UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 6(3), September (2026), 3648-3654
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Design and Simulation Validation of a Liquid–Liquid Heterojunction Triboelectric Nanogenerator Integrated with Photovoltaic Modules for All-Weather Energy Harvesting

Stanley Chinedu Okafor*
Industrial and Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State
Chika Edith Mgbemena
Industrial and Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State
Charles Chikwendu Okpala
Industrial and Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State
Ogochukwu Chinedum Chukwunedum
Industrial and Production Engineering, Nnamdi Azikiwe University, Awka, Anambra State

**Corresponding Author's E-mail: oc.chukwunedum@unizik.edu.ng*

Abstract

This study presents the design and simulation validation of a liquid–liquid heterojunction triboelectric nanogenerator (LL-H-TENG) integrated with photovoltaic (PV) modules for all-weather energy harvesting. The proposed system utilizes immiscible liquid interfaces within a horizontal microchannel to enable durable and transparent energy conversion under rainfall-induced excitation. A finite element model based on Poisson's equation was developed to evaluate the electrostatic behavior of the system. Simulation results demonstrate a stable electric potential distribution across the microchannel and a linear increase in output voltage with excitation frequency (1–5 Hz). The electric potential varied from approximately 1.0 V to 0 V across the microchannel, while the output voltage increased from approximately 0.2 V at 1 Hz to 1.0 V at 5 Hz, confirming the feasibility of LL-H-TENG architectures as durable and complementary energy harvesting systems for photovoltaic applications.

Keywords: Triboelectric Nanogenerator, Liquid–Liquid Heterojunction, Photovoltaic Integration, Finite-Element Simulation, Fenicsx, All-Weather Energy Harvesting.

1. Introduction

The global demand for sustainable and reliable energy sources has led to rapid growth in renewable energy technologies, particularly photovoltaic (PV) systems. PV modules convert solar radiation directly into electrical energy and offer advantages such as modularity, silent operation, and minimal maintenance requirements. Despite these benefits, the output of PV systems is highly dependent on environmental conditions, resulting in reduced power generation during cloudy, dusty, and rainy periods (Mekhilef, Saidur and Safari, 2015; Mellit, Kalogirou and Shaari, 2020).

Rainfall presents a dual challenge to photovoltaic systems. While rain can clean the surface of PV panels and improve long-term efficiency, it simultaneously reduces instantaneous solar irradiance, leading to a drop in electrical output. This intermittency limits the ability of PV systems to serve as reliable standalone energy sources, particularly in tropical regions where rainfall is frequent and unpredictable (Mekhilef, Saidur and Safari, 2015).

Triboelectric nanogenerators (TENGs) have emerged as a promising technology for harvesting low-frequency mechanical energy from ambient sources such as vibration, wind, and raindrops (Wang, 2017; Chen, Zhu, Yang, Jing and Wang, 2015). Hybrid systems combining PV modules with TENGs have therefore attracted increasing attention as a pathway towards all-weather energy harvesting (Yang, Zhang, Zhu and Wang, 2016; Zi, Wang, Wang and Wang, 2016).

Most existing PV–TENG hybrid systems rely on solid–solid or solid–liquid triboelectric interfaces, which are prone to mechanical wear, surface degradation, and humidity-induced charge dissipation (Niu and Wang, 2015; Wang, Zi and Wang, 2015). Liquid-based triboelectric nanogenerators have been proposed as an alternative approach, offering self-refreshing interfaces, improved durability, and enhanced environmental stability (Zi, Wang, Wang and Wang, 2016; Zhu, Zhang and Wang, 2018).

Recent studies have further explored hybrid and liquid-based triboelectric systems for improved durability and environmental adaptability (Zhu, Zi, Wang and Wang, 2019; Zi, Wang, Wang and Wang, 2016).

This study introduces a novel liquid–liquid heterojunction triboelectric nanogenerator (LL-H-TENG) integrated with a photovoltaic module for all-weather energy harvesting. Unlike conventional solid–solid triboelectric systems, the proposed design utilizes immiscible liquid interfaces within a horizontal microchannel configuration, which minimizes mechanical wear and enhances durability under repeated excitation. In addition, this work employs a finite-element-based simulation framework to analyze the electrostatic potential distribution and voltage response of the system under rainfall-induced conditions.

Despite recent advancements in triboelectric nanogenerators for hybrid energy systems, limited attention has been given to liquid–liquid heterojunction architectures specifically designed for photovoltaic integration. In addition, most existing studies focus on experimental prototypes without comprehensive numerical validation of electrostatic behavior under realistic environmental excitation.

