magnitude, and velocity of panel runoff can change temporally. While the only truly impervious area in (c) is occupied by the panel's support pillar (shown in gray), there is a 1.25–2.5 m distance over which the ground is shielded from direct rainfall, depending on the panel's rotation angle.

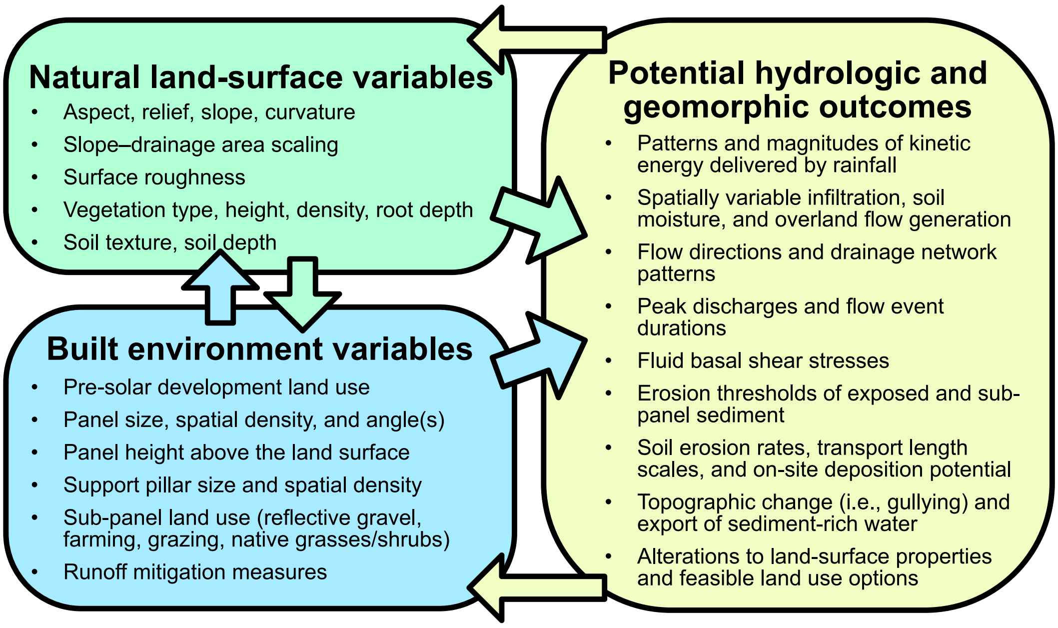

FIGURE 2 Variables governing the hydrogeomorphic outcomes of solar array development. Left-pointing arrows indicate the possibility that, over the design lifetime of the installation, surface processes might alter the land surface enough to influence site and array characteristics.

and surface roughness (e.g., Maxwell & Shobe, 2022), soil depth and texture (Istanbulluoglu & Bras, 2006; Wang & Shi, 2015), vegetation density and composition (Bond et al., 2020; Wainright et al., 2000), and other properties that affect the accumulation of overland flow as well as the resulting basal shear stresses exerted on the soil. Material properties of the soil surface, such as grain size and cohesion, set the threshold stress required to entrain and transport soil particles both in rills/gullies (e.g., Kirkby & Bracken, 2009) and interrill areas (e.g., Watson & Laflen, 1986). The relative magnitudes of the applied shear stress and threshold stress then determine the volume of soil eroded during a given storm event (e.g., Tucker et al., 2006). The extent to which soil eroded from a site reaches waterways depends on storm hydrology and site topography, including the presence of any stormwater retention structures.

Adding solar array infrastructure to a site complicates the dynamics of runoff and soil erosion (Figure 2). Because panels are tilted, they direct water in preferential directions (Figure 1a) with the quantity of runoff from each line of panels set by panel size. Many modern panels rotate to track the sun, making the area of land they cover unsteady in time (Figure 1c). Panel height may influence the kinetic energy that rainfall delivers to the land surface (Cook & McCuen, 2013), and the spatial density of panels sets the relative proportion of shielded versus open ground. The number, size, and spacing of panel support pillars govern the amount of truly impervious surface in a solar array given that panels otherwise overlie pervious ground. Aside from the configuration of the panels themselves, other choices like sub-panel land use (e.g., farming, grazing, or the spreading of reflective gravel for bifacial panels) and runoff mitigation measures also influence overland flow and soil erosion at solar installations.

The intricate interplay between landscape and built-environment variables makes it impossible to predict, through intuition alone, the effects of developing a given site for solar on runoff and soil erosion. It is easy to convince oneself that adding impervious panels drives increased runoff; it is equally easy to envision a scenario where sub-panel infiltration will prevent significant runoff and erosion. The geomorphic impacts of solar development can only be assessed by developing a process-based understanding of how natural and human-controlled variables interact to influence the dynamics of overland flow and sediment transport in these landscapes.

