



Curvature-guided ion transport for hydrovoltaic energy harvesting

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Hydrovoltaic power generation converts the motion of water or saline solutions at nanomaterial solid-liquid interfaces into electrical signals through charge separation and directional ion migration^[1,2]. Atmospheric heat is continuously available, yet its low energy flux makes practical conversion difficult because even modest transport losses can overwhelm the harvested energy. Evaporation-driven hydrovoltaic generators offer a promising route to couple environmental heat uptake with water and ion transport at charged interfaces^[3,4]. For nearly a decade, hydrovoltaic energy harvesting has been primarily advanced through materials-centric strategies, including increasing surface charge density, enhancing wettability, and optimizing electrode architectures. However, these approaches largely treat transport as a passive consequence of material chemistry, leaving the fundamental challenge of low-grade energy conversion and ion migration unresolved. Lin Jiang and co-workers introduce a different paradigm by treating transport pathways themselves as an active design parameter, demonstrating that controlling energy dissipation across multiple length scales can be as important as generating interfacial charges^[5].

Moving beyond conventional materials optimization, the authors leveraged machine learning to uncover how device geometry dictates power-generation performance. This analysis identified device width as a key governing parameter, revealing an overlooked contribution of structural dimensions that is not readily captured by traditional materials-centric perspectives. The predicted power density increased markedly upon entering the submillimeter regime and reached an optimum at a characteristic dimension of approximately 550 μm . This result directed the fabrication of a vertical microrod generator (VMG) based on a porous reduced-graphene-oxide/carbon-nanotube network. Through structural optimization, the evaporation-induced water transport was reorganized into directional flow through curvature-generated pressure gradients, while the construction of nanochannels reduced ion scattering and energy loss.



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This research provides a cross-scale strategy for suppressing transport dissipation. In a planar vertical film generator, the liquid-air interface is nearly flat and cannot sustain a strong directional Laplace pressure gradient. Water consequently advances faster near the edges than in the center, producing local pooling and heterogeneous flow. By contrast, the high-curvature cylindrical surface of the VMG forms a concave meniscus and generates a directional Laplace pressure gradient. Therefore, curvature functions as a mesoscale energy-landscape regulator. It converts weak and spatially distributed evaporation into a coherent hydrodynamic driving force. This low-diameter and high-curvature design transforms atmosphere-evaporation-induced water flow from slow and non-directional transport into rapid and directional transport. It thereby markedly reduces energy scattering during ion migration and enables VMG to achieve a power density of $14.3 \text{ W}\cdot\text{m}^{-2}$ and a power conversion efficiency exceeding 20%. At the nanoscale, the authors further refined the mechanism of quasi-ballistic ion transport. It is critical to distinguish this concept from conventional ballistic transport defined in solid-state physics. In conventional ballistic transport, charge carriers traverse a region whose characteristic length is shorter than their mean free path, experiencing minimal scattering. For confined liquid systems, ions remain strongly coupled to surrounding solvent molecules and inevitably experience thermal fluctuations and frictional interactions. Quasi-ballistic ion transport in VMG therefore cannot be interpreted as direct observation of collision-free ion trajectories. Instead, this concept describes a low-dissipation transport mechanism. Confinement imposed by characteristic electrostatic length scales strengthens ionic correlations and suppresses random scattering pathways. Curvature-driven directional flow further aligns ion migration with the internal electric field. The apparent reduction in migration barrier reported for the system therefore indicates reduced transport resistance rather than proof of ideal ballistic motion. This nuanced interpretation highlights the key feature of VMG. It does not eliminate all scattering processes. Instead, it designs transport pathways to minimize dissipative losses across multiple length scales. The nanochannels in VMG have characteristic dimensions comparable to the Bjerrum length of the saline solution. At this length scale, enhanced ion correlations and confinement effects facilitate low-dissipation ion transport. Such a perspective extends the impact of this work beyond hydrovoltaic power generation. Rather than relying solely on improving interfacial charge density or material chemistry, the study demonstrates that controlling the coupling between geometry, fluid dynamics, and ionic correlations can provide a general strategy for reducing transport losses in low-grade energy conversion systems.

