Solar-Powered Desalination and Water Treatment: Developing Solar-Powered Technologies

Axel Egon, Abill Robert and Kaledio Potter

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Abstract:

Access to clean water is a global challenge, with over 2 billion people lacking access to safely managed drinking water. Conventional water treatment and desalination technologies often rely on fossil fuels, contributing to greenhouse gas emissions. Solar-powered water technologies offer a sustainable alternative, leveraging renewable energy to purify saline, brackish, or contaminated water.

This paper reviews the latest advancements in solar-powered desalination and water treatment systems. It examines various technologies including solar stills, solar-powered reverse osmosis, and photocatalytic water purification. The review discusses the operating principles, efficiency, and scalability of these systems.

Key factors influencing the performance and viability of solar-powered water technologies are analyzed, such as solar irradiance, temperature, feed water quality, and system design. Challenges and opportunities for further improving the cost-effectiveness, reliability, and environmental benefits of these technologies are also explored.

The paper highlights the potential of solar-powered water treatment to increase access to clean water, particularly in remote and off-grid regions. It concludes that continued research and development in this field can play a crucial role in addressing global water scarcity and promoting sustainable water management practices.

Introduction

Access to safe, clean water is a fundamental human need and a global challenge. Currently, over 2 billion people worldwide lack access to safely managed drinking water [1]. This water crisis is exacerbated by factors such as population growth, urbanization, agricultural expansion, and climate change, which are straining freshwater resources.

Conventional water treatment and desalination technologies often rely on fossil fuels, which contribute to greenhouse gas emissions and environmental degradation. As the world transitions towards more sustainable energy sources, there is growing interest in

developing water purification systems powered by renewable energy, particularly solar energy.

Solar-powered water technologies offer a promising solution to address global water scarcity in an environmentally-friendly manner. By harnessing the abundant and clean energy of the sun, these systems can desalinate or treat saline, brackish, or contaminated water without the need for grid electricity or fossil fuels.

This paper provides a comprehensive review of the latest advancements in solar-powered desalination and water treatment technologies. It examines the operating principles, efficiency, and scalability of various systems, including solar stills, solar-powered reverse osmosis, and photocatalytic water purification. The review also discusses the key factors influencing the performance and viability of these technologies, as well as the challenges and opportunities for further improvements.

The introduction of this paper will establish the context and importance of developing solar-powered water treatment solutions to address the global water crisis. It will set the stage for a detailed exploration of the technological advancements, performance characteristics, and future prospects of this rapidly evolving field.

[1] World Health Organization and UNICEF, "Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines," 2017.

II. Fundamentals of Solar-Powered Water Desalination

The fundamental principle underlying solar-powered water desalination is the use of solar energy to drive the separation of water from dissolved salts and other impurities. This process exploits the natural water cycle, where solar radiation heats and evaporates water, leaving behind the dissolved salts and contaminants.

A. Solar Thermal Desalination
Solar thermal desalination technologies harness solar energy to provide the thermal energy required for the evaporation and subsequent condensation of water. These systems typically consist of a solar collector, an evaporation chamber, and a condensation unit.

Solar Stills: One of the simplest and oldest solar desalination technologies, solar stills use a transparent cover to trap the solar-heated water vapor, which then condenses and is collected as purified water.
Solar Pond Systems: These systems utilize a shallow, saltwater pond with a black bottom to absorb solar radiation and heat the water, driving the evaporation and condensation process.
Solar Thermal Collectors: More advanced solar thermal desalination systems employ concentrated solar thermal collectors, such as parabolic troughs or heliostats, to generate high-temperature steam for driving the desalination process.

B. Solar-Powered Membrane Desalination
Solar-powered membrane desalination techniques, such as solar-powered reverse osmosis (SPRO), use photovoltaic (PV) panels to generate electricity that powers the desalination process. These systems typically include a PV array, a water pump, a membrane-based desalination unit, and associated controls and storage components.

C. Hybrid Solar-Powered Desalination
Hybrid systems integrate both solar thermal and solar-powered membrane technologies to leverage the advantages of both approaches. These systems can improve overall efficiency and reliability by combining the thermal energy from solar collectors with the electrical energy from PV panels.

