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Solar Energy, National Security, and Sustainable Development: Technological Transformations, Regulatory Frameworks, and Challenges to Energy Sovereignty

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Solar Energy, National Security, and Sustainable Development: Technological Transformations, Regulatory Frameworks, and Challenges to Energy Sovereignty

Energia Solar, Segurança Nacional e Desenvolvimento Sustentável: Transformações Tecnológicas, Enquadramentos Regulatórios e Desafios à Soberania Energética

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ABSTRACT: The rapid scaling of solar photovoltaic (PV) technologies and the attainment of grid parity have fundamentally reshaped the global energy landscape. Solar generation has evolved from a mere economic alternative into a critical driver of national security and sustainable development. We systematise the core technological determinants of modern photovoltaics, including perovskite tandem structures, bifacial modules, battery storage systems (BESS), and artificial intelligence (AI) tools for grid forecasting. We analyse these developments through a geo-economics and hybrid threat lens. Our research identifies the structural conflict between centralised, carbon-intensive generation and the emerging paradigm of distributed, digitally controlled capacity. We establish that technological availability alone cannot secure strategic outcomes without a robust institutional framework. Consequently, we examine the legal and regulatory architecture required to accelerate technology deployment while protecting critical infrastructure. This analysis encompasses grid connection regimes, permitting processes, corporate Power Purchase Agreement (PPA) mechanisms, Foreign Direct Investment (FDI) screening, and cybersecurity requirements for cyber-physical energy systems. Ultimately, we argue that energy sovereignty requires a synthesis of technological autonomy and legal certainty, supported by supply chain diversification, mandatory security criteria, and adaptive regulatory models that address dynamic risks while preserving investment predictability.
KEYWORDS: solar photovoltaics; renewable energy sources; sustainable development; regulatory frameworks; national security; artificial intelligence; energy sovereignty.

RESUMO: A rápida expansão das tecnologias solares fotovoltaicas e a paridade de rede transformaram significativamente o panorama energético global, convertendo a geração solar de alternativa económica em fator de segurança nacional e de desenvolvimento sustentável. O artigo sistematiza os principais motores da fotovoltaica contemporânea, incluindo arquiteturas tandem de perovskita, módulos bifaciais, sistemas de armazenamento de energia em baterias (BESS) e ferramentas de inteligência artificial para previsão e operação da rede, avaliando-os à luz de ameaças geoeconómicas e híbridas atuais. O

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estudo clarifica o conflito estrutural entre a geração centralizada e intensiva em carbono e o paradigma emergente de capacidades distribuídas e digitalmente geridas, sublinhando que a disponibilidade tecnológica, por si só, não garante resultados de segurança sem um enquadramento institucional adequado. A análise incide sobre a arquitetura jurídico-regulatória que permite, simultaneamente, acelerar a implementação e proteger as infraestruturas críticas. Examinam-se os regimes de licenciamento e de ligação à rede, os mecanismos de contratos corporativos de aquisição de energia (PPA), o escrutínio do investimento estrangeiro, as exigências de cibersegurança para sistemas energéticos ciberfísicos e os requisitos de segurança das cadeias de abastecimento de componentes e de software críticos. Sustenta-se que a soberania energética exige a combinação de autonomia tecnológica e segurança jurídica, apoiada na diversificação das cadeias de abastecimento, na aplicação de critérios de segurança vinculativos e no desenvolvimento de modelos regulatórios adaptativos capazes de responder a riscos dinâmicos, preservando a previsibilidade do investimento e a prossecução do interesse público.
PALAVRAS-CHAVE: energia solar fotovoltaica; fontes de energia renováveis; desenvolvimento sustentável; regulação jurídica; segurança nacional; inteligência artificial.

1. INTRODUCTION

The transformation of the global energy system during the early 21st century has outgrown the limits of climate discourse, becoming a definitive factor in the reconfiguration of international security and sustainable development architectures. This ecological transition integrates environmental, economic, social, and institutional dimensions. It directly promotes climate justice and the equitable distribution of transition benefits and risks among states, financial sectors, and households. Within this framework, solar photovoltaic (PV) technologies have attained economic maturity and grid parity, moving beyond their previous status as auxiliary tools for developed economies.[4] In 2020, the International Energy Agency (IEA) designated solar power as the "new king of electricity"; currently, it is the most cost-effective source of electricity globally.[5] This shift intensifies the structural conflict between the emerging paradigm of distributed generation and the traditional model of power generation, which remains centralised and carbon-intensive.

For conceptual clarity, we operationalise the core terms of this research as analytical categories rather than rhetorical constructs. Energy sovereignty refers to a state's structural capacity to control electricity generation, distribution, and consumption. This concept involves minimising dependence on fossil fuel imports by

[4] LAZARD, "Lazard Releases 2025 Levelized Cost of Energy+ Report" [online], New York: *Lazard*, 2025, Executive Summary & LCOE Comparison. Available from: https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energyplus-report-pr/ [Accessed 11 Dec. 2025].
[5] INTERNATIONAL ENERGY AGENCY (IEA), "World Energy Outlook 2023" [online], Paris: *IEA Publications*, 2023, pp. 18-20 (Executive Summary). Available from: https://www.iea.org/reports/world-energy-outlook-2023 [Accessed 9 Dec. 2025].

deploying domestic renewable energy capacity. Technological autonomy signifies the possession of a complete or diversified national or allied supply chain for critical hardware components. These components include solar modules, inverters, and storage systems. Such autonomy precludes geo-economic coercion by monopolistic states. Regulatory sovereignty represents the institutional capacity of a state to establish and enforce its own legal frameworks. These frameworks include implementing cybersecurity standards, governing grid connection procedures, and screening foreign investment to safeguard critical infrastructure. Finally, hybrid threats in the energy sector encompass a spectrum of non-kinetic aggression. Examples include cyberattacks against smart grids, supply chain interference, and the exploitation of critical raw materials as instruments of geopolitical pressure.

Traditional energy supply architectures based on fossil fuels have shaped economic interactions and enduring political dependencies for decades. The concentration of generating capacity and control over supply routes enabled exporting states to weaponise energy resources as instruments of geopolitical pressure and hybrid aggression.[6] The massive deployment of photovoltaic systems disrupts this monopoly by decentralising production, posing an existential challenge to the beneficiaries of the established model. Consequently, the expansion of solar energy encounters institutional resistance. This resistance manifests in regulatory frameworks through administrative hurdles and artificial grid connection constraints, such as the Spanish sun tax[7] or the stringent financial limitations of the NEM 3.0 reform in California regarding export compensation rates[8]. Concurrently, proponents of conventional energy frame thermal generation as an indispensable guarantor of grid stability. This argument perpetuates carbon lock-in and stalls institutional modernisation.[9]

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[6] VAN DE GRAAF, Thijs, and SOVACOOL, Benjamin K., "Global Energy Politics" [online], Cambridge: *Polity Press*, 2020, pp. 54-56. ISBN 978-1-509-53048-9. Available from: https://www.politybooks.com/bookdetail?book_slug=global-energy-politics--9781509530489 [Accessed 9 Dec. 2025].

[7] TOMASI, Silvia, "The (Non) impact of the Spanish "Tax on the Sun" on photovoltaics prosumers uptake", *Energy Policy* [online], September 2022, vol. 168, art. 113041, pp. 2-3 (Section 2). Available from: https://doi.org/10.1016/j.enpol.2022.113041 [Accessed 1 Mar. 2026].

[8] CALIFORNIA PUBLIC UTILITIES COMMISSION (CPUC), "CPUC Modernizes Solar Tariff To Support Reliability and Decarbonization" [online], San Francisco: *CPUC*, 2022. Available from: https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-modernizes-solar-tariff-to-support-reliability-and-decarbonization [Accessed 22 Feb. 2026].

[9] SETO, Karen C., DAVIS, Steven J., MITCHELL, Ronald B., STOKES, Eleanor C., UNRUH, Gregory, and ÜRGE-VORSATZ, Diana, "Carbon Lock-In: Types, Causes, and Policy Implications", *Annual Review of Environment and Resources* [online], November 2016, vol. 41, pp. 433-435. Available from: https://doi.org/10.1146/annurev-environ-110615-085934 [Accessed 9 Dec. 2025].