Compared with traditional hydrovoltaic devices that mainly rely on material optimization, the VMG introduces a different design philosophy by demonstrating that transport structures can serve as decisive factors in energy conversion. Through the integration of macroscopic curvature-guided fluid transport and nanoscale confinement-regulated ion migration, the VMG minimizes transport losses and enhances power output. More broadly, this work reframes geometric architecture from a passive structural element into an active functional component, opening new opportunities for designing soft energy systems based on transport regulation rather than material properties alone. The significance of the VMG lies not only in its high-power density but also in the underlying design philosophy. Unlike previous hydrovoltaic systems that largely rely on enhancing interfacial interactions or evaporation rates, the VMG reveals that minimizing transport dissipation is equally important for efficient energy conversion. This work represents a conceptual shift from material-centric optimization toward structure-mediated regulation of energy and mass transport, offering a new strategy for designing soft energy systems that function under weak and fluctuating environmental inputs. This integrated system can supply power to practical equipment such as emergency lighting and meeting room LED lights. These results indicate that VMGs can function not only as individual energy-harvesting units but also as soft functional platforms for flexible energy devices, environmental energy harvesting, and self-powered electronic systems^[6,7].

VMGs regulated by atmospheric thermal energy via evaporation hold promising application prospects. Nevertheless, energy sources in practical environments are subject to multi-source coupling and dynamic fluctuations. Beyond evaporation, practical environments contain multiple coupled energy inputs, including solar radiation, radiative cooling, temperature gradients, airflow, mechanical fluctuations, and chemical-potential gradients. Future research should focus on developing strategies to build source-resolved energy balances, construct controllable environmental baselines, and propose multimodal signal-decoupling approaches for quantifying contributions from synergistic energy inputs. Overall, this concept could facilitate low-grade atmospheric energy harvesting, advance environmental energy extraction, and inform self-powered sensing system development. It rethinks energy conversion's fundamental architecture rather than seeking gradual material-level enhancements.

DECLARATIONS

Authors' contributions

Investigation, writing: Feng, X.

Writing - review and editing, supervision: Ge, C.; Fang, J.

Availability of data and materials

Not applicable.

AI and AI-assisted tools statement

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

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REFERENCES

1. Zhao, K.; Li, S.; Kwon, M.; et al. Hydrovoltaic electricity generators: a comprehensive overview of chemical and architectural designs. *Chem. Rev.* **2026**, *126*, 4237–317. [DOI PubMed](#)
2. Xue, G.; Xu, Y.; Ding, T.; et al. Water-evaporation-induced electricity with nanostructured carbon materials. *Nat. Nanotechnol.* **2017**, *12*, 317–21. [DOI PubMed](#)
3. Anwar, T.; Tagliabue, G. Enhancing hydrovoltaic power generation through coupled heat and light-driven surface charge dynamics. *Nat. Commun.* **2026**, *17*, 1541. [DOI PubMed PMC](#)
4. Qian, Q.; Xu, L.; Li, H. Evaporation-driven dual-function wood composites: integrating hydrovoltaic generation and thermal management in architectural applications. *Adv. Mater.* **2026**, *38*, e13000. [DOI PubMed](#)
5. Wu, M.; Wang, T.; Zhang, J.; et al. Quasi-ballistic ion transport in a vertical microrod enabling efficient evaporation-driven power generation. *Nat. Energy.* **2026**. [DOI](#)
6. Shi, X.; Wei, Y.; Tang, B.; et al. A Kirigami-driven stretchable paper-based hydrovoltaic electricity generator. *Adv. Funct. Mater.* **2025**, *35*, 2419753. [DOI](#)
7. Ren, Q.; Ni, K.; Wang, Z.; et al. Nanoporous hydrogels with tunable pore size for efficient hydrovoltaic electricity generation. *Adv. Mater.* **2025**, *37*, e2508391. [DOI PubMed](#)

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