This study addresses these gaps by introducing a horizontal liquid–liquid heterojunction triboelectric nanogenerator (LL-H-TENG) and providing finite-element-based simulation validation under rainfall-induced excitation. The key contributions of this work include:

1) the design of a stable liquid–liquid heterojunction architecture within a horizontal microchannel configuration;
2) the implementation of a finite-element model based on Poisson's equation to analyze electrostatic potential distribution;
3) the demonstration of stable and artifact-free electric field behavior under time-dependent excitation; and
4) the establishment of compatibility with photovoltaic systems for all-weather energy harvesting.

These contributions distinguish the present work from conventional solid-based triboelectric systems and provide a foundation for the development of durable hybrid energy harvesting technologies.

2.0 Materials and methods

2.1 System Design and Architecture

The proposed LL-H-TENG system is designed to harvest mechanical energy from rainfall while maintaining compatibility with photovoltaic modules. The device consists of an array of horizontal microchannels fabricated within a dielectric substrate. Each microchannel contains two immiscible liquids that form a stable liquid–liquid heterojunction along the channel length.

The selection of a horizontal microchannel configuration minimizes gravitational instability of the liquid interface and enables planar integration with PV modules. The microchannels are sealed using a transparent dielectric layer to preserve optical transmission and protect the liquids from environmental contamination.

The overall structure and operating principle of the proposed LL-H-TENG integrated with a photovoltaic module are illustrated in Fig. 1.

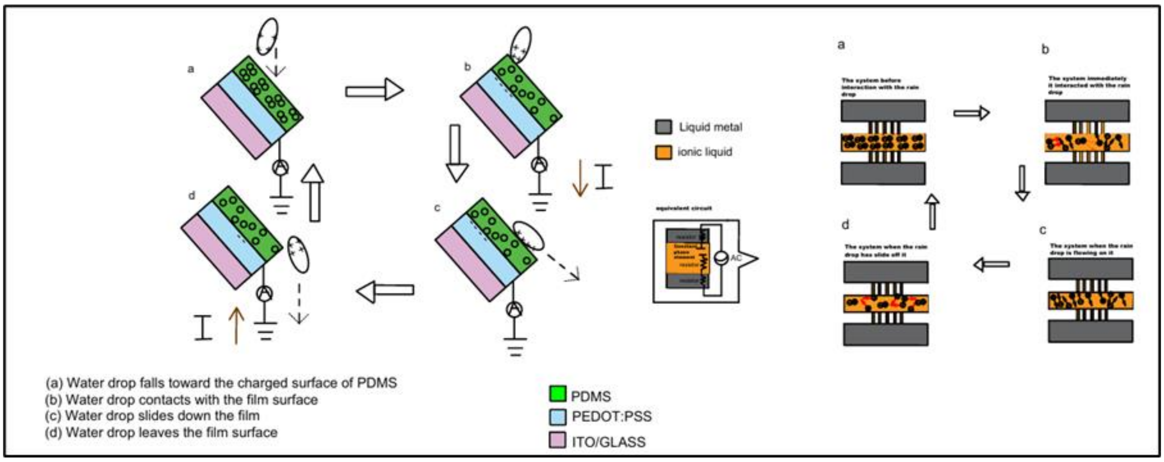

Fig. 1. Working mechanism of the liquid–liquid transparent heterojunction triboelectric nanogenerator (LL-H-TENG) integrated on a photovoltaic panel: (a) raindrop approaching the PDMS surface, (b) contact and charge transfer, (c) sliding-induced electrostatic induction, and (d) charge redistribution after droplet departure. The equivalent electrical circuit representation is also illustrated.

When raindrops impact the surface of the device, pressure fluctuations are transmitted to the liquid within the microchannels, causing periodic displacement of the liquid–liquid interface (Zi, Wang, Wang and Wang, 2016). This dynamic motion results in time-varying triboelectric charge separation at the interface, which induces an alternating electric potential between the electrodes connected to the system.

The LL-H-TENG is positioned adjacent to or above the photovoltaic module such that both systems can operate simultaneously. During periods of high solar irradiance, the PV module dominates energy generation, while during rainfall and low-light conditions, the LL-H-TENG provides supplementary electrical output (Yang, Zhang, Zhu and Wang, 2016; Zi, Wang, Wang and Wang, 2016).

The conceptual microchannel layout and structural configuration adopted for the proposed system are shown in Fig. 2.