The pace of technological advancement far outstrips the evolution of regulatory frameworks. Innovations within the photovoltaic sector, specifically advancements in bifacial modules and tandem perovskite cells, have substantially increased conversion efficiency while driving down the levelised cost of energy.[10][11] Digitalisation within the industry and the integration of artificial intelligence (AI) algorithms facilitate more precise generation forecasting and asset management. These tools partially mitigate the intermittency inherent to renewable sources.[12] Simultaneously, these shifts heighten national security challenges, particularly in protecting critical infrastructure against cyber threats, ensuring software reliability, and enhancing the resilience of global supply chains. China's dominance in manufacturing key PV components, battery materials, and inverters exacerbates this concern, creating systemic risks of technological and economic dependency.[13] Under these conditions, the legal framework must account for more than cost and deployment speed; it must also incorporate due diligence requirements concerning component provenance, cyber risks, and the social ramifications of the energy transition.[14]

Contemporary academic and political discourse regarding solar energy shifts from considerations of environmental expediency toward issues of energy sovereignty and a just transition. States that can establish a legal framework for integrating distributed generation and battery storage systems (BESS) gain a strategic advantage. They reduce vulnerability to external price shocks, minimise the risks of political pressure, and create conditions for a socially acceptable transition. These efforts include expanding access to individual energy generation and developing energy communities. This shift necessitates a broad revision of regulatory approaches. Key

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[10] NATIONAL RENEWABLE ENERGY LABORATORY (NREL), "Best Research-Cell Efficiency Chart" [online], Golden, CO: *National Renewable Energy Laboratory*, 2024. Available from: https://www.nrel.gov/pv/cell-efficiency.html [Accessed 9 Dec. 2025].

[11] LAZARD, "Lazard Releases 2025 Levelized Cost of Energy+ Report" [online], New York: *Lazard*, 2025, Executive Summary & LCOE Comparison. Available from: https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energyplus-report-pr/ [Accessed 11 Dec. 2025].

[12] WORLD ECONOMIC FORUM (WEF), "Harnessing Artificial Intelligence to Accelerate the Energy Transition" [online], In collaboration with BloombergNEF and Deutsche Energie-Agentur (dena), Geneva: *WEF*, September 2021. Available from: https://www.weforum.org/publications/harnessing-artificial-intelligence-to-accelerate-the-energy-transition/ [Accessed 11 Dec. 2025].

[13] INTERNATIONAL ENERGY AGENCY (IEA), "Special Report on Solar PV Global Supply Chains" [online], Paris: *IEA Publications*, 2022, pp. 7-9 (Executive Summary). Available from: https://www.iea.org/reports/solar-pv-global-supply-chains [Accessed 22 Feb. 2026].

[14] EUROPEAN COMMISSION, "Joint Communication to the European Parliament and the Council: European Economic Security Strategy" [online], JOIN(2023) 20 final, Brussels: *European Commission*, 20 June 2023, Section 2. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023JC0020 [Accessed 9 Dec. 2025].

areas include corporate power purchase agreement (PPA) mechanisms, Foreign Investment Screening procedures for energy infrastructure, cyber resilience requirements, and the transparency of algorithmic grid management.[15]

This article synthesises the techno-economic aspects of photovoltaic development from the perspective of national security and sustainability. We analyse the potential of regulatory instruments and technological innovations to overcome the institutional inertia of traditional energy actors. Furthermore, we establish governance regimes that integrate energy autonomy with legal certainty, cyber resilience, and the requirements of a just transition. Our research substantiates a decentralised energy system model where legal certainty guarantees state technological autonomy. This framework lays the foundation for long-term security and sustainable development.

2. Literature review

The evolution of scholarly discourse regarding the global energy transition reflects a fundamental reorientation of research priorities. Scholars are shifting from linear technological and economic models toward more complex social, political, and legal narratives. These narratives treat technology as a vehicle for redistributing power, shaping resource access, and strengthening institutional resilience. Contemporary doctrine no longer remains confined to issues of photovoltaic conversion efficiency. Instead, researchers increasingly situate renewable energy within the broader context of national security, countermeasures against hybrid threats, and technological sovereignty. From this perspective, the legal categories of resilience, justice, and accountability acquire particular significance. These categories determine how the state translates technological change into public goods and how it allocates the emerging risks associated with digitalisation and supply chains.

In their seminal political economy research, Van de GRAAF and SOVACOOL interpret current transformations not as a gradual replacement of energy sources but as a catalyst for systemic turbulence that enables the restructuring of geopolitical hierarchies.[16] This process involves the erosion of influence among traditional petro

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[15] TRANSNATIONAL INSTITUTE, “State of Power 2024: Energy, Power and Transition” [online], Amsterdam: *Transnational Institute*, February 2024, Introduction. Available from: https://www.tni.org/en/publication/energy-power-and-transition [Accessed 7 Dec. 2025].

[16] VAN DE GRAAF, Thijs, and SOVACOOL, Benjamin K., “Global Energy Politics” [online], Cambridge: *Polity Press*, 2020, pp. 202-206 (Chapter 8). ISBN 978-1-509-53048-9. Available from: https://www.politybooks.com/bookdetail?book_slug=global-energy-politics--9781509530489 [Accessed 9 Dec. 2025].

states and the emergence of new power centres whose strength rests on technological leadership and innovation management rather than control over mineral deposits. YERGIN develops this thesis further, noting a change in the very essence of energy security. While security in the 20th century focused on physical access to oil and gas reserves, the priority for the 21st century shifts toward controlling component supply chains and integrating renewable energy into national power grids. As a result, energy security concerns increasingly converge with industrial policy, access to infrastructure, and legal mechanisms for managing technological dependencies.[17]

This transformation encounters potent institutional resistance. The Transnational Institute Report examines this resistance in depth. Researchers define energy power as the ability of corporate and state actors to leverage control over centralised infrastructure to preserve the status quo. They emphasise that policymakers and traditional incumbents designed market architectures to serve the fossil fuel industry, thereby turning regulation into a theatre of conflict.[18] The concept of carbon lock-in proposed by SETO et al provides the theoretical foundation for such resistance. The combination of technological inertia in thermal generation and political lobbying creates artificial barriers to photovoltaic deployment, even when solar power possesses a clear economic advantage.[19] Annual analytical reports from LAZARD[20] and the IEA[21] provide the financial basis for this paradigm shift. By documenting historic lows in the LCOE for utility-scale solar plants, these reports confirm the arrival of price parity and raise a fundamental legal question: which regulatory regimes can convert this cost advantage into long-term societal outcomes without replicating new forms of dependency.

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[17] JOURNAL OF PETROLEUM TECHNOLOGY (JPT), "The New Map: Ten Visions for the Future-Daniel Yergin's Analysis of the Energy Transition" [online], Richardson, TX: *Society of Petroleum Engineers*, 2020. Available from: https://jpt.spe.org/new-map-ten-visions-future-daniel-yergins-analysis-energy-transition [Accessed 28 Feb. 2026].

[18] TRANSNATIONAL INSTITUTE, "State of Power 2024: Energy, Power and Transition" [online], Amsterdam: *Transnational Institute*, February 2024, Introduction. Available from: https://www.tni.org/en/publication/energy-power-and-transition [Accessed 7 Dec. 2025].

[19] SETO, Karen C., DAVIS, Steven J., MITCHELL, Ronald B., STOKES, Eleanor C., UNRUH, Gregory, and ÜRGE-VORSATZ, Diana, "Carbon Lock-In: Types, Causes, and Policy Implications", *Annual Review of Environment and Resources* [online], November 2016, vol. 41, pp. 429-435. Available from: https://doi.org/10.1146/annurev-environ-110615-085934 [Accessed 9 Dec. 2025].

[20] LAZARD, "Lazard Releases 2025 Levelized Cost of Energy+ Report" [online], New York: *Lazard*, 2025, Executive Summary & LCOE Comparison. Available from: https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energyplus-report-pr/ [Accessed 11 Dec. 2025].

[21] INTERNATIONAL ENERGY AGENCY (IEA), "World Energy Outlook 2025" [online], Paris: *IEA Publications*, October 2025, Executive Summary. Available from: https://www.iea.org/reports/world-energy-outlook-2025 [Accessed 9 Dec. 2025].

