https://jsras.rcc.edu.ly/
Vol.3 No.2 (2026), 43-48
Article history:
Received: 20 Apr. 2026
Accepted: 26 Jun. 2026
Published: 9 Jul. 2026

Journal of Sustainable Research in Applied Sciences

JSRAS

Energy Simulation Operational Systems Software: A Critical Review for Solar-Powered Electric Vehicle Integration

Abdulgader Alsharif [1,*], Rahma Elzer[2], Abdussalam Ali Ahmed[3], Esmail Mahmoud Esmail[4]
[1,4] Electrical and electronic engineering Department, College of Technical Science Sabha, Sabha, Libya
[2]Physics Department, Faculty of Science, Derna University, Derna, Libya
[3]Mechanical and Industrial Engineering Department, Bani Waleed University, Bani Walid, Libya
DOI: https://doi.org/10.36602/jsras.2026.3.2.5
* Corresponding author Alsharifutm@gmail.com

Index Terms

Energy simulation software, solar-powered electric vehicles, operational systems, photovoltaic integration, vehicle-to-grid (V2G), battery modeling, digital twin, microgrid optimization, critical review, real-time control.

Abstract

The synergistic integration of solar photovoltaic (PV) systems with electric vehicle (EV) charging infrastructure presents a transformative pathway toward sustainable transportation and decentralized energy systems. However, the technical and economic viability of this integration is critically dependent on sophisticated energy simulation operational systems software. This paper provides a critical review of state-of-the-art software platforms including MATLAB/Simulink, PVsyst, SAM (System Advisor Model), TRNSYS, and HOMER Pro evaluating their capabilities, limitations, and applicability for modeling solar-powered EV ecosystems. The analysis focuses on six core operational dimensions: (1) dynamic solar irradiance and temperature modeling, (2) EV battery degradation and charging profile simulation, (3) real-time load matching and grid interaction, (4) energy storage system (ESS) optimization, (5) vehicle-to-grid (V2G) bidirectional power flow modeling, and (6) lifecycle cost and carbon emission analytics. Key findings reveal significant gaps: most software lacks native co-simulation frameworks for concurrent solar-EV-Ess dynamics, inadequately handles stochastic driving and parking behaviors, and underestimates thermal management interactions. Furthermore, few platforms offer scalable, cloud-based operational digital twins for real-time supervisory control. The review concludes that while existing tools provide foundational capabilities, next-generation software must integrate machine learning for predictive energy management, edge computing for low-latency control, and standardized communication protocols (e.g., ISO 15118, OCPP) to enable true solar-powered EV integration. This work serves as a technical roadmap for software developers, energy system operators, and automotive engineers.

برمجيات أنظمة تشغيل محاكاة الطاقة: مراجعة نقدية لدمج المركبات الكهربائية التي تعمل بالطاقة الشمسية

عبد القادر الشريف[1،*]، رحمة الزير[2]، عبد السلام علي أحمد[3]، إسماعيل محمود إسماعيل[4]
[1،4]جامعة سبها، كلية العلوم التقنية، قسم الهندسة الكهربائية والإلكترونية، سبها، ليبيا
[2]جامعة درنة، كلية العلوم، قسم الفيزياء، درنة، ليبيا
[3]جامعة بني وليد، قسم الهندسة الميكانيكية والصناعية، بني وليد، ليبيا
DOI: https://doi.org/10.36602/jsras.2026.3.2.5
Alsharifutm@gmail.com * المؤلف المراسل