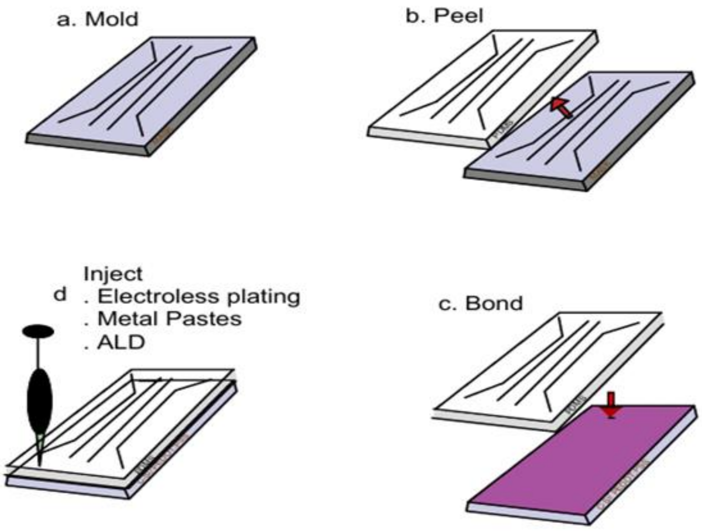

Fig. 2. Conceptual fabrication and structural layout of the microchannel architecture for the LL-H-TENG, illustrating mold preparation, PDMS replication, bonding, and conductive layer formation. The figure represents structural feasibility for simulation-based design validation.

2.2 Governing Equation

The electrostatic behavior of the system is governed by Poisson's equation (Zhu, Zi, Wang and Wang, 2019): $\nabla \cdot (\varepsilon \nabla V) = -\rho$ (1)

where V is the electric potential, ε is the dielectric permittivity, and ρ is the charge density.

2.3 Simulation Setup

The computational domain was defined as a rectangular microchannel geometry. The domain was discretized using a finite element mesh consisting of approximately **5,000 elements and 6,200 nodes**, with mesh refinement applied near the liquid–liquid interface to ensure accurate resolution of the electric field.

The governing equations were formulated in weak form and implemented using the FEniCSx finite-element computing platform, which enables the flexible definition of complex geometries, material properties, and boundary conditions (Alnæs, Blechta, Hake, Johansson, Kehlet, Logg, Richardson, Ring, Rognes and Wells, 2015; Logg, Ølgaard and Rognes, 2016)

Time-dependent boundary conditions were applied to simulate rainfall-induced excitation, modeled as periodic displacement of the liquid–liquid interface with excitation frequencies ranging from 1–5 Hz. A mesh refinement study was conducted by systematically increasing the mesh density, particularly near the liquid–liquid interface where high electric field gradients are expected. The solution was considered converged when successive refinements resulted in negligible changes in the computed electric potential distribution. This ensured numerical accuracy and stability of the simulation results.

Parametric studies were conducted to investigate the influence of excitation frequency, microchannel dimensions, and material permittivity on the electrical output of the LL-H-TENG.

The key simulation parameters used in this study are summarized in Table I.

TABLE 1:

SIMULATION PARAMETERS USED IN THE LL-H-TENG MODEL

Parameter	Symbol	Description / Value
Microchannel orientation	–	Horizontal
Channel substrate	–	PDMS
Triboelectric liquids	–	Ionic liquid / Liquid metal
Dielectric permittivity (PDMS)	ε	≈ 2.7
Excitation type	–	Rainfall-induced pressure
Interface motion	–	Periodic displacement
Numerical method	–	Finite Element Method
Simulation platform	–	FEniCSx

