ISCTE IUL
REPOSITÓRIO
INSTITUTO UNIVERSITÁRIO DE LISBOA

Repositório ISCTE-IUL

Deposited in *Repositório ISCTE-IUL*:
2026-08-31

Deposited version:
Accepted Version

Peer-review status of attached file:
Peer-reviewed

Citation for published item:
Costa, E. & Wells, P. (2026). Urban on-grid solar PV and the trade-offs between promise and practice. WIREs Energy and Environment. 15 (3)

Further information on publisher's website:
10.1002/wene.70039

Publisher's copyright statement:
This is the peer reviewed version of the following article: Costa, E. & Wells, P. (2026). Urban on-grid solar PV and the trade-offs between promise and practice. WIREs Energy and Environment. 15 (3), which has been published in final form at https://dx.doi.org/10.1002/wene.70039. This article may be used for non-commercial purposes in accordance with the Publisher's Terms and Conditions for self-archiving.

Use policy

Creative Commons CC BY 4.0
The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a link is made to the metadata record in the Repository
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Serviços de Informação e Documentação, Instituto Universitário de Lisboa (ISCTE-IUL)
Av. das Forças Armadas, Edifício II, 1649-026 Lisboa Portugal
Phone: +(351) 217 903 024 | e-mail: administrador.repositorio@iscte-iul.pt
https://repositorio.iscte-iul.pt

Urban On-Grid Solar PV and the Trade-offs Between Promise and Practice

Overview

Evaldo Costa[1], Peter Wells[2]*

[1]Instituto Universitário de Lisboa (ISCTE-IUL), DINAMIA'CET, PORTUGAL, ORCID: 0000-0003-2528-9587, Jose.Costa@iscte-iul.pt

[2]Cardiff University, Cardiff Business School, Cardiff, UK, ORCID: 0000-0002-4376-7178, WellsPE@cardiff.ac.uk

Conflict of Interest

The authors declare no conflicts of interest. During the preparation of this work

Version of Record

ABSTRACT

Although investments in renewable energy, particularly solar photovoltaic (PV) systems, have increased over the past decade, the energy transition still faces dilemmas related to several socio-technical and environmental aspects. To clarify the benefits, challenges, and trade-offs of distributed urban solar PV, this article conducts a multidimensional literature review and develops an integrated trade-off framework that considers technical, economic, social, regulatory, and environmental perspectives. The review highlights the controversial aspects that support and challenge the potential of on-grid urban solar systems to enhance energy security, improve efficiency, and support community engagement through technological innovation and novel social practices. Several concerns arise, including investment risks, social equity, energy security, environmental impact, maintenance, and aesthetics, all of which require strategic mitigation. Integrating solar PV into smart urban environments also presents constraints related to energy storage, consumer adaptability, business model innovation (BMI), stakeholder engagement, and potential health hazards. Addressing these issues requires balancing socio-technical and environmental aspects. Based on a systematic assessment of European case studies – including Amsterdam's solar-EV ecosystem, Spain's post-2018 regulatory reforms, and France's inclusive financing models – we find that successful pathways combine modernized interconnection standards, streamlined permitting, collective self-consumption frameworks, performance-based regulation, and targeted financial instruments for low-income households. BMI and policy reforms are essential drivers for the successful diffusion of solar PV systems. Achieving a sustainable energy future in urban areas requires stakeholder collaboration, public-private partnerships (PPPs), innovative solutions, and careful balancing of multiple trade-offs. This article sheds light on the current state of the art on distributed solar PV and emphasizes the need for informed decision-making to address the complexities of on-grid urban solar systems, aiming for a sustainable, resilient, efficient, and inclusive urban energy future.

1. Introduction

Rising energy consumption driven by population growth and socio-technical and environmental activities poses significant challenges for the global energy transition. Despite increased investment in renewable energy sources (RES) over the past decade, the growth of RES remains insufficient to meet decarbonization targets, and its expansion is accompanied by difficult trade-offs between environmental, economic, and

social objectives (Rabiee et al., 2026). The energy sector still accounts for nearly three-quarters of global greenhouse gas (GHG) emissions, making its transformation a central hurdle in the transition toward sustainability (IEA, 2024a).