Alongside the critique of institutional inertia, scholarly discourse exhibits distinct technological optimism. HAEGEL et al. proclaim the onset of a terawatt era, linking it to the modularity and scalability of photovoltaic technologies.[22] Nevertheless, NREL experts caution that market diffusion alone cannot suffice, as rapid capacity scaling without revising grid management principles creates risks of technical imbalances. Opponents of renewable energy use these imbalances to argue that stochastic generation remains unreliable.[23] Researchers increasingly identify digitalisation as a key instrument for overcoming these constraints, although the role of AI within the energy sector remains a subject of polarised debate. DE VRIES points to the rising electricity demand of AI algorithms, which exerts additional pressure on infrastructure.[24] In contrast, WEST et al.[25] and RADOVANOVIC et al.[26] advance the concept of carbon-aware computing and demonstrate how predictive algorithms effectively synchronise energy-intensive processes with solar generation peaks. Consequently, intermittency evolves from a systemic drawback into a manageable variable. This shift expands the scope of legal inquiries into security, transparency, and accountability regarding the algorithmic governance of critical infrastructure.

This technological advancement lays the groundwork for enhancing the autonomy of critical infrastructure facilities. However, a significant gap persists in scholarly discourse, in which most researchers treat cybersecurity and energy autonomy as separate domains. Publications from the NATO CCDCOE represent the first

[22] HAEGEL, Nancy M., ATWATER, Harry A., BARNES, Teresa, BREYER, Christian, BURRELL, Anthony, CHIANG, Yet-Ming, DE WOLF, Stefaan, DIMMLER, Bernhard, FELDMAN, David, GLUNZ, Stefan et al., “Terawatt-scale photovoltaics: Transform global energy”, *Science* [online], May 2019, vol. 364, no. 6443, pp. 836-838. Available from: https://doi.org/10.1126/science.aaw1845 [Accessed 9 Dec. 2025].

[23] DENHOLM, Paul, BROWN, Patrick, COLE, Wesley, GAGNON, Pieter, MASCENIK, Brian, O'CONNELL, Matthew, and FRAZIER, A. W., “Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035” [online], Technical Report NREL/TP-6A20-81644, Golden, CO: *National Renewable Energy Laboratory*, 2022, pp. 42-45. Available from: https://www.nrel.gov/docs/fy22osti/81644.pdf [Accessed 1 Mar. 2026].

[24] DE VRIES, Alex, “The Growing Energy Footprint of Artificial Intelligence”, *Joule* [online], October 2023, vol. 7, no. 10, pp. 2191-2194. Available from: https://doi.org/10.1016/j.joule.2023.09.004 [Accessed 9 Dec. 2025].

[25] WEST, Kathleen, LEHMANN, Fabian, BOUNTRIS, Vasilis, LESER, Ulf, ELKHATIB, Yehia, and THAMSEN, Lauritz, “Exploring the Potential of Carbon-Aware Execution for Scientific Workflows”, *arXiv preprint arXiv:2503.13705* [online], March 2025. Available from: https://arxiv.org/abs/2503.13705 [Accessed 9 Dec. 2025].

[26] RADOVANOVIC, Ana, KONINGSTEIN, Ross, SCHNEIDER, Ian, CHEN, Bokan, DUART, Alexandre, ROY BINZ, B., WOOD, D., RYAN, L., MILLER, S., WIKER, N. et al., “Carbon-Aware Computing for Datacenters”, *IEEE Transactions on Power Systems* [online], March 2023, vol. 38, no. 2, pp. 1270-1280. Available from: https://ieeexplore.ieee.org/document/9770383 [Accessed 9 Dec. 2025].

trajectory.[27] Recent research from Bruegel constitutes the second; MCWILLIAMS, TAGLIAPIETRA, and ZETTELMEYER argue that aligning Europe's clean industrialisation goals with the interests of the Global South is essential to avoid new forms of dependency.[28] Nevertheless, the literature still lacks comprehensive studies conceptualising the legal regulation of autonomous hybrid AI and photovoltaic systems as a national security instrument that accounts for institutional resilience and the equitable distribution of risks. Existing scholarship underestimates the systemic link between the energy autonomy of individual infrastructure nodes, such as data centres and communication facilities, and the overarching resilience of the state. This study aims to fill this gap by synthesising doctrinal perspectives on the technological potential of autonomy and the legal mechanisms for its implementation.

3. Theoretical basis and methodology

This research builds upon the principles of interdisciplinary synthesis. It treats the energy transition not as a linear process of technological substitution but as a complex transformation of social and technical systems.[29] Given the subject's multidimensional nature, the analysis moves beyond engineering determinism. We draw on the convergence of systems analysis, political economy, and comparative law. The theoretical framework integrates the concept of path dependency with a security-oriented perspective. This combination elucidates both the institutional inertia of the centralised model and the driving forces behind the state's regulatory role.

The concept of path dependency allows us to interpret centralised carbon generation as an institutionally locked system. Policymakers and system operators shaped technical standards, grid architectures, and regulatory instruments around fossil fuels, thereby reinforcing a structural asymmetry regarding infrastructure

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[27] NATO COOPERATIVE CYBER DEFENCE CENTRE OF EXCELLENCE (CCDCOE), “Publications Library: International Conference on Cyber Conflict (CyCon) Proceedings” [online], Tallinn: *NATO CCDCOE*, 2024. Available from: https://ccdcoe.org/library/publications/ [Accessed 10 Dec. 2025].

[28] MCWILLIAMS, Ben, TAGLIAPIETRA, Simone, and ZETTELMEYER, Jeromin, “Reconciling the European Union’s clean industrialisation goals with those of the Global South” [online], Policy Brief 18/2025, Brussels: *Bruegel*, 3 July 2025, pp. 1-2. Available from: https://www.bruegel.org/policy-brief/reconciling-european-unions-clean-industrialisation-goals-those-global-south [Accessed 10 Dec. 2025].

[29] INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA), “World Energy Transitions Outlook 2024: 1.5°C Pathway” [online], Abu Dhabi: *IRENA*, November 2024, Executive Summary. Available from: https://www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024 [Accessed 11 Dec. 2025].

access.[30] This perspective enables an understanding of regulatory resistance to photovoltaic deployment. It frames this resistance not as a set of situational administrative hurdles but as a systemic defensive reaction of the incumbent technological regime. Concurrently, we apply a national security priority approach. This involves tracking the discursive shift toward viewing renewable energy as a determinant of the state's existential resilience. Within this framework, we justify the use of investment screening, supply chain protection, and cybersecurity requirements for critical infrastructure. These mechanisms fall outside the toolkit of classical liberal markets. Nevertheless, they function as necessary instruments of state policy in the current geopolitical environment.[31]

We test the proposed hypotheses using a combined methodological toolkit. Our systems analysis employs structural mapping to compare the topologies of centralised energy systems with those of distributed photovoltaic networks. The centralised model concentrates risks at key nodes, while a distributed architecture enhances resilience by increasing the number of generation points. This logic aligns with DOE research on virtual power plants (VPP).[32]

Our selection of literature and empirical data adhered to the PRISMA protocol and encompassed three consecutive stages: identification, screening, and eligibility assessment. During the identification phase, we conducted searches within the Scopus, Web of Science, and Google Scholar databases using keywords such as photovoltaics, energy sovereignty, grid cybersecurity, the NIS2 directive, and LCOE. Additionally, we used English descriptors including solar photovoltaic, grid integration, PPA, perovskite tandem, and supply chain resilience. We retrieved statistical and regulatory materials from the official repositories of the IEA, IEA PVPS,[33] IRENA,

[30] INTERNATIONAL ENERGY AGENCY (IEA), "Electricity Grids and Secure Energy Transitions" [online], Paris: *IEA Publications*, 2024, pp. 11-14 (Executive Summary). Available from: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions [Accessed 11 Dec. 2025].
[31] O'SULLIVAN, Meghan, OVERLAND, Indra, and SANDALOW, David, "The Geopolitics of Renewable Energy" [online], HKS Working Paper No. RWP17-027, Cambridge, MA: *Harvard Kennedy School*, 26 June 2017, pp. 16-21. Available from: https://dx.doi.org/10.2139/ssrn.2998305 [Accessed 11 Dec. 2025].
[32] U.S. DEPARTMENT OF ENERGY (DOE), LOAN PROGRAMS OFFICE, "Virtual Power Plants" [online], Washington, D.C.: *DOE*, 2025. Available from: https://www.energy.gov/lpo/virtual-power-plants [Accessed 11 Dec. 2025].
[33] IEA PHOTOVOLTAIC POWER SYSTEMS PROGRAMME (IEA-PVPS), "Trends in Photovoltaic Applications 2024" [online], Report IEA-PVPS T1-46:2024, St. Ursen: IEA-PVPS, 2024. Available from: https://iea-pvps.org/trends-reports/ [Accessed 11 Dec. 2025].