الملخص

يمثل التكامل التآزري بين أنظمة الخلايا الشمسية الكهروضوئية (PV) وبنية شحن المركبات الكهربائية (EV) مسارًا تحويليًا نحو النقل المستدام وأنظمة الطاقة اللامركزية. ومع ذلك، فإن الجدوى التقنية والاقتصادية لهذا التكامل تعتمد بشكل حاسم على برمجيات متطورة لأنظمة تشغيل محاكاة الطاقة. تقدم هذه الورقة مراجعة نقدية لأحدث المنصات البرمجية – بما في ذلك MATLAB/Simulik و PVsyst و SAM (نموذج نظام المحلل) و TRNSYS و – HOMER Pro مع تقييم قدراتها وقيودها وقابليتها لتطبيق نمذجة النظم البيئية للمركبات الكهربائية التي تعمل بالطاقة الشمسية. يركز التحليل على ستة أبعاد تشغيلية أساسية: (1) نمذجة الإشعاع الشمسي الديناميكي ودرجة الحرارة، (2) محاكاة تدهور بطارية المركبة الكهربائية وملف الشحن، (3) مطابقة الحمل في الوقت الفعلي والتفاعل مع الشبكة، (4) تحسين نظام تخزين الطاقة (ESS)، (5) نمذجة تدفق الطاقة ثنائي الاتجاه من المركبة إلى الشبكة(V2G) ، و(6) تحليلات التكلفة دورة الحياة وانبعاثات الكربون. تكشف النتائج الرئيسية عن فجوات كبيرة: تفتقر معظم البرمجيات إلى أطر المحاكاة المشتركة الأصلية للديناميكيات المتزامنة (الشمسية – الكهربائية – التخزين)، ولا تعالج بشكل كافٍ سلوكيات القيادة والتوقف العشوائية، وتقلل من شأن تفاعلات الإدارة الحرارية. علاوة على ذلك، تقدم عدد قليل من المنصات توائم رقمية تشغيلية قابلة للتطوير ومستندة إلى السحابة للتحكم الإشرافي في الوقت الفعلي. تخلص المراجعة إلى أنه على الرغم من أن الأدوات الحالية توفر قدرات أساسية، إلا أن برمجيات الجيل القادم يجب أن تدمج التعلم الآلي للإدارة التنبؤية للطاقة، والحوسبة الطرفية (الحافة) للتحكم منخفض الكمون، وبروتوكولات الاتصال الموحدة) مثل ISO 15118 و (OCPP لتمكين التكامل الحقيقي للمركبات الكهربائية التي تعمل بالطاقة الشمسية. يعمل هذا العمل كخريطة طريق تقنية لمطوري البرمجيات، ومشغلي أنظمة الطاقة، ومهندسي السيارات.

الكلمات المفتاحية

برمجيات محاكاة الطاقة، المركبات الكهربائية التي تعمل بالطاقة الشمسية، أنظمة التشغيل، التكامل الكهروضوئي، المركبة إلى الشبكة (V2G)، نمذجة البطارية، التوأم الرقمي، تحسين الشبكات الصغيرة، مراجة نقدية، التحكم في الوقت الفعلي.

1. INTRODUCTION

The rapid global shift toward sustainable energy systems demands advanced tools for the efficient planning, design, and operation of renewable energy technologies. Solar photovoltaic (PV) systems are central to this transition, offering a clean and abundant power source. At the same time, the growing number of electric vehicles (EVs) brings both opportunities and challenges for grid stability and energy management. The convergence of these two domains especially for solar-powered EV charging infrastructure and vehicle-integrated photovoltaics (VIPV) requires sophisticated simulation software capable of accurately modeling complex energy flows and interactions [1].

Simulation software helps reduce risks, improve performance, and lower costs for solar energy and EV integration. These tools allow researchers and engineers to predict energy yield, analyze system efficiency, and evaluate techno-economic feasibility under different environmental and operational conditions. However, the landscape of available software is vast and diverse, including both commercial and open-source platforms, each with unique strengths, limitations, and underlying physical models [2]. This diversity often makes it difficult for researchers and practitioners to choose the most appropriate tool for a given application, especially when dealing with the intricate physics of PV systems and the dynamic energy demands of EVs.

Despite the importance of these simulation tools, a comprehensive, physics-focused comparative analysis for solar-powered EV integration is still missing. Existing reviews tend to list software features rather than critically evaluate physical models, simulation accuracy, or adaptability to emerging technologies like advanced energy management and bidirectional power flow vehicle-to-grid (V2G) [3]. This paper aims to fill that gap by offering a critical review of prominent energy simulation software, with special attention to their capabilities and limits in modeling solar PV systems for EV applications. Our goal is to provide a clear, academically rigorous guide to help researchers and engineers make informed decisions for optimized solar-powered EV solutions.