Within this context, solar photovoltaic (PV) systems have expanded rapidly, supported by falling costs and technological advances. Solar power capacity in Europe nearly doubled between 2021 and 2023, while global solar costs declined by around 80% between 2010 and 2020 (Boehm et al., 2023). Yet, despite this momentum, the deployment of urban distributed photovoltaics (DPV) faces multiple constraints that limit its contribution to accelerating low-carbon transitions.

Urban environments concentrate energy demand, emissions, and vulnerabilities associated with centralized electricity systems. Smart urban areas (where technology, data, and sustainable strategies are integrated to optimize infrastructure, mobility, energy use, and quality of life) offer a promising context for on-grid urban DPV expansion (Hoang & Nguyen, 2021). Grid-connected solar systems installed on residential rooftops, commercial buildings, industrial facilities, community solar initiatives, and solar canopies can enhance energy security, reduce transmission losses, and promote community engagement in energy generation and consumption (Costa & Mercier-Laurent, 2025; Rezaee & Silva, 2026).

Technological innovations (including artificial intelligence (AI), digital twins (DT), smart building energy management systems (BEMS), and vehicle-to-grid (V2G) technologies) further strengthen urban DPV by improving forecasting, enhancing resilience, and enabling electric vehicle (EV) batteries to function as distributed storage units (Almadhor et al., 2022; Huy et al., 2023; Taminiau et al., 2021).

However, the expansion of on-grid urban DPV also raises concerns. High upfront investment costs, dependence on government incentives, limited rooftop availability, shading from dense urban structures, heritage restrictions, grid compatibility issues, market uncertainty, and consumer awareness gaps remain significant barriers (Fathoni & Boer, 2021; Andrade-Arias et al., 2025; Costa & Pereirinha, 2025). Environmental and health considerations – including lifecycle emissions, end-of-life management of PV modules and batteries, and potential exposure to electromagnetic fields (EMF) – add further complexity (Chowdhury et al., 2020; Lyu et al., 2020; Verbeek et al., 2021)

Although the literature addresses many of these dimensions, existing review studies generally examine technical, economic, social, environmental, or regulatory aspects separately, or integrate only a limited subset of these criteria. Consequently, they provide valuable insights into specific challenges but offer a more limited understanding of how these dimensions interact to shape urban DPV deployment. While some studies have adopted multidimensional or multi-criteria perspectives, they do not fully synthesize the dynamic trade-offs that emerge from the interaction of technical, economic, social, regulatory, environmental, and health dimensions in urban settings (Gholami, 2024).

Version of Record

Accordingly, this review's contribution is to illustrate that urban DPV should be understood as a socio-technical system in which these dimensions evolve through continuous interactions rather than independently. Accordingly, the review proposes a multidimensional trade-off framework that synthesizes these interactions. We provide a conceptual perspective for understanding how the interactions influence policy effectiveness, market development, stakeholder decisions, and the practical implementation of urban distributed solar PV. By emphasizing these dynamic relationships, the review extends beyond a conventional synthesis of benefits and barriers and offers a more integrated understanding of the opportunities and constraints shaping urban solar transitions. This multidimensional perspective also helps explain why stakeholders are often left "between the sun and a hard place" when making decisions about urban solar deployment.

Building upon this conceptual framework, the review provides a multidimensional and integrative analysis of on-grid urban DPV. Its principal contribution goes beyond synthesizing the existing literature, to explain how interactions among technical, economic, social, regulatory, environmental, and health dimensions shape urban solar deployment and create trade-offs that influence implementation outcomes. Specifically, the review:

- Synthesizes key benefits and opportunities;
- Exams technical, economic, social, regulatory, environmental, and health challenges;
- Identifies the trade-offs inherent to each dimension;
- Presents international case studies that illustrate practical solutions;
- Compare policy and regulatory pathways;
- And outlines a future research agenda focused on innovation, equity, and system resilience.