NREL, the World Bank,[34] and Our World in Data. At the screening stage, we appraised sources by title and abstract to filter irrelevant results. In the eligibility phase, we examined full-text documents against inclusion criteria, specifically publications appearing from 2015 to 2025 in English or Ukrainian. These sources required a mandatory interdisciplinary connection between energy technology development and legal regulation. We deliberately excluded purely technical reports on material efficiency that lacked a security, economic, or regulatory context.

Our prospective research section applies the method of scenario synthesis and extrapolation. We treat temporal benchmarks, specifically the window between 2036 and 2038 and the 2075 horizon, not as deterministic outcomes but as illustrations of scenario trajectories for fossil fuel displacement. These trajectories remain sensitive to technological and regulatory uncertainties. This approach relies on aggregated IEA Net Zero Emissions scenario data[35] and BNEF analytical forecasts.[36] Under the accelerated transition scenario, solar generation surpasses fossil fuels between 2034 and 2036. Conversely, the announced pledges scenario shifts this intersection point to the period between 2038 and 2040. Consequently, the window from 2036 to 2038 represents the median value between these trajectories. These scenario illustrations remain sensitive to BESS deployment rates, the volume of investment in grid modernisation, and the geopolitical stability of supply chains. The 2075 horizon serves as an analytical tool for conceptualising long-term stabilisation within a mature cyber-physical energy system.

This article uses dynamic LCOE modelling as an analytical framework to substantiate a shift in the legal paradigm rather than as a new econometric model. To evaluate the economic indicators of tandem perovskite structures and bifacial modules, our modelling incorporates CAPEX, OPEX, discount rates, and degradation coefficients over a standard 25-year asset life cycle. The learning curve, specifically the Wright Swanson law, describes cost reduction dynamics where the projected cost remains a function of the baseline cost and cumulative installed capacity. We calibrate

[34] WORLD BANK, "World Development Indicators: Energy and Mining" [online], Washington, D.C.: *The World Bank Group*, 2025. Available from: https://databank.worldbank.org/source/world-development-indicators [Accessed 11 Dec. 2025].
[35] INTERNATIONAL ENERGY AGENCY (IEA), "Electricity Grids and Secure Energy Transitions" [online], Paris: *IEA Publications*, 2024, Chapter 2. Available from: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions [Accessed 11 Dec. 2025].
[36] BLOOMBERGNEF, "Global Energy Storage Boom: Three Things to Know" [online], New York: BloombergNEF, 2025. Available from: https://about.bnef.com/insights/clean-energy/global-energy-storage-boom-three-things-to-know/ [Accessed 12 Dec. 2025].

the model against external benchmark data with a stable cost reduction rate of 20 to 24 percent per doubling of capacity.[37] We directly employ these results in legal argumentation to demonstrate that price parity indicates that solar generation has emerged from a phase of dependency on state subsidies. This transition justifies shifting the regulatory focus from economic support instruments toward stringent cybersecurity standards and the paradigm of technological sovereignty. Furthermore, the legal dimension relies on a comparative analysis of regulatory ecosystems, where market analytics[38] assist in evaluating PPA mechanisms, and scenario modelling accounts for the prospects of AI integration for the management of stochastic generation.[39]

4. Technological determinants and geo-economic imperatives of photovoltaic transformation

Renewable energy capacities surpassed the initial development phase and entered an exponential stage of industrial growth. According to IEA PVPS data, the cumulative installed capacity of solar photovoltaics worldwide exceeded 2.25 TW. Within a single calendar year, the sector added approximately 600 GW of new generating assets. This volume represents an unprecedented peak in annual growth.[40] No other energy segment expands at comparable rates. This acceleration reflects the synergy of deep LCOE parity with traditional generation, the deflationary impact of a global industrial surplus of components, and a shift in state strategies from direct subsidies toward investment regimes that support capacity deployment.

At the same time, the geographic architecture of this breakthrough reveals an asymmetry that requires a distinct security analysis. China accounts for over 1,000 GW of cumulative installed capacity and controls 80 percent of the global polysilicon, ingot,

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[37] INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA), "World Energy Transitions Outlook 2024: 1.5°C Pathway" [online], Abu Dhabi: *IRENA*, November 2024, Technology Costs Section. Available from: https://www.irena.org/Publications/2024/Nov/World-Energy-Transitions-Outlook-2024 [Accessed 11 Dec. 2025].
[38] PEXAPARK, "Pexapark Renewables Market Outlook 2025" [online], Zurich: *Pexapark*, January 2025. Available from: https://pexapark.com/pexapark-renewables-market-outlook-2025/ [Accessed 11 Dec. 2025].
[39] WORLD ECONOMIC FORUM (WEF), "Harnessing Artificial Intelligence to Accelerate the Energy Transition" [online], In collaboration with BloombergNEF and Deutsche Energie-Agentur (dena), Geneva: *WEF*, September 2021. Available from: https://www.weforum.org/publications/harnessing-artificial-intelligence-to-accelerate-the-energy-transition/ [Accessed 11 Dec. 2025].
[40] INTERNATIONAL ENERGY AGENCY (IEA), "Renewables 2024: Analysis and forecast to 2030" [online], Paris: *IEA Publications*, January 2025, Executive Summary. Available from: https://www.iea.org/reports/renewables-2024 [Accessed 12 Dec. 2025].

and wafer supply chains.[41] Under these conditions, solar energy partially loses its character as a neutral market product. It acts increasingly as an instrument of geo-economic influence. This creates a strategic vulnerability for other key actors, including the USA, the EU, and India, whose transition rates depend on the manufacturing capacity of a single dominant supplier. Such dependence highlights issues of strategic autonomy and energy sovereignty even for the most advanced economies worldwide (Figure 1).

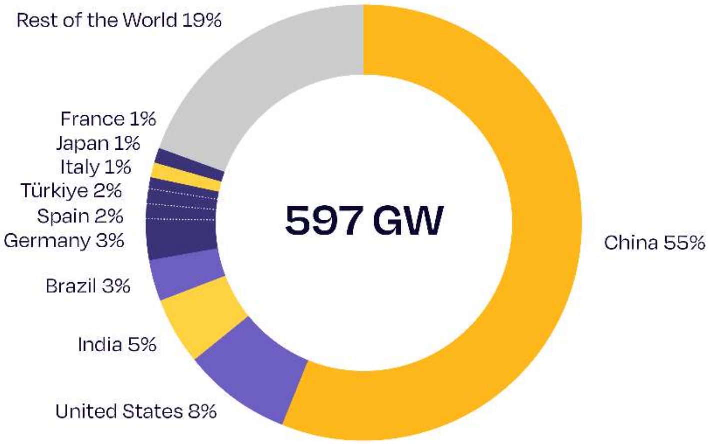

Figure 1. The global structure of solar photovoltaic installed capacity and market shares for the top ten nations in 2024

Source: Compiled from SolarPower Europe data[42]

Note: Structure represents the percentage of cumulative direct current installed capacity among the top ten national markets. Data relies on global market estimates as of the end of 2024. Reported alternating current capacity connected to the grid may differ slightly from the actual direct current module capacity.

The technological foundations of this transformation evolve through two complementary trajectories. Initially, classical PERC technology reached its limits for further improvement. Consequently, the industry is transitioning to large-scale implementation of TOPCon and HJT cells. These advancements bring the efficiency of silicon modules in mass production close to the theoretical Shockley Queisser limit.[43] Furthermore, the development of tandem perovskite architectures accelerates the overcoming of the physical limitations of silicon. Concurrently, the deployment of

[41] INTERNATIONAL ENERGY AGENCY (IEA), “Energy Technology Perspectives 2024” [online], Paris: *IEA Publications*, December 2024, Solar PV Manufacturing and Supply Chains. Available from: https://www.iea.org/reports/energy-technology-perspectives-2024 [Accessed 12 Dec. 2025].

[42] SOLARPOWER EUROPE, “Global Market Outlook for Solar Power 2025-2029” [online], Brussels: *SolarPower Europe*, 2025. Available from: https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2025-2029/detail [Accessed 16 Dec. 2025].

[43] VDMA, “International Technology Roadmap for Photovoltaic (ITRPV)” [online], Frankfurt am Main: *VDMA Photovoltaic Equipment*, 2025. Available from: https://www.vdma.eu/en-GB/international-technology-roadmap-photovoltaic [Accessed 12 Dec. 2025].

bifacial modules expands rapidly to increase yield through surface albedo effects. When combined with solar tracking systems, these innovations significantly shift the balance between capital and operational expenditures.