The choice of solar-powered desalination technology depends on various factors, including water salinity, system scale, energy requirements, and local environmental conditions. Understanding the fundamental principles of these technologies is crucial for designing and optimizing solar-powered water desalination systems.

III. Solar Thermal Desalination Technologies

Solar thermal desalination technologies harness the thermal energy provided by solar radiation to drive the evaporation and condensation of water, thereby separating it from dissolved salts and contaminants. These technologies can be further categorized into three main types: solar stills, solar pond systems, and solar thermal collectors.

A. Solar Stills
Solar stills are one of the simplest and most widely used solar thermal desalination technologies. They consist of a basin filled with saline or brackish water, covered by a transparent material (such as glass or plastic) that traps the solar-heated water vapor, which then condenses and is collected as purified water.

Operating Principle: Solar radiation heats the water in the basin, causing it to evaporate. The water vapor then condenses on the cooler, transparent cover and is collected as distilled water.
Efficiency and Limitations: Solar stills have relatively low thermal efficiencies, typically ranging from 0.1% to 4% [1]. Their production capacity is also limited, making them suitable primarily for small-scale, off-grid applications.
Advancements: Researchers have explored various modifications to solar stills, such as using multiple basins, incorporating heat storage materials, and integrating with renewable energy sources, to improve their efficiency and scalability.
B. Solar Pond Systems
Solar pond systems utilize a shallow, saltwater pond with a black bottom to absorb and store solar radiation, creating a temperature gradient that drives the evaporation and condensation of water.

Operating Principle: The black bottom of the pond absorbs solar radiation, heating the water at the bottom of the pond. This heat is then trapped by the higher-salinity water at the top, creating a temperature gradient that drives the evaporation and condensation of water.

Efficiency and Applications: Solar pond systems can achieve thermal efficiencies of 1-2% and are suitable for medium-scale desalination applications, such as agricultural or industrial water treatment.

Advancements: Researchers have explored ways to improve the efficiency and performance of solar pond systems, such as using different pond designs, improving heat transfer, and integrating with other renewable technologies.

C. Solar Thermal Collectors

More advanced solar thermal desalination systems employ concentrated solar thermal collectors, such as parabolic troughs or heliostats, to generate high-temperature steam for driving the desalination process.

Operating Principle: Concentrated solar radiation heats a working fluid, which is then used to produce steam for driving a thermal desalination process, such as multi-stage flash (MSF) or multi-effect distillation (MED).

Efficiency and Scalability: Solar thermal collector-based desalination systems can achieve higher thermal efficiencies, typically in the range of 20-30% [2], and are suitable for large-scale, grid-connected applications.

Advancements: Researchers are exploring ways to improve the cost-effectiveness, reliability, and integration of solar thermal collector-based desalination systems, as well as exploring hybrid configurations with other renewable technologies.

[1] Kabeel, A. E., & El-Agouz, S. A. (2011). Review of researches and developments on solar stills. Desalination, 276(1-3), 1-12.

[2] Zamen, M., Soufari, S. M., Monjezi, M., & Amidpour, M. (2015). Modeling and optimization of a solar-powered multi-effect desalination system. Desalination, 354, 1-8.

IV. Solar-Powered Membrane Desalination

Solar-powered membrane desalination technologies leverage the electrical energy generated by photovoltaic (PV) panels to power membrane-based desalination processes, such as reverse osmosis (RO). These systems offer an alternative to solar thermal desalination technologies, providing a more direct conversion of solar energy into the electrical energy required for desalination.

A. Solar-Powered Reverse Osmosis (SPRO)

Solar-powered reverse osmosis (SPRO) is a widely studied and implemented solar-powered membrane desalination technology.

Operating Principle: PV panels generate electrical energy, which is used to power a water pump that pressurizes the feed water and drives it through a semi-permeable membrane. The membrane allows the passage of water molecules while retaining dissolved salts and other contaminants, producing clean, purified water.

Efficiency and Scalability: SPRO systems can achieve overall system efficiencies of 5-15% [1], depending on factors such as membrane performance, pump efficiency, and PV panel characteristics. They are suitable for a wide range of applications, from small-scale, off-grid systems to larger, grid-connected desalination plants.

Advancements: Researchers are working on improving the efficiency, reliability, and cost-effectiveness of SPRO systems, through innovations in membrane materials, energy recovery devices, and system integration with other renewable technologies.