Section 2 presents the analytical framework and methodology. Section 3 synthesizes benefits and opportunities. Section 4 examines challenges and embedded trade-offs. Section 5 presents case studies and best practices illustrating how specific trade-offs have been addressed in real-world contexts. Section 6 analyzes policy and regulatory pathways. Section 7 outlines a future research agenda. Section 8 concludes**.**

2. Analytical framework and methodology

This review builds upon the multidimensional trade-off framework introduced in Section 1 and uses it both as an analytical structure for organizing the literature and as the conceptual lens of the review. The framework synthesizes the diverse technical, economic, social, regulatory, environmental, health, and business model dimensions that shape the deployment of on-grid urban DPV systems. Rather than examining these dimensions independently, it emphasizes their dynamic interactions and the trade-offs that emerge among them, providing an integrated perspective for understanding urban DPV deployment.

Version of Record

This proposed framework is distinct from formal multi-criteria analysis (MCA). Rather than applying weighted scoring or decision-analytic procedures, it provides a qualitative conceptual lens for synthesizing and interpreting evidence from narrative and thematic literature. The methodological approach follows established practices for integrative reviews, emphasizing breadth, conceptual synthesis, and the identification of interactions and trade-offs across multiple dimensions of urban DPV deployment.

The literature search was conducted using three major scientific databases: Web of Science (WoS), Scopus, and Google Scholar, selected for their comprehensive coverage of peer-reviewed publications across engineering, environmental sciences, urban studies, and energy policy. The search strategy employed combinations of keywords related to the core dimensions of the study, including: "Solar PV", "Urban Solar", "On-Grid", "Distributed", "Stakeholder", "Business Model Innovation", "Policy", "Regulation", and "Health". These terms were derived from an initial exploratory reading of the literature to identify recurring themes and conceptual clusters.

Only English-language publications explicitly addressing on-grid or distributed solar PV in urban contexts were retained. Studies focusing exclusively on off-grid systems, rural electrification, or non-solar renewable technologies were excluded. Additional filtering considered conceptual relevance and contribution to at least one of the analytical dimensions examined in this review. In addition to peer-reviewed scientific literature, the review included selected non-scientific sources such as government reports, regulatory documents, industry publications, and specialized news. These sources capture recent pilot studies, emerging regulatory developments, and real-world implementation examples not yet documented in academic research.

Business model innovation in urban DPV systems

Business model innovation (BMI) plays a pivotal role in shaping how urban DPV create, deliver, and capture value within evolving socio-technical systems (Stauch & Vuichard, 2019). BMI emerges when technological, regulatory, and social changes alter the boundary conditions under which firms operate, enabling new forms of coordination, new value propositions, and new cross-sector interactions and societal involvement (Xue et al., 2022). As demonstrated in prior research on the confluence between the electricity and automotive sectors, BMI often arises when established actors confront pressures that destabilize traditional practices and open space for experimentation across system boundaries (Costa, Wells et al., 2022).

In the context of urban DPV, BMI is increasingly driven by decentralization, digitalization, and the rise of prosumer participation (Gómez-Navarro et al., 2021). These shifts enable new organizational structures including community energy cooperatives, peer-to-peer trading platforms, and aggregator-based flexibility markets along with as well as new organizational processes, including dynamic pricing, bundled energy-mobility services, and integrated solar-storage-EV offerings (Stauch, 2021). Such innovations challenge incumbent utility logics and require new forms of

Version of Record

coordination between municipalities, distribution system operators (DSOs), technology providers, and consumers.

BMI also functions as a mechanism for managing institutional misalignments. Urban DPV systems often involve conflicting logics: centralized grid governance versus distributed generation, utility revenue stability versus prosumer empowerment, and heritage protection versus rooftop solar expansion. BMI can help reconcile these tensions by enabling hybrid arrangements such as shared ownership models, leasing schemes, or performance-based service contracts that redistribute risks, benefits, and responsibilities among actors (Sierro & Blumer, 2024).