The increase in efficiency and the corresponding decline in capital costs reduced the levelised cost of energy to levels where coal and gas generation cannot compete. This holds even in the absence of carbon pricing (see Section 3).[44] Photovoltaics transitioned from an advantage driven by subsidies to a strategically prioritised market option in most decarbonisation scenarios. In many jurisdictions, investors select solar projects not for environmental reasons but for their financially attractive payback profiles. Data from Our World in Data and economic analysis from Lazard confirm this trend.[45]

The integration of gigawatt-scale stochastic generation into power systems designed for inertial turbines reveals a structural conflict between innovative technologies and the legacy grid architecture. The intermittency of solar energy correlates with diurnal cycles and meteorological conditions. This reality necessitates a reimagining of the system's operational principles. Without the concurrent deployment of BESS and other flexible capacities, the rapid expansion of photovoltaics may lead to market distortions, negative prices in the day-ahead market, and system operator commands for generation curtailment.[46] Leading economies confirm that scaling remains structurally constrained without significant investment in grid flexibility and the modernisation of interconnections. Meanwhile, market mechanisms for monetising balancing services grow increasingly critical. Consequently, the competitiveness of solar energy depends not only on module prices but also on system-integration costs. This shifts the focus from generating clean energy to providing firm capacity.[47]

[44] RITCHIE, Hannah, ROSADO, Pablo, and ROSER, Max, "Energy Production and Consumption" [online], *Our World in Data*, 2024. Available from: https://ourworldindata.org/energy [Accessed 11 Dec. 2025].

[45] LAZARD, "Lazard Releases 2025 Levelized Cost of Energy+ Report" [online], New York: *Lazard*, 2025, Unsubsidized LCOE Analysis. Available from: https://www.lazard.com/news-announcements/lazard-releases-2025-levelized-cost-of-energyplus-report-pr/ [Accessed 11 Dec. 2025].

[46] INTERNATIONAL ENERGY AGENCY (IEA), "Integrating Solar and Wind: Global experiences and emerging challenges" [online], Paris: *IEA Publications*, 2024. Available from: https://www.iea.org/reports/integrating-solar-and-wind [Accessed 12 Dec. 2025].

[47] SEPULVEDA, Nestor A., JENKINS, Jesse D., DE SISKIND, Fernando J., and LESTER, Richard K., "The Role of Firm Low-Carbon Resources in Deep Decarbonization of Power Generation", *Joule* [online], November 2018, vol. 2, no. 11, pp. 2403-2420. Available from: https://doi.org/10.1016/j.joule.2018.08.006 [Accessed 28 Feb. 2026].

Digitalisation on a large scale is the primary tool for overcoming these constraints. Artificial intelligence algorithms enable precise solar irradiance forecasting, predictive maintenance, and effective management of virtual power plants. Furthermore, telemetry and digital twin technologies reduce operational expenses and increase the capacity factor.[48] At the same time, the deep integration of IT solutions into energy infrastructure creates a new vector of vulnerability. Traditional generation functioned as a relatively isolated system. In contrast, a modern photovoltaic plant increasingly acts as an Internet of Things node. Attackers who compromise management software or intercept telemetry data could trigger cascading failures at the national level. Consequently, technological progress in the photovoltaic sector remains inextricably dependent on the implementation of cybersecurity protocols. Information security constitutes a fundamental condition for the stability of the energy system.[49]

Solar photovoltaics shed the label of alternative energy. If current trends persist, they could form the foundation of future energy systems' architecture. Their competitive advantages, including modularity, a low carbon footprint, minimal operational costs, and significant decentralisation potential, make this technology a viable replacement for generation based on fossil fuels. However, this potential cannot materialise through market logic alone. The fragility of supply chains, the necessity for deep grid modernisation, and mounting cyber risks require active involvement from state regulators. This ensures not only economic efficiency but also the physical and digital resilience of critical infrastructure. These challenges necessitate a revision of the regulatory framework. This process ranges from simple financial support mechanisms, such as green tariffs, to a comprehensive toolkit designed to ensure national security within the energy sector.[50]

5. Regulatory architecture of energy sovereignty: from market incentives to security protocols

Energy sovereignty increasingly depends not only on the volume of available resources and the resilience of critical infrastructure, but also on the state's capacity to

[48] DNV, "Energy Transition Outlook 2024: Technology Progress Report" [online], Høvik: DNV, October 2024. Available from: https://www.dnv.com/energy-transition-outlook/ [Accessed 12 Dec. 2025].
[49] EUROPEAN UNION AGENCY FOR CYBERSECURITY (ENISA), "ENISA Threat Landscape 2024" [online], Athens: *ENISA*, November 2024. Available from: https://www.enisa.europa.eu/publications/enisa-threat-landscape-2024 [Accessed 12 Dec. 2025].
[50] REN21, "Renewables 2025 Global Status Report: Policy Module" [online], Paris: *REN21 Secretariat*, June 2025. Available from: https://www.ren21.net/reports/global-status-report/ [Accessed 12 Dec. 2025].

establish regulatory regimes for new generation and technologies for grid management. The integration of distributed solar generation poses a challenge to the legal order. This transition requires a regulatory framework that aligns market incentives with requirements for security, cybersecurity, and continuity of supply. A review of the current legal landscape reveals a shift in the regulatory paradigm. This movement shifts from protecting static assets, such as deposits and power plants, to managing dynamic processes, data, and control algorithms. Table 1 summarises the differences between the traditional approach to energy security and the model of technological sovereignty. Our proposed matrix draws empirical grounds from a comparative analysis of specific European legal acts that define the new security architecture.

Table 1. The transformation of the legal paradigm of energy security: from resource control to technological sovereignty

Legal analysis criteria	Paradigm 1.0: The centralised model of resource sovereignty	Paradigm 2.0: The distributed photovoltaic model of technological sovereignty	Primary legal sources and benchmarks
1. Legal ontology of security	Material concept based on physical control over deposits and fuel.	Technological concept based on control over technologies and supply chains.	Critical Raw Materials Act; Net Zero Industry Act[51][52]
2. Energy legal personality	Vertical asymmetry where the consumer acts as a passive beneficiary of protection.	Network symmetry, recognizing active consumers and prosumers.	RED III; REPowerEU Plan[53][54]

[51] EUROPEAN UNION, "Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials (Critical Raw Materials Act)" [online], *Official Journal of the European Union*, L, 2024/1252, 3 May 2024. Available from: http://data.europa.eu/eli/reg/2024/1252/oj [Accessed 12 Dec. 2025].
[52] EUROPEAN UNION, "Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's Net-Zero technology products manufacturing ecosystem (Net-Zero Industry Act)" [online], *Official Journal of the European Union*, L, 2024/1735, 25 June 2024. Available from: http://data.europa.eu/eli/reg/2024/1735/oj [Accessed 12 Dec. 2025].
[53] EUROPEAN UNION, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources (RED III)" [online], *Official Journal of the European Union*, L, 2023/2413, 31 October 2023. Available from: http://data.europa.eu/eli/dir/2023/2413/oj [Accessed 27 Feb. 2026].
[54] EUROPEAN COMMISSION, "REPowerEU Plan" [online], Communication from the Commission COM (2022) 230 final, Brussels: *European Commission*, 18 May 2022. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN [Accessed 12 Dec. 2025].

3. Grid access regime	Permissive approach with a presumption of a capacity deficit.	An imperative approach with a legislative right to connection.	RED III Article 16; REPowerEU[55][56]
4. Legal liability system	Centralised tort liability of system operators.	Diffuse model with liability for the quality of software products and smart contracts.	EU AI Act; Cyber Resilience Act[57][58]
5. Critical infrastructure protection	Focus on physical protection and counterterrorism measures.	Cyber-physical approach with cybersecurity as a licensing requirement.	NIS2 Directive; NIST SP 800 82r3[59][60]
6. International trade regime	A liberal approach, prioritizing WTO rules and efficiency.	Trade through the prism of security, investment screening, and localisation.	GATT Article XXI; EU FDI Screening Regulation[61][62]
7. Nature of contractual relations	Public contracts with rigid tariff regulation.	Private autonomy, corporate PPA, and peer-to-peer trading.	RED III; Pexapark Market Outlook[63][64]

Source: The authors developed this matrix. Our empirical grounding relies on a comparative analysis of

[55] EUROPEAN UNION, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources (RED III)" [online], *Official Journal of the European Union*, L, 2023/2413, 31 October 2023. Available from: http://data.europa.eu/eli/dir/2023/2413/oj [Accessed 27 Feb. 2026].