B. Other Solar-Powered Membrane Desalination Technologies

In addition to SPRO, other solar-powered membrane desalination technologies have been developed, including:

Solar-Powered Electrodialysis: This technology uses PV-generated electricity to power an electrodialysis process, where ions are selectively removed from the feed water through ion-exchange membranes.

Solar-Powered Membrane Distillation: This approach combines solar thermal energy with membrane-based separation, where the thermal energy is used to evaporate water, which then passes through a hydrophobic membrane and is condensed as purified water.

Hybrid Solar-Powered Membrane Desalination: These systems integrate both solar thermal and solar-powered membrane technologies, leveraging the advantages of both approaches to improve overall efficiency and reliability.

The choice of solar-powered membrane desalination technology depends on factors such as water salinity, energy requirements, system scale, and local environmental conditions. Ongoing research and development in this field aim to further improve the performance, cost-effectiveness, and widespread adoption of these technologies.

[1] Ghaffour, N., Bundschuh, J., Mahmoudi, H., & Goosen, M. F. (2015). Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications. Desalination, 356, 94-114.

V. Integrated Solar-Powered Water Treatment

In addition to solar-powered desalination technologies, researchers have also explored the development of integrated solar-powered water treatment systems that combine multiple technologies to address a broader range of water purification needs.

A. Hybrid Solar-Powered Water Treatment Systems

Hybrid solar-powered water treatment systems integrate various technologies, such as solar thermal, solar-powered membrane, and solar-powered adsorption or photocatalytic processes, to provide a comprehensive solution for water treatment.

Operating Principle: These systems leverage the advantages of different solar-powered technologies to address multiple contaminants and produce high-quality water. For example, a system may combine solar-powered reverse osmosis for desalination with solar-powered ultraviolet (UV) disinfection or solar-powered adsorption for the removal of organic and inorganic pollutants.

Efficiency and Applications: Hybrid systems can achieve higher overall efficiencies and provide more versatile water treatment capabilities compared to single-technology approaches. They are suitable for various applications, from small-scale, decentralized systems to larger, grid-connected water treatment facilities.

Advancements: Researchers are exploring ways to optimize the integration and synergies between different solar-powered water treatment technologies, as well as developing advanced control systems and energy management strategies to improve the overall performance and efficiency of these integrated systems.

B. Solar-Powered Water Treatment for Specific Contaminants

In addition to comprehensive water treatment, researchers have also investigated the development of solar-powered technologies for the targeted removal of specific contaminants, such as heavy metals, organic pollutants, or microbiological contaminants.

Solar-Powered Adsorption and Photocatalysis: These technologies use solar energy to drive adsorption or photocatalytic processes for the removal of specific contaminants from water, such as heavy metals, pesticides, or pharmaceutical residues.

Solar-Powered UV Disinfection: The use of solar-powered ultraviolet (UV) light for the disinfection of water has been explored, particularly for small-scale, off-grid applications in developing regions.

Integrated Solar-Powered Treatment Trains: Researchers have also investigated the development of treatment trains that combine multiple solar-powered technologies, such as solar-powered adsorption, photocatalysis, and UV disinfection, to provide a comprehensive solution for water purification.

The integration of various solar-powered technologies into holistic water treatment systems is an active area of research, with the goal of developing affordable, reliable, and sustainable solutions for water purification in both centralized and decentralized applications.

VI. System Design and Optimization

The design and optimization of solar-powered desalination and water treatment systems involve several key considerations to ensure their efficiency, reliability, and cost-effectiveness.

A. System Components and Integration

PV Panels: The selection and configuration of photovoltaic (PV) panels are crucial, as they determine the available solar energy input and system efficiency.

Energy Storage: Incorporating energy storage systems, such as batteries or thermal energy storage, can improve the system's ability to meet fluctuating energy demands and provide continuous water production.

Water Pretreatment: Appropriate pretreatment of the feed water is essential to protect the membranes or other treatment processes from fouling and scaling, ensuring long-term system performance.

Desalination or Treatment Technology: The choice of desalination or water treatment technology, such as reverse osmosis, electrodialysis, or adsorption, depends on the water quality, energy requirements, and targeted contaminants.

System Integration: Integrating the various components, including PV panels, pumps, membranes, and control systems, is critical for optimizing the overall system performance and efficiency.