Therefore, BMI represents one of the mechanisms through which the multidimensional trade-offs identified in this review are managed and, in some cases, reconciled. Economic trade-offs (e.g., upfront costs versus long-term savings), social trade-offs (e.g., accessibility versus complexity), and regulatory trade-offs (e.g., standardization versus local autonomy) all influence the viability of BMI. As urban DPV systems evolve, BMI will remain essential for integrating technical solutions with social acceptance, adaptive regulation, and equitable value creation.

3. Benefits and opportunities of on-grid urban solar

The potential of on-grid urban DPV systems extends far beyond clean electricity generation. When integrated into smart urban infrastructures, these systems can enhance energy security, improve public health, optimize limited space, and create new economic opportunities. These benefits, however, are accompanied by trade-offs that require careful management and are examined in detail in Section 4.

Enhanced energy autonomy and resilience. Urban DPV strengthens local energy autonomy by enabling households, businesses, and communities to generate part of their own electricity, reducing exposure to centralized supply disruptions (Griego et al., 2022). Distributed generation also strengthens resilience by lowering transmission losses and helping balance urban electricity demand, especially during peak periods (Etukudoh et al., 2024; Ufa et al., 2022). High-density DPV deployment can contribute to grid resilience by helping maintain critical loads during disruptions, a capability particularly valuable for emergency services and vulnerable populations (Sheng & Liu, 2023; Griego et al., 2022). Beyond technical resilience, cities such as Freiburg, Germany, demonstrate how renewable energy integration, green spaces, and car-free zones can simultaneously enhance environmental quality, public health, and social equity, thereby strengthening community resilience (Allam & Soomauroo, 2025).

Lower emissions and improved air quality. Urban solar PV contributes directly to climate mitigation by reducing reliance on fossil fuel-based power plants (Jin et al., 2023). Because generation occurs close to consumption points, emissions associated with transmission and distribution are minimized. For example, a study of rooftop PV deployment in Wuhan reported that the Wuhan New Energy Research Institute achieved a 15% reduction in building-level CO_2 emissions between 2014 and 2015 **(**Jin et al.,

Version of Record

2023; C40 Cities, 2016**).** Improved air quality is particularly relevant in densely populated cities, where reductions in fine particulate matter (PM2.5) and nitrogen oxides (NOx) have measurable public health benefits – including lower rates of asthma and cardiovascular disease (Kobashi et al., 2021). These environmental gains align with broader urban sustainability goals and climate neutrality commitments.

Efficient use of urban space. Innovative solar designs, such as building-integrated photovoltaics (BIPV), solar façades, agrivoltaics, and floating solar, enable cities to optimize limited space while expanding renewable capacity (Fathoni & Boer, 2021; Ren et al., 2023). Rooftops, façades, parking canopies, and underutilized surfaces become productive energy assets, reducing pressure on peri-urban land and supporting compact, resource-efficient urban development. The city of Seoul, for example, has been the subject of extensive "solar city" assessment methods combining GIS technology and hill shade analysis to map rooftop solar potential across its dense urban fabric (Taminiau et al., 2021). These analyses suggest that widespread rooftop PV deployment could supply nearly 30% of Seoul's annual electricity consumption without requiring additional land (Taminiau et al., 2021).

Strengthened urban sustainability and institutional image. The adoption of urban solar PV reinforces municipal and corporate sustainability agendas, enhancing environmental credibility and attracting climate-conscious investors (Vimpari & Junnila, 2017). Green bonds, sustainability-linked loans, and environmental, social, and governance (ESG) criteria have increasingly prioritized cities and companies with visible renewable energy commitments. PPPs and community-based initiatives further expand opportunities for collaborative governance, enabling cities to mobilize diverse stakeholders toward shared energy transition objectives (Costa, Vicente et al., 2025).

Improved local supply-demand matching. Producing renewable energy near consumption centers increases system efficiency and reduces transmission losses. In the United States, long-distance transmission loses approximately 2% of electricity, while distribution adds another 4%, although these figures vary significantly by population density and grid infrastructure (Wirfs-Brock, 2015). In countries with aging infrastructure or higher demand density, total grid losses can be substantially higher (Chen et al., 2024). Smart grids and storage solutions facilitate real-time balancing between production and consumption, enabling more flexible and adaptive urban energy systems. This proximity also supports demand response strategies and enhances the value of self-consumption.