[56] EUROPEAN COMMISSION, "REPowerEU Plan" [online], Communication from the Commission COM (2022) 230 final, Brussels: European Commission, 18 May 2022. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN [Accessed 12 Dec. 2025].

[57] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2024/1689 of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act)" [online], *Official Journal of the European Union*, L, 2024/1689, 12 July 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1689 [Accessed 27 Feb. 2026].

[58] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2024/2847 of 24 October 2024 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act)" [online], *Official Journal of the European Union*, L, 2024/2847, 20 November 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R2847 [Accessed 27 Feb. 2026].

[59] EUROPEAN UNION, "Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union (NIS 2 Directive)" [online], *Official Journal of the European Union*, L, 2022/2555, 27 December 2022. Available from: http://data.europa.eu/eli/dir/2022/2555/oj [Accessed 12 Dec. 2025].

[60] STOUFFER, Keith, PEASE, Michael, TANG, CheeYee, ZIMMERMAN, Timothy, PILLITTERI, Victoria, LIGHTMAN, Suzanne, HAHN, Adam, SARAVIA, Stephanie, SHERULE, Aslam, and THOMPSON, Michael, "Guide to Operational Technology (OT) Security" [online], NIST Special Publication 800-82r3, Gaithersburg: *National Institute of Standards and Technology*, September 2023. Available from: https://doi.org/10.6028/NIST.SP.800-82r3 [Accessed 12 Dec. 2025].

[61] WORLD TRADE ORGANIZATION (WTO), "General Agreement on Tariffs and Trade 1994 (GATT 1994), Article XXI: Security Exceptions", Geneva: *WTO*, 1994. Available from: https://www.wto.org/english/docs_e/legal_e/06-gatt_e.htm [Accessed 28 Feb. 2026].

[62] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2019/452 of 19 March 2019 establishing a framework for the screening of foreign direct investments into the Union" [online], *Official Journal of the European Union*, L 79I/1, 21 March 2019. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0452 [Accessed 27 Feb. 2026].

[63] EUROPEAN UNION, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources (RED III)" [online], *Official Journal of the European Union*, L, 2023/2413, 31 October 2023. Available from: http://data.europa.eu/eli/dir/2023/2413/oj [Accessed 27 Feb. 2026].

[64] PEXAPARK, "Pexapark Renewables Market Outlook 2025" [online], Zurich: *Pexapark*, January 2025. Available from: https://pexapark.com/pexapark-renewables-market-outlook-2025/ [Accessed 11 Dec. 2025].

European legal instruments. Relevant legal sources support each dimension.

Under conditions of intensifying hybrid threats and geo-economic turbulence, the regulatory framework of the energy sector no longer functions solely as an economic instrument. Instead, it constitutes an integral part of the national security architecture. The regulatory landscape must balance the promotion of decentralised generation with the reduction of institutional inertia within traditional monopolies. Simultaneously, it must incorporate legal safeguards against hostile influence on critical infrastructure through economic and cybernetic mechanisms. Consequently, we should evaluate the effectiveness of legislation not only by the volume of investment attracted. We must also consider the energy system's ability to remain operational in autonomous mode during crisis scenarios. Recent European regulation follows this logic. Specifically, the Net Zero Industry Act shifts the focus from cost efficiency to supply chain resilience.[65]

Mechanisms to protect supply chains and screen the jurisdictional origin of capital constitute a key element of the new regulatory architecture. Given the global market for photovoltaic components' dependence on a limited number of manufacturers, regulatory policy must move beyond the price-competition paradigm. Public procurement and licensing now require security criteria independent of price. These criteria encompass diversifying sources of critical materials, specifically polysilicon, inverter equipment, and power electronics.[66] They also provide incentives for industrial cooperation with geopolitically reliable partners to build supply chains resilient to sanctions and logistical disruptions. Concurrently, the screening process for foreign direct investment into strategic energy assets serves as an effective barrier. It prevents entities with interests that conflict with national goals from establishing control over generating capacities. The state requires the authority to block transactions that create a risk of concentrating vital capacities in foreign hands, even if their economic benefits in the short term appear substantial.[67]

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[65] EUROPEAN UNION, "Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's Net-Zero technology products manufacturing ecosystem (Net-Zero Industry Act)" [online], *Official Journal of the European Union*, L, 2024/1735, 25 June 2024. Available from: http://data.europa.eu/eli/reg/2024/1735/oj [Accessed 12 Dec. 2025].

[66] EUROPEAN UNION, "Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials (Critical Raw Materials Act)" [online], *Official Journal of the European Union*, L, 2024/1252, 3 May 2024. Available from: http://data.europa.eu/eli/reg/2024/1252/oj [Accessed 12 Dec. 2025].

[67] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2019/452 of 19 March 2019 establishing a framework for the screening of foreign direct investments into the Union" [online], *Official*

A distinct trajectory of regulatory policy concerns cyber resilience within the digitalised energy sector. Modern photovoltaic plants and BESS rely on complex algorithms and connect to information networks. This connectivity expands the risk surface. Consequently, the regulatory framework must encompass not only physical assets but also the virtual management environment. This environment includes software, data exchange protocols, and telemetry protection. The Cyber Resilience Act reinforces this logic by establishing horizontal security requirements for digital products.[68] The regulation of AI systems for balancing and dispatching becomes particularly important. The sector requires rules that mandate that operators ensure transparency in models, document decisions, and maintain mechanisms for human oversight. These mechanisms enable rapid override by management during cyberattacks or systemic failures. The AI Act substantiates this approach by classifying systems for the management of critical infrastructure as high-risk systems.[69] Consequently, cybersecurity no longer remains the prerogative of IT departments. It now constitutes a licensing requirement for market entry. A failure to comply entails liability commensurate with the risks to national security.

Energy sovereignty also requires removing regulatory barriers that artificially constrain distributed generation. Traditional and centralised systems based on fossil fuels often employ onerous connection procedures and opaque market rules to preserve the status quo. Evidence indicates that the primary obstacle to deploying solar generation is bureaucratic architecture and regulatory bottlenecks, rather than technological limitations. The following analysis presents specific examples from various jurisdictions to illustrate these challenges.

In the United States, the lack of unified federal rules creates high soft costs. These permitting, inspection, and interconnection expenses account for up to 60

Journal of the European Union, L 79I/1, 21 March 2019. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32019R0452 [Accessed 27 Feb. 2026].

[68] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2024/2847 of 24 October 2024 on horizontal cybersecurity requirements for products with digital elements (Cyber Resilience Act)" [online], *Official Journal of the European Union*, L, 2024/2847, 20 November 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R2847 [Accessed 27 Feb. 2026].

[69] EUROPEAN PARLIAMENT AND THE COUNCIL, "Regulation (EU) 2024/1689 of 13 June 2024 laying down harmonised rules on artificial intelligence (Artificial Intelligence Act)" [online], *Official Journal of the European Union*, L, 2024/1689, 12 July 2024. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1689 [Accessed 27 Feb. 2026].

percent of the total cost of residential solar systems.[70] Furthermore, data from the LBNL report shows that outdated regulations from system operators prolong wait times in interconnection queues. For commercial projects, these delays now average between four and five years. This administrative inertia represents a significant barrier to the rapid deployment of generating assets.[71]

Researchers observe similar structural barriers within the European market. In Germany, despite leadership in implementing renewable energy sources, inverter certification takes a significant amount of time. Obtaining a certificate of conformity for the grid parameters can take between six and twelve months. This delay artificially postpones the commissioning of completed facilities. In Poland, massive investor interest encounters infrastructure and administrative constraints. Due to a shortage of available capacity and the opacity of its allocation, distribution system operators reject between 60 and 80 percent of new applications for connecting solar power plants. Such high rejection rates indicate that the grid's physical capacity and the regulatory rules governing its access fail to keep pace with technological progress.[72][73]

Spain offers a prominent example of a politically motivated regulatory barrier. Between 2015 and 2018, the sun tax established by Real Decreto 900/2015 remained in effect. This measure penalised energy generated for on-site consumption. Consequently, the legislation effectively discouraged prosumers throughout that period.[74] In Ukraine, administrative obstacles manifest as complex procedures for changing land use designations and stringent technical conditions for connection. These requirements frequently compel investors to install BESS to support grid

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[70] DONG, Changgui, NEMET, Gregory, GAO, Xue, BARBOSE, Galen, SIGRIN, Ben, and O'SHAUGHNESSY, Eric, "Machine learning reduces soft costs for residential solar photovoltaics", *Scientific Reports* [online], May 2023, vol. 13, no. 1, art. 7213. Available from: https://doi.org/10.1038/s41598-023-33014-4 [Accessed 28 Feb. 2026].