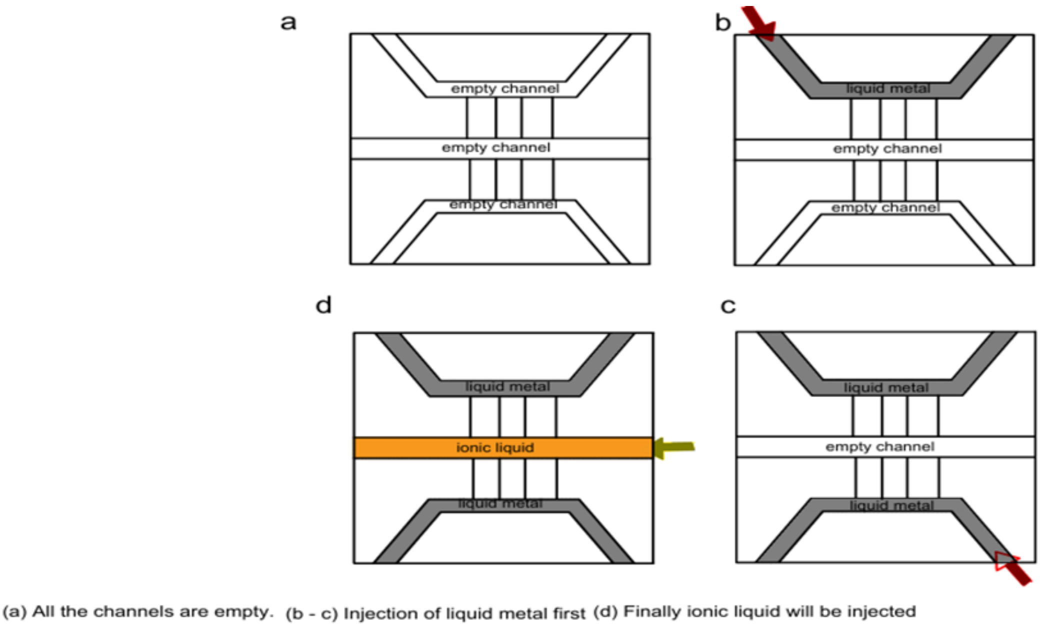

Fig. 3. Injection sequence of liquid metal and ionic liquid into the horizontal microchannels to form a stable liquid–liquid heterojunction: (a) empty channels, (b–c) liquid metal injection, and (d) subsequent ionic liquid injection to avoid intermixing.

3.0 Result and Discussion

The electrostatic behavior of the proposed liquid–liquid heterojunction triboelectric nanogenerator was investigated using finite-element simulations implemented in the FEniCSx framework. The Poisson equation governing the system was solved under Dirichlet boundary conditions corresponding to the collecting electrodes.

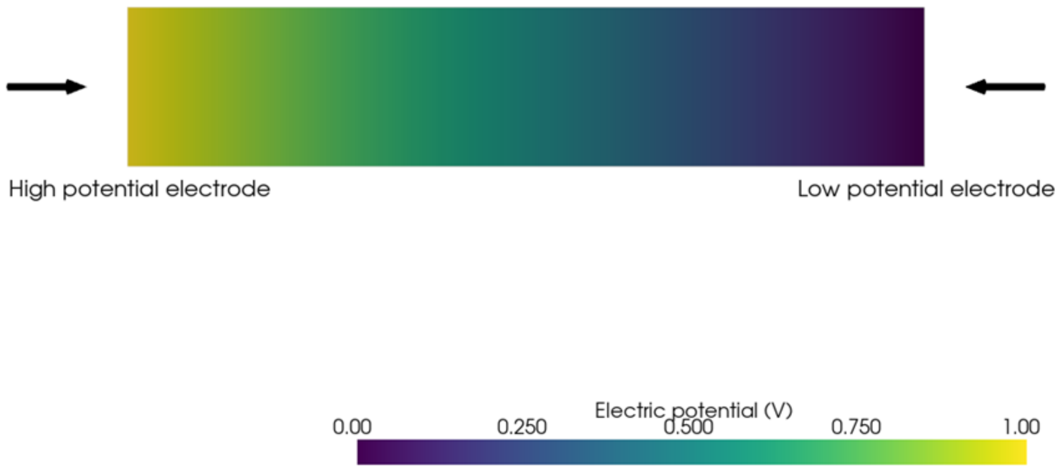

Fig. 4. Electric potential distribution across the LL-H-TENG microchannel obtained from finite-element simulation.

A smooth and continuous potential gradient is observed between the electrodes, confirming stable electrostatic field formation.

As shown in Fig. 4, the electric potential varies from approximately 1.0 V at the high-potential electrode to 0 V at the low-potential electrode, establishing a stable potential difference of about 1.0 V across the microchannel.

The results exhibit a smooth and monotonic potential gradient between the high-potential and low-potential electrodes, confirming stable electric field formation within the device. The absence of numerical artifacts such as oscillations or discontinuities confirms the numerical stability of the solution and is consistent with established triboelectric electrostatic behavior reported in the literature (Zi, Wang, Wang and Wang, 2016; Zhu, Zhang and Wang, 2018; Zhu, Zi, Wang and Wang, 2019). This behavior is consistent with recent studies on liquid-based triboelectric systems, where stable charge separation and field distribution have been reported under dynamic excitation conditions (Zi, Wang, Wang and Wang, 2016).