Integration with smart technologies and electric mobility. Advanced digital tools, such as AI-based forecasting, Internet of Things (IoT) sensors, and digital twins, improve operational planning and system transparency (Almadhor et al., 2022; Diagne et al., 2013). BEMS optimize consumption patterns and enhance resilience (Byrne et al., 2017; Zhang et al., 2022). The integration of EVs through V2G, Vehicle-to-Home (V2H), and Vehicle-to-Building (V2B) technologies further strengthens system flexibility. EV batteries can function as distributed storage units that mitigate

Version of Record

intermittency and support self-consumption (Huy et al., 2023; Rezaei et al., 2022). Real-world pilot projects, such as ACCIONA Energía's V2G network in the Balearic Islands, involving 8 EVs and 16 bidirectional charging points, demonstrate the potential of small EV fleets to support RES integration, provide distributed storage functionality, and contribute to peak demand management in local energy systems (Murray, 2022).

Trade-offs associated with benefits. Despite these advantages, several trade-offs accompany the expansion of urban DPV. Increased self-consumption can reduce utility revenues, challenging cost-recovery models and potentially affecting long-term grid stability (Petrou et al., 2021; Tolmasquim et al., 2021). Optimizing urban space through solar installations may conflict with aesthetic or heritage preservation priorities, especially in historic districts (Fathoni & Boer, 2021). While digitalization enhances efficiency, it also increases system complexity and may require costly upgrades to legacy infrastructure (Sheng & Liu, 2023; Rangarajan et al., 2023). Although EV-integrated solar systems improve flexibility, they depend on consumer adoption patterns and battery degradation considerations (Bommana et al., 2023; Hasan et al., 2021). These multidimensional trade-offs reinforce one of the central messages of this review: maximizing the benefits of urban DPV requires coordinated technical, economic, social, and regulatory strategies rather than isolated interventions. A detailed analysis of these trade-offs is presented in Section 4.

4. Challenges and barriers to on-grid urban solar

On-grid urban DPV systems offer significant opportunities for decarbonization, resilience, and urban sustainability. However, their deployment remains constrained by a complex set of technical, economic, social, and regulatory challenges that interact across multiple dimensions and stakeholders. These interdependencies are central to the multidimensional trade-off framework proposed in this review. Supplementary Appendix A, Table A1.2. An emerging example is the rapid diffusion of plug-in solar devices (PSD), particularly in Germany, which illustrates how technological innovation can simultaneously expand deployment opportunities while creating new regulatory and safety challenges (Rzepucha-Hlubek, 2026).

4.1 Technical challenges

Urban DPV systems face a series of technical constraints (Supplementary Appendix A, Table A1.1) related to grid integration, intermittency, system design, and the physical characteristics of dense urban environments (Sheng et al., 2023; Fathoni & Boer, 2021). These challenges are particularly pronounced in cities where aging infrastructure, limited space, and high load density complicate the integration of distributed generation. In addition, long-term performance decline and module degradation represent an important technical barrier, as PV systems deployed in urban settings are exposed to environmental stressors that accelerate aging and reduce reliability over time (Alimi et al., 2022).

Version of Record

4.1.1 Intermittency, variability, and forecasting limitations

Solar PV generation is inherently intermittent, with output fluctuating due to cloud cover, shading, atmospheric conditions, and seasonal variations (Diagne et al., 2013; Almadhor et al., 2022). In dense urban areas, shading from buildings, trees, and urban morphology further reduces predictability and increases mismatch between production and demand. Although advanced forecasting models using AI and machine learning (ML) have improved accuracy, short-term variability remains a challenge for grid operators, requiring additional balancing resources and reserve capacity (IEA, 2024b).

4.1.2 Grid congestion, voltage instability, and bidirectional flows

Urban distribution grids were historically designed for unidirectional power flows (from centralized generation to consumers). High penetration of DPV introduces reverse flows, voltage fluctuations, and congestion in low-voltage feeders (Sheng et al., 2023). These issues can lead to curtailment, increased transformer loading, and accelerated equipment degradation. In some cities, grid operators impose connection limits or require costly upgrades to accommodate additional PV capacity (Etukudoh et al., 2024).