[71] RAND, Joseph, et al., "Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023" [online], Berkeley, CA: *Lawrence Berkeley National Laboratory*, April 2024, Executive Summary. Available from: https://emp.lbl.gov/publications/queued-characteristics-power-plants [Accessed 25 Feb. 2026].

[72] EURELECTRIC, "Gridlock to grid growth: tackling connection queues for a smoother energy transition" [online], Brussels: *Eurelectric*, April 2024. Available from: https://www.eurelectric.org/blog/gridlock-to-grid-growth/ [Accessed 28 Feb. 2026].

[73] DENTONS, "Poland's development plans for transmission and distribution networks" [online], Warsaw: *Dentons*, November 2024. Available from: https://www.dentons.com/en/insights/newsletters/2024/november/21/powered-by-dentons/powered-by-dentons--november-2024/polands-development-plans-for-transmission-and-distribution-networks [Accessed 28 Feb. 2026].

[74] BOLETÍN OFICIAL DEL ESTADO (BOE), "Real Decreto 900/2015, de 9 de octubre, por el que se regulan las condiciones administrativas, técnicas y económicas de las modalidades de suministro de energía eléctrica con autoconsumo y de producción con autoconsumo" [online], Madrid: *BOE*, 10 October 2015. Available from: https://www.boe.es/eli/es/rd/2015/10/09/900 [Accessed 27 Feb. 2026].

balancing. Presently, the regulatory environment lacks adequate mechanisms for financial compensation regarding such investments. Such conditions increase developers' risk profile and hinder the pace of the energy transition.

In contrast to the barriers mentioned, the experience of Australia and of specific states with a high share of distributed generation demonstrates the effectiveness of transitioning from a permissive to a declarative principle. This model simplifies the integration of small capacities. It replaces complex approval processes with a standard notification to the operator. Such a regulatory shift encourages rapid adoption while maintaining network safety.[75]

Policymakers counteract institutional resistance by legalising corporate PPA agreements. These direct electricity purchase-and-sale contracts allow producers and consumers to conclude deals without monopolistic intermediaries. Spain is the undisputed leader of the European corporate PPA market. Instead of state green tariffs, the Spanish regulatory framework facilitates direct agreements between developers of gigawatt-scale solar parks and large industrial consumers. Concurrently, the use of standard terms in long-term PPA contracts ensures the financial attractiveness of projects without state subsidies. This provides the industry with a hedge against volatility in fossil fuel prices.[76] Simplified procedures also prove crucial for the deployment of autonomous hybrid systems at critical infrastructure facilities. These systems support hospitals, water utilities, and other vital services that require service continuity during crisis scenarios. REPowerEU enshrines this logic. It defines the deployment of renewable energy as a matter of overriding public interest.[77] Legal certainty for microgrids and energy cooperatives transforms active consumers into resilience assets. This reduces the vulnerability of decentralised architecture to kinetic and economic shocks.

The German case regarding the protection of distributed energy resources illustrates the practical implementation of strict security standards. The GNDEW

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[75] AUSTRALIAN ENERGY MARKET COMMISSION (AEMC), "Rule Determination: National Electricity Amendment (Access, pricing and incentive arrangements for distributed energy resources) Rule 2021" [online], Sydney: AEMC, 12 August 2021. Available from: https://www.aemc.gov.au/rule-changes/access-pricing-and-incentive-arrangements-distributed-energy-resources [Accessed 3 Mar. 2026].

[76] PEXAPARK, "Pexapark Renewables Market Outlook 2025" [online], Zurich: *Pexapark*, January 2025, European PPA Market Overview. Available from: https://pexapark.com/pexapark-renewables-market-outlook-2025/ [Accessed 11 Dec. 2025].

[77] EUROPEAN COMMISSION, "REPowerEU Plan" [online], Communication from the Commission COM (2022) 230 final, Brussels: *European Commission*, 18 May 2022. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN [Accessed 12 Dec. 2025].

mandates the integration of decentralised generation systems into the grid exclusively through certified Smart Meter Gateways.[78] These hardware devices comply with rigorous standards set by the Federal Office for Information Security to serve as cryptographic barriers. The implementation of this architecture ensures that no external actor can execute widespread remote cyberattacks on the inverters of solar power plants to create an artificial frequency imbalance in the grid. The German experience confirms that regulatory sovereignty requires the deep integration of information technology security standards into grid connection standards. Such a framework transforms technical protocols into a robust shield for national energy stability.

Evidence from outside the European Union supports the proposed architecture of regulatory sovereignty. The United States offers a prominent example of how industrial policy integrates organically with mechanisms for national security. The Inflation Reduction Act of 2022 incentivises the deployment of domestic supply chains for photovoltaic components and battery storage systems. Localisation bonuses effectively reduce reliance on dominant foreign suppliers. Meanwhile, the Committee on Foreign Investment in the United States actively blocks transactions involving the acquisition of infrastructure assets by companies from jurisdictions of concern.[79] Concurrently, the North American Electric Reliability Corporation establishes standards for protecting critical infrastructure. These protocols require strict cybersecurity for systems used in distributed generation.[80] The American model correlates clearly with Paradigm 2.0 (see Table 1). The transition from price-based competition toward technological autonomy and grid protection represents a universal regulatory trend. Law serves as an instrument to create an environment in which energy independence remains technically achievable and legally protected.

6. Discussion of results: synthesis of technological autonomy and legal certainty

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[78] BUNDESGESETZBLATT, "Gesetz zum Neustart der Digitalisierung der Energiewende (GNDEW)" [online], *Bundesgesetzblatt Teil I*, Nr. 133, Bonn: Bundesministerium der Justiz, 26 May 2023. Available from: https://www.recht.bund.de/bgbl/1/2023/133/VO.html [Accessed 27 Feb. 2026].

[79] JACKSON, James K., and CIMINO-ISAACS, Cathleen D., "The Committee on Foreign Investment in the United States (CFIUS)" [online], CRS Report RL33388, Washington, D.C.: *Congressional Research Service*, 2024. Available from: https://crsreports.congress.gov/product/pdf/RL/RL33388 [Accessed 25 Feb. 2026].

[80] U.S. DEPARTMENT OF THE TREASURY, "The Committee on Foreign Investment in the United States (CFIUS)" [online], Washington, D.C.: *U.S. Department of the Treasury*, 2024. Available from: https://home.treasury.gov/policy-issues/international/the-committee-on-foreign-investment-in-the-united-states-cfius [Accessed 25 Feb. 2026].

Large-scale photovoltaic deployment transcends the boundaries of economic and environmental discourse. The integration of these technologies acquires a precise dimension of state sovereignty. The correlation between the rapid decline in the levelised cost of energy and the rise in geopolitical risks necessitates a reassessment of the traditional energy policy trilemma. That framework historically balances security, affordability, and environmental sustainability. While economic efficiency served as the primary goal in previous decades, the current landscape of hybrid threats shifts the focus. National strategies now prioritise the physical resilience and autonomy of the energy system.[81]

Combining a retrospective analysis of global energy trends over 50 years with predictive modelling up to 2075 indicates a fundamental shift in the worldwide energy regime. A transition of this scale potentially leads to an era of solar energy dominance. To clarify the boundaries of prospective analysis, the study distinguishes analytical forecasts from normative hypotheses.[82] Extrapolating current rates of technological diffusion suggests that the window of strategic inversion occurs between 2036 and 2038. At that point, if existing investment trends continue, solar generation volumes may exceed fossil fuel output for the first time. Conversely, the assertion that hydrocarbons will ultimately lose their role as the anchor of the global energy system constitutes a political hypothesis rather than a deterministic fact. Achieving this scenario depends on the deployment rates of energy storage and the capacity to modernise grids. Success also relies on governments' institutional capacity to overcome resistance from traditional energy monopolies. Energy monopolies continue to serve as providers of flexible capacity to cover peak demand. The identified timeframes remain sensitive to political decisions. Subject to the effective implementation of strategic measures, the shift may occur as early as the beginning of the 2030s.[83]

Alongside technological innovations, regulatory architecture and mechanisms for financial pressure play a crucial role. The simplification of permitting procedures and

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[81] WORLD ENERGY COUNCIL, "World Energy Issues Monitor 2025" [online], London: *World Energy Council*, 2025, Executive Summary. Available from: https://www.worldenergy.org/publications/entry/world-energy-issues-monitor-2025 [Accessed 12 Dec. 2025].