2. METHODOLOGY

This critical review follows a systematic approach to evaluate energy simulation software relevant to solar PV and EV integration. We selected software tools based on several criteria to ensure broad coverage of widely used and academically recognized platforms:

- **Prominence and academic citation:** Tools frequently cited in peer-reviewed literature and widely adopted in academic and industrial research (e.g., PVsyst, SAM, HOMER Energy).
- **Scope of application:** Tools capable of modeling various aspects of solar PV systems, from individual component performance to grid-scale integration, including EV charging infrastructure.
- **Underlying physical models:** Software that provides in depth insights into physical modeling, such as solar radiation models, PV cell models, and loss calculation methods.
- **Recent developments:** Tools with significant updates or demonstrated integration with advanced concepts like AI-driven optimization or digital twins (2023–2025) have shown improved efficiency and accuracy in modeling solar PV systems and their interactions with EV charging infrastructure

We conducted an extensive literature search across academic databases (Scopus, Web of Science, IEEE Xplore, ScienceDirect) using keywords such as "solar energy simulation software," "PV modeling tools," "electric vehicle charging simulation," "VIPV simulation," and "V2G energy management." We then analyzed the selected tools based on their technical

specifications, simulation capabilities, and reported accuracy in prior studies, paying special attention to comparative analyses or validations against empirical data. The findings form the basis for a detailed comparative discussion highlighting strengths and weaknesses in the context of solar-powered EV integration.

3. Comparative Analysis of Simulation Software for Solar PV and EV Integration

This section offers a critical comparison of prominent simulation tools, focusing on their ability to model solar PV systems and their relevance to EV integration. We examine underlying physical models, simulation accuracy, and specific features that make each tool suitable or less suitable for different research and application scenarios.

3.1 Overview of Key Simulation Software

Several software packages dominate solar PV system simulation. While each offers unique features, their core strength lies in predicting energy production and evaluating system performance. This review focuses on PVsyst, System Advisor Model (SAM), HOMER Energy, PV*SOL, and RETScreen due to their widespread academic and industrial adoption [1, 2, 4].

- **PVsyst:** Considered an industry standard, PVsyst provides detailed physical modeling of PV systems, with comprehensive tools for system design, shading analysis, and performance evaluation. Its strengths include meticulous loss calculations and an extensive meteorological database [5].
- **System Advisor Model (SAM):** Developed by NREL, SAM is a techno-economic model for renewable energy project decisions. It combines performance modeling with financial analysis, making it especially useful for evaluating the economic viability of solar PV and storage systems [6].
- **HOMER Energy (Hybrid Optimization Model for Electric Renewables):** HOMER specializes in optimizing hybrid power systems that combine solar PV, wind, generators, and battery storage. It is well suited for finding optimal system configurations and operational strategies to minimize the levelized cost of energy (LCOE) [7].
- **PV*SOL:** A commercial software for designing and simulating grid-connected and off-grid PV systems. It offers user-friendly interfaces and detailed 3D modeling for accurate shading analysis and visualization.
- **RETScreen Expert:** Developed by Natural Resources Canada, RETScreen is a clean energy management system that evaluates energy production, savings, costs, emission reductions, and financial viability. It is often used for feasibility studies and project screening.

3.2. Physical Modeling and Simulation Accuracy

Simulation accuracy is fundamentally tied to the sophistication of underlying physical models. For solar PV systems, key aspects include solar radiation modeling, PV module performance under varying conditions, and quantification of loss mechanisms.

3.2.1 Solar Radiation Models

Different software tools use different models to convert global horizontal irradiance (GHI) to plane-of-array (POA) irradiance, which is crucial for accurate PV performance prediction. These range from simpler isotropic models (e.g., Liu-Jordan) to more complex anisotropic models (e.g., Perez, Hay-Davies) that account for sky-diffuse radiation anisotropy. PVsyst offers several advanced anisotropic models, contributing to its high accuracy across diverse climates [5]. SAM also includes multiple radiation models, allowing users to choose based on data availability and desired precision [6].

3.2.2 PV Module Performance Models

The electrical behavior of PV modules is typically modeled using equivalent circuit diagrams, most commonly the one-diode model or, less often, two-diode models. These describe current-voltage (I-V) characteristics as functions of irradiance and temperature. PVsyst and SAM provide robust implementations of these models, allowing detailed characterization of module performance, including temperature coefficients and spectral effects [5, 6]. PV*SOL also includes detailed module databases and performance models to simulate real-world behavior.

3.2.3 Loss Mechanisms

Accurate simulation requires accounting for various losses that reduce actual energy yield compared to ideal conditions: temperature losses, optical losses (incidence angle, soiling), electrical losses (mismatch, wiring), and inverter efficiency losses. PVsyst is especially known for its comprehensive loss diagram, which quantifies each loss component in detail [5]. SAM and HOMER also include loss models, though with less granularity [6, 7]. Recent studies emphasize the necessity of accurately modeling soiling losses, especially in arid environments, where PVsyst and SAM have shown good agreement with empirical data [4].