The relatively modest body of work on solar array hydrology and geomorphology to date indicates that all else equal, simply adding solar panels to a landscape does not necessarily increase peak water discharge, one important metric for predicting soil erosion, in contrast to what intuition might suggest. However, this result is contingent on whether or not rainfall-runoff models assume that panels add significantly to the landscape's impervious surface (Bajehbaj et al., 2022; Cook & McCuen, 2013), the same question at issue in Virginia's regulatory debate. Some preliminary calculations suggest that rainwater running off photovoltaic panels might impart substantially greater kinetic energy to the ground than raindrops do (Cook & McCuen, 2013), meaning that though the water does ultimately make contact with a pervious surface, that surface may respond differently to panel runoff than to rainfall. There has not been sufficient work to fully explore the parameter space of natural and built-environment variables that influence solar array hydrology and geomorphology. All we really know is that solar installations do not function exactly like the pre-solar landscape, but also do not function like majority-impervious land uses like asphalt parking lots (Bajehbaj et al., 2022; Barnard et al., 2017).

Producing useful geomorphic impact assessments of solar arrays requires integrating theoretical and empirical approaches to build a set of tools that are both scientifically sound and widely available to practitioners. Recent advances in computational geomorphology provide an opportunity to use dynamical, process-based approaches rather than inherited empiricisms that once dominated soil erosion studies (e.g., RUSLE; Renard et al., 1997). The advent of open-source, customizable hydrologic and surface process models (e.g., Barnhart et al., 2019; Barnhart, Hutton, et al., 2020; Kuffour et al., 2020) has expanded access to dynamical modeling tools. Users can, for example, assess not just the likelihood that a gully may form on a given landscape, but forecast its probable rates of lateral and vertical growth (e.g., Hancock & Willgoose, 2021).

Dynamical surface process models, just like their empirical counterparts, require constraints from data (e.g., Barnhart, Tucker, Doty, Shobe, et al., 2020; Batista et al., 2019; Hancock & Willgoose, 2021). Though detailed understanding of solar array hydrogeomorphic processes may currently be lacking, the fundamental controls on landscape hydrology and sediment transport still apply to the question of how solar arrays generate and concentrate erosive overland flow. We can recast longstanding basic science concepts into terms applicable to the solar runoff problem to advance policy-relevant understanding. What are the entrainment thresholds associated with common under-panel material properties and vegetation types? How does panel size modulate the competition between shielding of the ground from raindrop impacts and the potential concentration of overland flow below panel edges? Under what topographic and soil conditions do the portions of the landscape shielded from direct rainfall by panels still help absorb water through lateral surface or subsurface flow? All of these questions can be addressed empirically and the results used to inform process-based models. Being conscious of the energy transition as an overarching societal goal when we ask fundamental research questions will enable science-based assessments of the geomorphic feasibility and impacts of solar arrays.

Questions of geomorphic feasibility and impacts continue to arise as we look beyond solar towards other avenues for decarbonization. If we scale up nuclear energy production, how can we store the resulting radioactive waste in erosionally stable environments (e.g., Barnhart, Tucker, Doty, Glade, et al., 2020)? Where can hydropower production be increased to offset much-needed dam removals in the most ecologically sensitive environments (e.g., Warrick et al., 2015)? As surface mining for lithium and other rare-earth elements accelerates globally, how can we design mine reclamation strategies to restore as much natural landscape function as possible while reducing post-mining erosion (e.g., Hancock et al., 2019; Reed & Kite, 2020)?

Beneath every one of these questions lurks an important fundamental science topic that surface process scientists have been working on for over a century. What sets the width, depth, and incision rate of the gullies that threaten radioactive waste repositories and erode reclaimed surface mines (e.g., Vanmaercke et al., 2021)? How do rivers and their deposits respond to the addition and removal of obstructions (e.g., Korup & Tweed, 2007)? What role does vegetation play in modulating relationships among topography, climate, and sediment flux (e.g., Istanbulluoglu & Bras, 2005, 2006)?

The task that remains is to apply insights derived from decades of fundamental science to assess the geomorphic feasibility and impacts of key components of the energy transition. We are not currently able to supply the information that policymakers need as they attempt to balance the imperative to transition away from fossil energy as quickly as possible with the need to avoid negative environmental side-effects. Knowledge gaps lead to either stricter-than-necessary design regulations that raise costs and slow development of renewables, or regulations that are too lax, driving land and water degradation. Neither situation is good.

George Perkins Marsh was a pragmatic conservationist as well as a politician, and would recognize the need for balancing caution and speed as we race to enter a post-fossil-fuel age. In the final paragraph of *Man and Nature*, he admonishes us that "our limited faculties are at present, perhaps forever, incapable of weighing" the consequences of human modifications to Earth's surface. And yet we must weigh them; building the infrastructure to enable the energy transition is not optional. Applying 150 years' worth of progress in geomorphology to assess the feasibility and impacts of energy transition technologies will provide much-needed insight as we face our most pressing environmental challenge.

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AUTHOR CONTRIBUTIONS

CMS conceived the ideas and wrote the article.

DATA AVAILABILITY STATEMENT

No data was produced or analyzed.

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