B. Energy Management and Optimization

Load Matching: Optimizing the matching between the solar energy generation and the energy demand of the desalination or water treatment process can improve the system's energy efficiency and reduce the need for energy storage.

Energy Recovery: Incorporating energy recovery devices, such as pressure exchangers or turbines, can significantly improve the overall energy efficiency of the system.

Hybrid Energy Systems: Combining solar-powered technologies with other renewable energy sources, such as wind or geothermal, can enhance the system's reliability and resilience.

System Modeling and Simulation: Advanced modeling and simulation tools can help optimize the system design, predict performance, and analyze the impact of various design parameters.

C. Environmental and Economic Considerations

Water Quality and Environmental Impact: Ensuring the produced water meets the required quality standards and minimizing the environmental impact of the system's brine or waste streams are crucial considerations.

System Scalability and Modularity: Designing scalable and modular systems can enhance their adaptability to different water demands and facilitate their deployment in various settings, from small-scale to large-scale applications.

Life-Cycle Cost Analysis: Evaluating the life-cycle costs, including capital expenditures, operational expenses, and maintenance requirements, is essential for assessing the economic viability of the solar-powered systems.

Policy and Regulatory Framework: Aligning the system design with relevant policies, regulations, and incentives can improve the overall feasibility and adoption of solar-powered desalination and water treatment technologies.

Ongoing research and development in these areas aim to further optimize the design, integration, and performance of solar-powered desalination and water treatment systems, ultimately contributing to their widespread adoption and the provision of sustainable water solutions.

VII. Deployment Challenges and Solutions

While the development of solar-powered desalination and water treatment technologies has made significant progress, there are still several challenges that need to be addressed for their widespread deployment and adoption.

A. Technical Challenges

Scalability and Modularity: Scaling up solar-powered systems to meet the water demands of larger communities or industrial applications can be technically complex, requiring the integration of multiple modules or units.

Reliability and Durability: Ensuring the long-term reliability and durability of solar-powered systems, especially in harsh environmental conditions, is crucial for their widespread acceptance and adoption.

Maintenance and Operation: Simplifying the maintenance and operation of these systems, particularly in remote or off-grid locations, can improve their accessibility and usability for local communities.

B. Economic Challenges

Capital and Operating Costs: The initial capital costs of solar-powered systems can be higher compared to conventional water treatment technologies, hindering their adoption, especially in resource-constrained regions.

Financing and Funding: Securing appropriate financing and funding mechanisms, such as government subsidies, public-private partnerships, or microfinancing, can facilitate the deployment of these technologies.

Market Development and Commercialization: Establishing a robust market ecosystem, including local supply chains, system integrators, and after-sales support, is essential for the widespread commercialization of solar-powered water treatment solutions.

C. Social and Institutional Challenges

Community Engagement and Acceptance: Engaging with local communities, understanding their water needs and cultural preferences, and ensuring the systems are tailored to their specific requirements can improve the acceptance and long-term sustainability of these technologies.

Capacity Building and Training: Providing comprehensive training and capacity-building programs for the operation and maintenance of solar-powered systems is crucial for their successful deployment and long-term viability.

Policy and Regulatory Frameworks: Developing supportive policy and regulatory frameworks, including appropriate water quality standards, incentives, and infrastructure planning, can facilitate the large-scale adoption of solar-powered desalination and water treatment technologies.

D. Potential Solutions and Strategies

Collaborative Research and Development: Fostering interdisciplinary collaborations among researchers, engineers, policymakers, and local communities can help address the multifaceted challenges and develop tailored solutions.

Pilot Deployments and Demonstration Projects: Implementing pilot projects and demonstration sites can provide valuable insights into the real-world performance, challenges, and user acceptance of solar-powered water treatment systems.

Knowledge Sharing and Capacity Building: Establishing knowledge-sharing platforms, training programs, and technical assistance initiatives can help disseminate best practices and support the deployment of these technologies in various contexts.

Innovative Financing and Business Models: Exploring innovative financing mechanisms, such as pay-as-you-go models, microfinancing, or public-private partnerships, can improve the affordability and accessibility of solar-powered water treatment solutions.

Policy and Regulatory Harmonization: Developing harmonized policies, regulations, and standards across different regions and countries can facilitate the widespread adoption and scaling of solar-powered water treatment technologies.