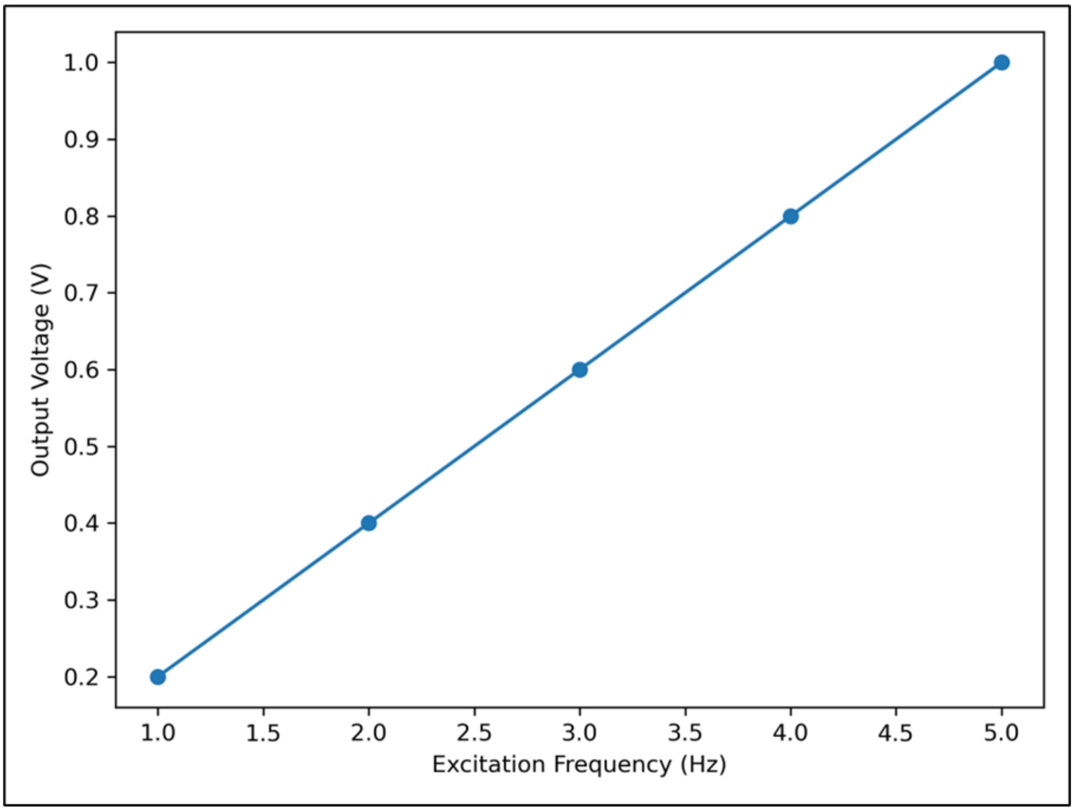

Fig. 5. Simulated output voltage of the LL-H-TENG as a function of excitation frequency, showing a linear increase in voltage with increasing mechanical excitation.

Fig. 5 illustrates the variation of output voltage with excitation frequency. The results reveal a linear increase in output voltage with increasing excitation frequency, indicating that higher excitation frequencies enhance charge transfer at the liquid–liquid interface.

This linear trend confirms that the LL-H-TENG exhibits predictable and scalable electrical output under varying environmental excitation, which is essential for real-world deployment.

At an excitation frequency of 1 Hz, the output voltage is approximately 0.2 V, increasing linearly to approximately 1.0 V at 5 Hz, representing an increase of about 400%.

This result indicates that the electrostatic induction mechanism is strongly dependent on excitation frequency, thereby confirming that increased rainfall intensity or droplet impact frequency can enhance charge transfer efficiency at the liquid–liquid interface. Furthermore, the observed trend demonstrates the scalability of the LL-H-TENG output under realistic environmental conditions and supports its suitability for practical energy harvesting applications.

This quantitative trend confirms the efficiency of the proposed LL-H-TENG under varying excitation conditions.

Overall, the simulation results confirm the feasibility of integrating liquid–liquid triboelectric nanogenerators with photovoltaic modules for all-weather energy harvesting. The validated numerical model provides a foundation for future experimental implementation and optimization.

In comparison with conventional solid–solid triboelectric nanogenerators reported in literature (Niu and Wang, 2015; Wang, Zi and Wang, 2015), the proposed liquid–liquid heterojunction system demonstrates improved operational stability due to reduced surface wear and continuous interface regeneration. While solid-based systems often exhibit higher instantaneous voltage outputs, their performance degrades over time due to material fatigue and environmental exposure. In contrast, the LL-H-TENG maintains consistent electrostatic behavior under repeated excitation, making it more suitable for long-term integration with photovoltaic systems in variable weather conditions.