3.3 Relevance to Electric Vehicle Integration

Integrating solar PV with EVs adds complexity, requiring simulation tools to model energy management strategies, battery storage, and bidirectional power flow. While most tools can handle PV production and battery storage, their EV-specific features vary significantly.

- **Energy Management Systems (EMS):** HOMER Energy excels at optimizing EMS for hybrid systems, which can be extended to manage energy flow among solar PV, battery

storage, and EV charging [7]. SAM also allows detailed modeling of battery storage and dispatch strategies for EV charging applications [6].

- **Vehicle-Integrated Photovoltaics (VIPV):** Simulating VIPV requires tools capable of modeling PV modules on non-optimal orientations and complex geometries. While general PV simulation tools can be adapted, specialized modules or advanced 3D modeling capabilities (e.g., in PV*SOL) are beneficial for accurate VIPV performance prediction.
- **Vehicle-to-Grid (V2G) and Smart Charging:** Modeling V2G scenarios and smart charging strategies (where EVs can both consume and supply power to the grid) is a more advanced feature. While direct V2G simulation modules are less common in standard PV software, tools with robust battery dispatch algorithms and external API integration capabilities (e.g., SAM with Python scripting) can be adapted for such analyses [6]. Research is actively exploring dedicated simulation frameworks for EV charging stations that integrate renewable energy sources [2, 8].

Example Application: Consider a researcher designing a solar-powered EV charging hub for a university campus. Using SAM, they could model a 100 kW PV array with a 200 kWh battery storage system. By writing a simple Python script within SAM's SDK, they can import real-world EV charging demand data (e.g., hourly profiles from campus parking lots) and simulate different dispatch strategies such as "charge EVs only from surplus solar" versus "grid peak shaving with V2G." This flexibility makes SAM a strong choice for such integrated studies, despite its less detailed PV loss modeling compared to PVsyst.

3.4 Comparative Table of Key Simulation Software

To provide a clearer overview, Table I summarizes key features and physical modeling capabilities of the discussed software tools for solar PV and EV integration. (See table below—formatting preserved as in original but with clarified column headers.)

TABLE I . COMPARATIVE ANALYSIS OF KEY SIMULATION SOFTWARE FOR SOLAR PV AND EV INTEGRATION:

Feature / Software	PVsyst	SAM (NREL)	HOMER Energy	PV*SOL	RETScreen Expert
Primary Focus	PV System Design & Analysis	Techno-Economic Analysis	Hybrid System Optimization	PV System Design & Visualization	Feasibility & Project Screening
Solar Radiation Models	Advanced Anisotropic (Perez, Hay-Davies)	Multiple (Perez, TMY, User-defined)	Multiple (User-defined, TMY)	Multiple (User-defined, TMY)	Simplified (User-defined, TMY)
PV Module Models	Detailed One-Diode Model	One-Diode Model, Extensive Database	Simplified, User-defined	Detailed, Extensive Database	Simplified
Loss Mechanisms	Comprehensive (Temperature, Optical, Electrical, Soiling)	Detailed (Temperature, Soiling, Mismatch)	Simplified (Temperature, Battery Degradation)	Detailed (Temperature, Shading, Electrical)	Simplified
Battery Storage Modeling	Basic	Advanced (Dispatch Strategies)	Advanced (Optimization)	Basic	Basic
EV Charging Simulation	Limited	Moderate (via Dispatch)	Moderate (via Load Profile)	Limited	Limited
V2G Capabilities	No Direct	Adaptable (via Scripting)	Adaptable (via Control)	No Direct	No Direct
Techno-Economic Analysis	Basic LCOE	Advanced (LCOE, NPV, IRR)	Advanced (LCOE, NPC)	Basic LCOE	Advanced (Financial Metrics)
Open-Source / API	No / Limited API	Yes (Python SDK)	No / Limited API	No	No
Typical Use Case	Detailed PV System Design	Economic Feasibility, Research	Microgrid Optimization	Residential/Commercial Design	Project Screening, Policy

4. DISCUSSION

Our comparison shows that while many simulation tools exist for solar PV systems, and fewer for EVs, a significant gap remains for truly integrated, physics-driven modeling of solar-powered EV applications. PVsyst excels at meticulous physical modeling of PV systems, offering high accuracy for energy yield prediction and loss analysis [5] This makes it invaluable for detailed PV system design, where understanding solar radiation, module performance, and loss mechanisms is paramount. However, its direct support for EV-specific functions like V2G or advanced energy management for charging is limited, often requiring external tools or manual integration.