Addressing these technical, economic, and social challenges through collaborative efforts, pilot deployments, capacity building, and supportive policy frameworks can pave the way for the widespread adoption and large-scale implementation of solar-powered desalination and water treatment technologies.

VIII. Case Studies and Best Practices

To illustrate the successful deployment and real-world applications of solar-powered desalination and water treatment technologies, this section presents several case studies and highlights best practices.

A. Case Studies

Seawater Desalination in Remote Islands
Location: Archipelago of the Maldives
Challenge: Providing reliable and affordable freshwater to remote island communities
Solution: Deployment of solar-powered reverse osmosis (SWRO) desalination systems
Key features: Modular design, integration with battery storage, remote monitoring and control
Outcomes: Improved water security, reduced reliance on diesel generators, and community engagement
Brackish Water Treatment for Irrigation
Location: Kutch region, India
Challenge: Saline groundwater contamination and limited freshwater availability for agriculture
Solution: Implementation of solar-powered electrodialysis reversal (EDR) systems
Key features: Decentralized, community-based approach, integration with drip irrigation
Outcomes: Increased crop yields, reduced soil salinization, and improved livelihoods
Off-Grid Drinking Water Production
Location: Remote villages in Sub-Saharan Africa
Challenge: Lack of access to safe drinking water in off-grid communities
Solution: Deployment of solar-powered membrane filtration systems
Key features: Simplicity of operation, low maintenance requirements, community engagement
Outcomes: Improved health and sanitation, reduced waterborne diseases, and enhanced community resilience

B. Best Practices

Community Engagement and Ownership
Involving local communities in the design, implementation, and maintenance of solar-powered water systems
Fostering a sense of ownership and responsibility among community members
Capacity Building and Training
Providing comprehensive training programs for system operators and local technicians
Ensuring the long-term sustainability of the deployed technologies
Adaptable and Modular Design
Developing scalable and modular systems that can be easily replicated and expanded
Allowing for flexibility in accommodating changing water demands and community needs
Integrated Monitoring and Remote Management
Implementing real-time monitoring and control systems to optimize system performance
Enabling remote troubleshooting and maintenance support
Innovative Business and Financing Models
Exploring pay-as-you-go, microfinancing, and public-private partnership schemes
Ensuring the affordability and accessibility of solar-powered water solutions
These case studies and best practices highlight the potential of solar-powered desalination and water treatment technologies to address the water scarcity challenges in various geographic and socioeconomic settings. By learning from these successful deployments and incorporating the identified best practices, the widespread adoption and scalability of these sustainable water solutions can be further accelerated.

IX. Future Trends and Research Directions

As the field of solar-powered desalination and water treatment continues to evolve, several promising future trends and research directions have emerged that can further enhance the capabilities and impact of these technologies.

A. Technological Advancements

Improved Membrane and Material Science: Ongoing research to develop more efficient, durable, and cost-effective membrane materials and coatings for desalination and water purification.
Advanced Energy Storage Solutions: Exploring the integration of high-capacity, long-duration energy storage systems, such as flow batteries and thermal energy storage, to improve the reliability and resilience of solar-powered water treatment systems.
Hybrid and Integrated Systems: Investigating the synergies between solar-powered technologies and other renewable energy sources, such as wind or geothermal, to create hybrid systems that optimize energy utilization and water production.

Artificial Intelligence and Automation: Leveraging the advancements in artificial intelligence, machine learning, and automation to enhance the monitoring, control, and optimization of solar-powered water treatment systems.

B. Innovative Applications and Scaling

Desalination for Agriculture: Developing solar-powered desalination systems tailored for irrigation and crop water requirements, particularly in water-stressed regions.
Decentralized and Community-Based Solutions: Designing scalable, modular, and user-friendly solar-powered water treatment technologies for off-grid and remote communities.
Industrial and Commercial Applications: Exploring the deployment of solar-powered water treatment systems in industrial and commercial settings, such as manufacturing, mining, and hospitality, to reduce water footprint and enhance sustainability.
Integrated Water-Energy-Food Nexus: Investigating the synergies and interdependencies between solar-powered water treatment, renewable energy generation, and sustainable agriculture to address the water-energy-food challenges in a holistic manner.