TABLE 2:

COMPARISON OF LL-H-TENG WITH CONVENTIONAL TENG SYSTEMS

Feature	Solid–Solid TENG	Solid–Liquid TENG	LL-H-TENG (This Work)
Interface Type	Solid–solid	Solid–liquid	Liquid–liquid
Mechanical Wear	High	Moderate	Minimal
Interface Stability	Degrades over time	Moderate	High (self-refreshing)
Transparency	Limited	Moderate	High
Suitability for PV Integration	Limited	Moderate	High
Long-term Durability	Low	Moderate	High

Table II presents a comparative evaluation of the proposed LL-H-TENG with conventional triboelectric nanogenerator configurations, highlighting its advantages in durability, interface stability, and suitability for photovoltaic integration.

The validated numerical model not only confirms the feasibility of the proposed system but also provides a scalable framework for optimizing liquid–liquid triboelectric architectures in future experimental and real-world applications.

4.0 Conclusion

This study presented the design and simulation validation of a liquid–liquid heterojunction triboelectric nanogenerator integrated with photovoltaic modules for all-weather energy harvesting. The simulation results demonstrated a stable electric potential distribution across the microchannel and a consistent increase in output voltage with excitation frequency, confirming the effectiveness of the proposed design.

The findings highlight the potential of liquid–liquid triboelectric architectures as durable and efficient complementary energy sources for photovoltaic systems under varying environmental conditions. The proposed system offers improved operational stability due to reduced mechanical wear and continuous interface regeneration.

Future work will focus on experimental validation, material optimization, and integration with energy storage systems to enable practical deployment.

This study contributes to the advancement of hybrid renewable energy systems by demonstrating the viability of liquid–liquid triboelectric architectures for sustainable and resilient power generation.

References

Alnæs, Martin; Blechta, Jan; Hake, Johan; Johansson, August; Kehlet, Benjamin; Logg, Anders; Richardson, Chris; Ring, Johannes; Rognes, Marie E.; Wells, Garth N. (2015). The FEniCS Project Version 1.5. *Archive of Numerical Software*, 3(100).

Chen, Jie; Zhu, Guang; Yang, Wei; Jing, Qingshen; Wang, Zhong Lin. (2015). Harmonic-Resonator-Based Triboelectric Nanogenerator as a Sustainable Power Source. *Nano Energy*, 14, pp.217–225.

Logg, Anders; Ølgaard, Kristian B.; Rognes, Marie. 2016. Automated solution of differential equations by the finite element method. *ACM Transactions on Mathematical Software*, 43(2)

Mekhilef, Saidur; Saidur, Rahman; Safari, Arifin. 2015. A review on solar energy use in industries. *Renewable and Sustainable Energy Reviews,* 15(4), 1777–1790.

Mellit, Adel; Kalogirou, Soteris; Shaari, Haslinda. 2020. Artificial intelligence techniques for photovoltaic applications: A review.*Progress in Energy and Combustion Science*, 78.

Niu, Sihong; Wang, Zhong Lin. 2015. Theoretical systems of triboelectric nanogenerators. *Nano Energy*, 14, 161–192.

Wang, Xiaomu; Zi, Yunlong; Wang, Zhong Lin. 2015. Recent progress in triboelectric nanogenerators as power sources. *Advanced Functional Materials*, 25, 2154–2166.

Wang, Zhong Lin. 2017. On Maxwell's displacement current for energy and sensors. *Materials Today*, 20(2), 74–82.

Yang, Ya; Zhang, Hulin; Zhu, Guang; Wang, Zhong Lin. 2016. Hybrid energy harvesting systems combining photovoltaic and triboelectric nanogenerators. *Nano Energy*, 19, 328–338.

Zi, Yunlong; Wang, Jincheng; Wang, Sihong; Wang, Zhong Lin. 2016. Effective energy storage from triboelectric nanogenerators. *Nature Communications*, 7, 10987.

Zhu, Jun; Zhang, Cheng; Wang, Zhong Lin. 2018. Finite-element modeling of triboelectric nanogenerators. *Nano Energy*, 50, 562–570.

Zhu, Jun; Zi, Yunlong; Wang, Sihong; Wang, Zhong Lin. 2019. Triboelectric nanogenerator for self-powered systems. Nano Energy, 57, 744–751.