In contrast, SAM and HOMER Energy shine in techno-economic analysis and hybrid system optimization, respectively [6] . SAM's robust financial modeling, combined with its performance models, is ideal for evaluating the economic viability of solar-plus-storage systems that could serve EV charging stations. Its open-source nature and Python SDK offer flexibility for researchers to add custom EV charging profiles or V2G algorithms. HOMER's strength in optimizing complex microgrids including various renewables and storage

positions it well for designing off-grid or grid-tied EV charging hubs with solar PV. However, the depth of physical PV modeling in these tools may not match PVsyst's granularity.

The main challenge in solar-powered EV integration lies in the dynamic interplay between intermittent solar generation, variable EV charging demand, and battery degradation. Current tools often address these aspects in isolation or require significant customization for a holistic view. The limited direct V2G capabilities in most standard software point to a critical area for future development. While some tools can be adapted through scripting, a dedicated, physics-based simulation environment that seamlessly integrates PV performance, battery state-of-charge, EV charging protocols, and grid interaction remains an active research area [1, 8].

Emerging AI-driven optimization and digital twin frameworks offer promising ways to overcome these limits. AI can improve forecasting accuracy for solar generation and EV demand, while digital twins can provide real-time monitoring and predictive maintenance for integrated systems. Future simulation software will likely incorporate these techniques to offer more dynamic, adaptive, and accurate modeling of solar-powered EV ecosystems moving beyond static performance predictions to real-time operational optimization.

5. CONCLUSION

This critical review has systematically examined leading energy simulation software for solar PV systems and their integration with electric vehicles. We have shown that while PVsyst offers unmatched detail in PV physical modeling, and SAM and HOMER provide robust techno-economic and hybrid system optimization, a fully integrated solution for solar-powered EV applications especially for advanced energy management and V2G is still evolving. Physical models, simulation accuracy, and specific features vary significantly across platforms, requiring careful selection based on the research question or application.

For researchers and engineers in physics and engineering, understanding the nuances of these tools' physical models is essential. The choice between a detailed PV modeler (e.g., PVsyst) and a flexible techno-economic optimizer (e.g., SAM) depends on the study's primary focus. Future research should focus on developing integrated simulation platforms that combine high-fidelity physical modeling of PV systems with advanced EV energy management strategies, incorporating AI and digital twins for better predictive capabilities and real-time optimization. This will help accelerate the deployment of sustainable and efficient solar-powered electric vehicle infrastructure worldwide.

REFERENCES

Babu, R.M., et al., Towards Sustainable and Clean Energy Futures: A Techno-Economic Review of Solar PV Systems, Challenges, and Opportunities. IEEE Access, 2025.

Raji, L., A. Razak, and A. Sharol, Comparative assessment of PV simulation tools for a megawatt-scale rooftop solar photovoltaic system in tropical climate. Next Energy, 2025. 9: p. 100452.

Singla, P., et al., Design and simulation of 4 kW solar power-based hybrid EV charging station. Scientific Reports, 2024. 14(1): p. 7336.

Jain, S., et al., Performance Modeling of Rooftop PV Systems in Arid Climate, a Case Study for Qatar: Impact of Soiling Losses and Albedo Using PVsyst and SAM. Energies, 2025. 18(22): p. 5876.

Mashaly, A., et al., Novel and cost-efficient design of stand-alone PV system with simulation using PVsyst and experimental validation. Scientific Reports, 2025.

Shamsul, N.A., M.A.M. Azmi, and M.I. Azaman. Modeling and analyzing of photovoltaic solar power systems using pvsyst. in 2022 IEEE 8th International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA). 2022. IEEE.

Badhan, K.F., Techno-Economic Feasibility and Environmental Assessment of Multi-Energy Storage Hybrid Systems for EV Charging Solution in the Arctic Region. 2025.

Lhaden, T., Development of Electric Vehicle Charging Station Microgrid With Simulation Modelling. 2024, The University of Texas at El Paso.

Alsharif, A. H., Ahmed, A. A., Nassar, Y. F., Khaleel, M. M., El-Khozondar, H. J., Alhoudier, T. E., & Esmail, E. M. (2023). Mitigation of dust impact on solar photovoltaics performance considering Libyan climate zone: A review. Wadi Alshatti University Journal of Pure and Applied Sciences, 22-27.