C. Socioeconomic and Policy Considerations

Inclusive and Equitable Access: Ensuring that solar-powered water solutions are designed and deployed in a manner that promotes universal and equitable access to clean water, particularly for marginalized communities.
Capacity Building and Knowledge Transfer: Developing comprehensive training programs and knowledge-sharing platforms to empower local communities, technicians, and policymakers in the operation, maintenance, and scaling of solar-powered water technologies.
Enabling Policy and Regulatory Frameworks: Advocating for the development of supportive policy and regulatory environments that incentivize the adoption of solar-powered water treatment solutions and promote sustainable water management practices.
Collaborative Partnerships and Funding Mechanisms: Fostering multi-stakeholder collaborations, including public-private partnerships and international development initiatives, to mobilize the necessary financial and technical resources for the widespread deployment of solar-powered water technologies.
By embracing these future trends and research directions, the solar-powered desalination and water treatment sector can continue to evolve, addressing the pressing challenges of water scarcity and accessibility while contributing to the broader goals of sustainable development and environmental stewardship.

Conclusion

Solar-powered desalination and water treatment technologies have emerged as a promising and sustainable solution to address the global challenge of water scarcity. These innovative technologies harness the abundant and renewable energy of the sun to power various water purification and desalination processes, providing clean and affordable water to communities in need.

Throughout this report, we have explored the fundamental principles, key components, and technical advancements in the field of solar-powered water treatment. We have discussed the various desalination and water purification technologies, their respective advantages and limitations, and the strategies for optimizing their performance and integration with solar energy systems.

The presented case studies have demonstrated the successful real-world deployment of these technologies in diverse geographical and socioeconomic settings, highlighting the transformative impact they can have on communities facing water scarcity challenges. The identified best practices, such as community engagement, capacity building, and innovative financing models, provide valuable insights for practitioners and policymakers to ensure the long-term sustainability and scalability of these solutions.

Looking to the future, we have outlined several trends and research directions that hold the potential to further enhance the capabilities and impact of solar-powered water treatment technologies. These include technological advancements in materials and energy storage, the emergence of hybrid and integrated systems, the exploration of innovative applications, and the consideration of socioeconomic and policy factors.

As the global community strives to achieve the United Nations Sustainable Development Goals, the widespread adoption and scaling of solar-powered desalination and water treatment technologies will be crucial in addressing the water crisis and ensuring equitable access to clean and reliable water resources. By fostering collaborative partnerships, mobilizing resources, and implementing supportive policies, the solar-powered water treatment sector can pave the way for a more sustainable and water-secure future for all.

References

1) Rezk, A-m A. "Solar energy engineering." International Journal of Heat and Mass Transfer/International Journal of Heat and Mass Transfer, vol. 22, no. 6, June 1979, pp. 984–85. https://doi.org/10.1016/0017-9310(79)90046-2.

2) Xie, Xiuqiang, Katja Kretschmer, and Guoxiu Wang. "Advances in graphene-based semiconductor photocatalysts for solar energy conversion: fundamentals and materials engineering." Nanoscale 7.32 (2015): 13278-13292.

3) Ali, Sadaquat, et al. "A matlab-based modelling to study and enhance the performance of photovoltaic panel configurations during partial shading conditions." *Frontiers in Energy Research* 11 (2023): 1169172.

4) Goswami, D. Yogi, et al. "New and emerging developments in solar energy." Solar energy 76.1-3 (2004): 33-43.

5) Şen, Zekai. "Solar energy in progress and future research trends." Progress in energy and combustion science 30.4 (2004): 367-416.

6) Kabir, Ehsanul, et al. "Solar energy: Potential and future prospects." Renewable and Sustainable Energy Reviews 82 (2018): 894-900.

7) Ciriminna, Rosaria, et al. "Rethinking solar energy education on the dawn of the solar economy." Renewable and Sustainable Energy Reviews 63 (2016): 13-18.

8) Ali, Sadaquat, et al. "Corrigendum: A matlab-based modelling to study and enhance the performance of photovoltaic panel configurations during partial shading conditions." *Frontiers in Energy Research* 11 (2023): 1326175.

9) Barber, James. "Biological solar energy." Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365.1853 (2007): 1007-1023.

10) Devabhaktuni, Vijay, et al. "Solar energy: Trends and enabling technologies." Renewable and Sustainable Energy Reviews 19 (2013): 555-564.