4.1.3 Limited rooftop suitability and spatial constraints

Urban areas often have limited rooftop availability due to structural constraints, heritage preservation rules, roof orientation, or competing uses such as heating, ventilation, and air conditioning (HVAC) equipment (Fathoni & Boer, 2021). Even when rooftops are available, many buildings, especially older ones, lack the structural integrity to support PV installations. Multi-apartment buildings introduce additional complexity due to shared ownership and wiring configurations (Fathoni & Boer, 2021).

4.1.4 Integration with storage and electric mobility

While storage and EVs offer flexibility, their integration introduces technical challenges. Battery systems require sophisticated control strategies, safety protocols, and thermal management (Rezaei et al., 2022). V2G and V2H/V2B technologies depend on bidirectional chargers, standardized communication protocols, and consumer participation patterns (Huy et al., 2023). Without coordinated management, EV charging may increase peak demand instead of mitigating it.

4.1.5 Cybersecurity and digital infrastructure vulnerabilities

The digitalization of urban solar systems (through IoT sensors, smart inverters, and digital twins) creates new cybersecurity risks. Unauthorized access to control systems can compromise grid stability, manipulate production data, or disrupt critical loads (Azzuni & Breyer, 2018). Ensuring secure communication protocols and robust encryption is essential but costly and technically demanding.

4.1.6 Trade-offs in technical integration

The technical challenges discussed above illustrate one of the central findings of this review: technological advances often generate new multidimensional trade-offs rather

Version of Record

than eliminating existing constraints. Despite technological advances, several trade-offs constrain technical solutions. First, increasing automation and digitalization enhances grid management but expands cybersecurity vulnerabilities, requiring investments in protection systems that may outpace available budgets. Second, energy storage improves reliability and self-consumption but introduces high upfront costs, degradation uncertainties, and end-of-life disposal challenges that can undermine lifecycle benefits. Third, smart inverters and advanced monitoring systems enable higher DPV penetration but require legacy infrastructure upgrades that are costly and difficult to implement in dense urban environments. These multidimensional trade-offs demonstrate that technical solutions cannot be evaluated independently of economic, regulatory, and institutional contexts, reinforcing the integrated analytical framework proposed in this review (Supplementary Appendix A, Table A1.3).

4.2 Economic and financial challenges

Economic and financial barriers remain among the most significant constraints on the widespread deployment of urban DPV. Supplementary Appendix A, Table A2.1, summarizes the principal economic benefits that underpin its value proposition, providing context for the challenges discussed below. Despite these benefits, households, businesses, utilities, and investors, continue to face financial constraints that influence investment decisions and the long-term viability of urban DPV.

The key economic and financial challenges identified in the literature are summarized in Supplementary Appendix A, Table A2.2, which illustrates how high upfront costs, financing constraints, payback uncertainty, and market design limitations continue to hinder broader DPV deployment.

4.2.1 High upfront investment costs

Despite declining PV module prices, the upfront costs of urban solar installations remain substantial, especially when considering structural reinforcement, permitting, and grid connection fees (Korsnes & Throndsen, 2021; Vimpari et al., 2017). For many households and small businesses, these costs represent a prohibitive barrier. In multi-unit buildings, the financial burden must be shared among residents, complicating decision-making.

4.2.2 Dependence on incentives and policy uncertainty

Urban DPV economics are highly sensitive to government incentives, feed-in tariffs, net metering schemes, and tax credits. Although policy dependence affects all electricity generation technologies, including large-scale low-carbon options such as nuclear power, distributed PV is particularly sensitive to short-term policy changes. Investment decisions are typically made by households and small businesses with limited capital reserves, making investor confidence highly dependent on stable regulatory conditions (To et al., 2022). Sudden policy changes, such as retroactive tariff cuts in Greece (Loumakis et al., 2019), can therefore undermine investor confidence, trigger market

Version of Record

contractions, and stall deployment. Long-term regulatory uncertainty also discourages investment in storage, smart inverters, and other enabling technologies**.**