[82] EMBER, "Global Electricity Review 2025" [online], London: *Ember*, May 2025. Available from: https://ember-energy.org/latest-insights/global-electricity-review-2025/ [Accessed 12 Dec. 2025].

[83] INTERNATIONAL ENERGY AGENCY (IEA), "World Energy Outlook 2024" [online], Paris: *IEA Publications*, October 2024. Available from: https://www.iea.org/reports/world-energy-outlook-2024 [Accessed 12 Dec. 2025].

the reduction of project approval times are key imperatives. The speed of administrative processes now directly defines outcomes for energy security. RED III enshrines this logic by limiting the deployment of renewable energy on the grounds of overriding public interest.[84] Coupled with the abolition of subsidies for fossil fuels and the rising cost of carbon emissions, these measures make traditional generation economically viable only until the point of capital repair. This shift brings the issue of stranded assets to the forefront. However, a low levelised cost of energy does not guarantee the inevitability of complete solar hegemony. This transition remains neither linear nor irreversible. The future architecture of the energy system depends on several uncertainties. These include technological factors, such as the speed of scaling systems for long-term storage and the modernisation of grids. Political factors, including changes in government priorities and trade wars, also influence the outcome. Furthermore, social challenges, such as NIMBY opposition to large-scale land allocation for solar parks, persist. Accordingly, the success of the technology depends not only on price parity but also on institutions' ability to manage these multilevel risks.[85]

The conducted analysis demonstrates that the dual nature of digitalisation makes market-oriented regulatory models structurally insufficient.[86][87] Digitalisation simultaneously serves as an optimisation tool and an expansion of the surface area for cyberattacks. This duality justifies more than the mere supplementation of existing regimes with new technical requirements. It demands a conceptual transition to regulatory sovereignty. Under this paradigm, the state ceases to act as a passive market arbiter. Instead, the government becomes an active guarantor of the digital

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[84] EUROPEAN UNION, "Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources (RED III)" [online], *Official Journal of the European Union*, L, 2023/2413, 31 October 2023. Available from: http://data.europa.eu/eli/dir/2023/2413/oj [Accessed 27 Feb. 2026].

[85] INTERNATIONAL MONETARY FUND (IMF), "Fossil Fuel Subsidies Data: 2024 Update" [online], Washington, D.C.: *IMF*, 2024. Available from: https://www.imf.org/en/Topics/climate-change/energy-subsidies [Accessed 12 Dec. 2025].

[86] STOUFFER, Keith, PEASE, Michael, TANG, CheeYee, ZIMMERMAN, Timothy, PILLITTERI, Victoria, LIGHTMAN, Suzanne, HAHN, Adam, SARAVIA, Stephanie, SHERULE, Aslam, and THOMPSON, Michael, "Guide to Operational Technology (OT) Security" [online], NIST Special Publication 800-82r3, Gaithersburg: *National Institute of Standards and Technology*, September 2023. Available from: https://doi.org/10.6028/NIST.SP.800-82r3 [Accessed 12 Dec. 2025].

[87] KHALYMON, S., TYSHCHUK, V., "General Artificial Intelligence and the US–PRC Arms Race: Impacts on Global Militarization and International Law", *Revista Jurídica Portucalense* [online], 2026, no. 39, pp. 43-75. Available from: https://doi.org/10.34625/issn.2183-2705(39.1)2026.ic-3 [Accessed 27 Feb. 2026].

resilience of critical infrastructure. The technological autonomy of photovoltaics remains inextricably linked to digital sovereignty. Without such sovereignty, the infrastructure remains vulnerable regardless of the volume of installed capacity.[88]

Unlike fossil fuels, which require continuous import of resources, photovoltaics create dependence primarily during equipment installation. This specific feature opens a window for strategic manoeuvring through supplier diversification, the development of domestic production, investment screening, and strengthened partnerships.[89] Under these conditions, legal certainty regarding measures to support national industry and protect the market performs a function of state security. This role goes beyond classical protectionism. The ability of the state to ensure the entire cycle, from equipment production to safe operation, becomes a marker of its geopolitical subjectivity.

The combination of technological and legal perspectives forms a holistic concept for the resilience of distributed energy systems. Unlike the inertial centralised model, which concentrates risks in critical nodes, a distributed grid relies on numerous autonomous photovoltaic systems with local storage. This topology promotes self-balancing and maintains operability even after partial infrastructure damage. Legal norms simplify the creation of autonomous grids and permit their operation in island mode. Such regulations act as an institutional catalyst for this resilience.[90] Consequently, the end consumer becomes an active security actor. Energy independence ceases to be the exclusive prerogative of state monopolies. Instead, independence emerges from collective actions enabled by photovoltaic technologies and secured by legal certainty. Under these conditions, energy sovereignty depends primarily on designing the grid as a resilient system. This architecture must feature distributed sources, local storage, the ability to operate in island mode, and clearly defined legal regimes for access and liability.

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[88] EUROPEAN UNION, "Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union (NIS 2 Directive)" [online], *Official Journal of the European Union*, L, 2022/2555, 27 December 2022. Available from: http://data.europa.eu/eli/dir/2022/2555/oj [Accessed 12 Dec. 2025].

[89] INTERNATIONAL RENEWABLE ENERGY AGENCY (IRENA), "Geopolitics of the Energy Transition: Critical Materials" [online], Abu Dhabi: *IRENA*, 2023. Available from: https://www.irena.org/Publications/2023/Jul/Geopolitics-of-the-energy-transition-Critical-materials [Accessed 12 Dec. 2025].

[90] INTERNATIONAL ENERGY AGENCY (IEA), "World Energy Outlook 2024" [online], Paris: *IEA Publications*, October 2024. Available from: https://www.iea.org/reports/world-energy-outlook-2024 [Accessed 12 Dec. 2025].

CONCLUSIONS

Solar photovoltaics has undergone a fundamental shift in its role within energy policy. Although the technology initially focused on environmental and climate goals, it now serves as a primary instrument for national security and state sovereignty. The achievement of grid parity and technological progress has elevated photovoltaics to a leading position within the energy sector. Concurrently, this evolution transforms the risk landscape. Such changes require qualitatively new approaches to industry management. In hybrid confrontations, energy infrastructure faces kinetic and cyber threats. Under these circumstances, decentralised generation maintains operability more effectively than inertial centralised systems.

The quality of legal and regulatory design determines whether solar energy can serve national security goals. Market mechanisms alone do not guarantee the security of supply or the resilience of critical infrastructure. An effective model of energy sovereignty relies on three interconnected elements. These components include stricter screening of foreign investments in strategic assets, legally mandated cybersecurity requirements within management systems, and strategic diversification of supply chains. Legal certainty regarding systems for battery energy storage and mechanisms for direct contracting provides more than just economic incentives for business. Reliable legal frameworks also form the foundation of a distributed grid capable of withstanding external shocks.

Modern energy independence arises from the combination of technological autonomy and the state's institutional capacity to protect the domestic market and information space. Further development of the sector depends on governments' ability to align the pace of innovation with the implementation of security protocols and mechanisms for liability. Key innovations in this field include perovskite tandem solutions and the use of artificial intelligence for load distribution. Further research should focus on adaptive regulatory models capable of responding to challenges in real time. These frameworks must maintain a balance between openness to innovation and the protection of national interests. In the broader context of law and sustainable development, the proposed concept facilitates alignment between decarbonisation goals and the requirements of energy affordability. This approach also ensures the legal protection of vulnerable consumers.

The results of this study require governments to transition from fragmented renewable energy stimulation to a comprehensive architecture of energy sovereignty.

This framework provides specific recommendations for policymakers and national regulators. Authorities should integrate diversification requirements and cybersecurity criteria not based on price into all procedures for auctions and public procurement. Regulators must introduce mandatory screening of foreign investments in grid management systems, with particular focus on inverters and battery storage systems. Furthermore, governments should transition the procedures for connecting decentralised capacities to a declaratory principle. Only interagency coordination of priorities regarding climate, markets, and security will effectively enable the energy transition to protect national interests amid geo-economic turbulence.

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