11) El Iysaouy, Lahcen, et al. "Performance enhancements and modelling of photovoltaic panel configurations during partial shading conditions." *Energy Systems* (2023): 1-22.

12) Hou, Yu, Ruxandra Vidu, and Pieter Stroeve. "Solar energy storage methods." Industrial & engineering chemistry research 50.15 (2011): 8954-8964.

13) Camacho, Eduardo F., and Manuel Berenguel. "Control of solar energy systems." IFAC proceedings volumes 45.15 (2012): 848-855.

14) Kannan, Nadarajah, and Divagar Vakeesan. "Solar energy for future world:-A review." Renewable and sustainable energy reviews 62 (2016): 1092-1105.

15) Hu, Jun, et al. "Band Gap Engineering in a 2D Material for Solar-to-Chemical Energy Conversion." Nano Letters, vol. 16, no. 1, Dec. 2015, pp. 74–79. https://doi.org/10.1021/acs.nanolett.5b02895.

16) Jung, Eui Hyuk, et al. "Bifunctional Surface Engineering on SnO2 Reduces Energy Loss in Perovskite Solar Cells." ACS Energy Letters, vol. 5, no. 9, Aug. 2020, pp. 2796–801. https://doi.org/10.1021/acsenergylett.0c01566.

17) Mussgnug, Jan H., et al. "Engineering photosynthetic light capture: impacts on improved solar energy to biomass conversion." Plant Biotechnology Journal, vol. 5, no. 6, Aug. 2007, pp. 802–14. https://doi.org/10.1111/j.1467-7652.2007.00285.x.

18) Ramachandra, T. V., et al. "Milking Diatoms for Sustainable Energy: Biochemical Engineering versus Gasoline-Secreting Diatom Solar Panels." Industrial & Engineering Chemistry Research, vol. 48, no. 19, June 2009, pp. 8769–88. https://doi.org/10.1021/ie900044j.

19) Ran, Lei, et al. "Defect Engineering of Photocatalysts for Solar Energy Conversion." Solar RRL, vol. 4, no. 4, Jan. 2020, https://doi.org/10.1002/solr.201900487.

20) Sharma, Atul, et al. "Review on thermal energy storage with phase change materials and applications." Renewable & Sustainable Energy Reviews, vol. 13, no. 2, Feb. 2009, pp. 318–45. https://doi.org/10.1016/j.rser.2007.10.005.

21) Wang, Pengyang, et al. "Gradient Energy Alignment Engineering for Planar Perovskite Solar Cells with Efficiency Over 23%." Advanced Materials, vol. 32, no. 6, Jan. 2020, https://doi.org/10.1002/adma.201905766.

22) Wang, Xiaotian, et al. "Engineering Interfacial Photo-Induced Charge Transfer Based on Nanobamboo Array Architecture for Efficient Solar-to-Chemical Energy Conversion." Advanced Materials, vol. 27, no. 13, Feb. 2015, pp. 2207–14. https://doi.org/10.1002/adma.201405674.

23) Xu, Mingfei, et al. "Energy-Level and Molecular Engineering of Organic D-π-A Sensitizers in Dye-Sensitized Solar Cells." Journal of Physical Chemistry. C./Journal of Physical Chemistry. C, vol. 112, no. 49, Nov. 2008, pp. 19770–76. https://doi.org/10.1021/jp808275z.

24) Yang, Guang, et al. "Interface engineering in planar perovskite solar cells: energy level alignment, perovskite morphology control and high performance achievement."

Journal of Materials Chemistry. A, vol. 5, no. 4, Jan. 2017, pp. 1658–66. https://doi.org/10.1039/c6ta08783c.

25) Zhang, Ning, et al. "Oxide Defect Engineering Enables to Couple Solar Energy into Oxygen Activation." Journal of the American Chemical Society, vol. 138, no. 28, July 2016, pp. 8928–35. https://doi.org/10.1021/jacs.6b04629.

26) Zhu, Haiming, and Tianquan Lian. "Wavefunction engineering in quantum confined semiconductor nanoheterostructures for efficient charge separation and solar energy conversion." Energy & Environmental Science, vol. 5, no. 11, Jan. 2012, p. 9406. https://doi.org/10.1039/c2ee22679k.