4.2.3 Geopolitical risks and supply-chain dependencies

Urban DPV deployment is increasingly exposed to geopolitical risks arising from highly concentrated global supply chains. A large share of the world's polysilicon, wafers, and PV modules is produced in China, creating vulnerabilities related to trade disputes, export restrictions, and price volatility. These dependencies can increase project costs, delay installations, and introduce ethical concerns, including documented cases of forced-labor practices in parts of the solar supply chain. As highlighted by Su et al., (2021), renewable energy transitions increasingly intersect with geopolitical dynamics, and supply-chain concentration can amplify strategic risks for countries seeking to expand distributed solar capacity.

4.2.4 Limited access to financing and credit constraints

Low-income households and small businesses often face difficulties accessing loans or financing mechanisms for solar installations. Even when financing is available, interest rates or collateral requirements may be prohibitive (Judson & Zirakbash, 2022). Community solar and shared ownership models can mitigate these barriers but require supportive regulatory frameworks.

4.2.5 Utility revenue erosion and cost-recovery challenges

High levels of self-consumption may reduce utility revenues, challenge traditional cost-recovery models and potentially increasing tariffs for non-solar customers (Petrucci et al., 2022). This creates tension between utilities and prosumers, particularly in regions where grid maintenance costs are socialized. Without appropriate regulatory reform, utilities may have fewer incentives to support rapid DPV deployment and may introduce new tariff structures or grid charges to recover network costs.

4.2.6 Economic viability of storage and flexibility solutions

Although storage enhances system flexibility, battery costs remain high, and payback periods are often long. The economic case for V2G and V2H/V2B is still emerging, with uncertainties regarding battery degradation, compensation mechanisms, and consumer willingness to participate (Hasan et al., 2021).

4.2.7 Lifecycle environmental impacts

Although solar PV generates low-carbon electricity during operation, evaluating its overall sustainability requires consideration of the entire lifecycle including manufacturing, transport, installation, and end-of-life management. Polysilicon production is energy-intensive, and global supply chains (dominated by China) add transport-related emissions. End-of-life disposal poses challenges: while recycling technologies exist, they are not yet widely deployed, and hazardous materials require careful handling (Chowdhury et al., 2020). The energy payback time for rooftop PV in

Version of Record

Europe is typically 2-3 years, meaning lifecycle emissions are substantially lower than fossil alternatives, but further improvements in circularity are needed (Fthenakis & Kim, 2011).

4.2.8 Trade-offs in economic viability

The economic challenges discussed above illustrate another central finding of this review: financial mechanisms that facilitate urban DPV deployment frequently generate new multidimensional trade-offs rather than eliminating existing constraints. Economic barriers are often intertwined with difficult trade-offs. First, incentives such as feed-in tariffs and tax credits accelerate adoption but create long-term fiscal dependencies and expose markets to policy uncertainty; when incentives are withdrawn abruptly, investment may decline substantially. Second, high levels of self-consumption can erode utility revenues and complicate cost-recovery models, raising concerns about fairness and the distribution of grid maintenance costs. Third, financing mechanisms that lower upfront costs **(**e.g., leasing arrangements and power purchase agreements (PPAs)) can improve accessibility but may also extend the period over which economic benefits are realized or reduce lifetime financial returns**,** creating a trade-off between accessibility and long-term value (Supplementary Appendix A, Table A2.3). These multidimensional trade-offs demonstrate that improving the economic viability of urban DPV depends not only on financial incentives but also on coordinated regulatory, technical, and institutional strategies, reinforcing the integrated analytical framework proposed in this review.

4.3 Social and behavioral challenges

The main social and health benefits associated with urban DPV adoption are summarized in Supplementary Appendix A, Table A3.1, providing essential context for understanding the social and behavioral challenges discussed in this section. These benefits help explain why urban DPV is generally viewed positively across diverse social groups.

Several studies show that DPV adoption can also stimulate positive behavioral change. Households often become more aware of their own energy production and, as a result, adjust consumption patterns, reduce overall demand, or shift appliance use to align with PV generation. Widén (2014), for example, found that PV ownership increases energy awareness and encourages more careful and deliberate electricity use in residential settings.

Despite these benefits, social and behavioral factors represent one of the key dimensions of the multidimensional trade-off framework proposed in this review. Social acceptance, behavioral patterns, and equity considerations critically shape the adoption and performance of urban DPV systems. These factors influence installation decisions, long-term engagement, and the distribution of benefits across different segments of the population. Challenges arise from information gaps, aesthetic concerns, trust in institutions, perceived complexity of participation, and unequal access to suitable

Version of Record

rooftops or financing mechanisms, all of which can limit the inclusiveness and scalability of urban DPV.

4.3.1 Awareness, information gaps, and perceived complexity

Many urban residents lack clear information about the benefits, costs, and performance of solar PV systems and often perceive installation processes as complex or bureaucratic (Petrou et al., 2021; Andrade-Arias et al., 2025). Misconceptions regarding maintenance requirements, payback periods, and system reliability further reduce willingness to adopt DPV, particularly in multi-apartment buildings where coordination among residents adds complexity.

4.3.2 Equity, energy poverty, and distributional impacts

DPV adoption tends to favor higher-income households with access to capital and suitable rooftops (Judson & Zirakbash, 2022). Without targeted policies, distributed solar can exacerbate existing inequalities by lowering energy bills for wealthier prosumers while leaving vulnerable groups exposed to rising electricity costs (Andrade-Arias et al., 2025). These distributional effects highlight the need for inclusive financing and community-based models.

4.3.3 Aesthetic concerns and heritage preservation

A consolidated overview of social and behavioral challenges is provided in Supplementary Appendix A, Table A3.2, complementing the thematic discussion in this subsection and highlighting how aesthetic perceptions and cultural values shape public acceptance of DPV. In historic or culturally sensitive districts, aesthetic considerations and heritage protection rules restrict visible PV installations (Fathoni & Boer, 2021; Nuñez-Jimenez et al., 2023). These constraints reduce the feasible area for deployment and can delay permitting, creating tensions between climate goals and urban preservation priorities.

4.3.4 Behavioral patterns affecting system performance

The effectiveness of self-consumption strategies depends on behavioral adjustments, such as shifting appliances to daylight hours. Without automation or smart energy management technologies, many users struggle to adapt their electricity consumption patterns, reducing both the economic and environmental benefits of DPV (Korsnes & Throndsen, 2021).

4.3.5 Trust, participation, and community engagement

Collective solar initiatives require trust among participants and between communities and utilities. Abrupt policy changes or inconsistent incentives can erode this trust, reducing willingness to participate in community solar or shared-ownership schemes (Loumakis et al., 2019).

Version of Record

4.3.6 Health considerations.

Current evidence indicates that EMF exposure from inverters and smart meters remains well below international safety thresholds (ICNIRP, 2020). Nevertheless, perceived health risks may still influence public acceptance of urban DPV. More substantiated concerns relate to occupational hazards for installers and the end-of-life management of hazardous materials (Samaniego-Rascón et al., 2019). Transparent communication and strict safety standards are essential to address both perceived and evidence-based risks.

4.3.7 Trade-offs in social acceptance and equity

The social and behavioral challenges discussed above further illustrate that improving public acceptance of urban DPV frequently involves multidimensional trade-offs rather than simple technical or financial solutions. Community engagement improves acceptance but increases transaction costs and slows deployment. Targeted subsidies enhance equity but add administrative complexity, while universal incentives risk disproportionately benefiting wealthier homeowners. Heritage preservation protects cultural assets but restricts DPV deployment in historic districts, requiring context-sensitive design solutions rather than blanket exemptions. These multidimensional trade-offs demonstrate that successful urban DPV deployment depends not only on technological and economic solutions but also on policies that strengthen public trust, promote social inclusion, and accommodate local cultural contexts, reinforcing the integrated analytical framework proposed in this review (Supplementary Appendix A, Table A3.3).

4.4 Regulatory and institutional challenges

Regulatory and institutional benefits associated with urban DPV are summarized in Supplementary Appendix A, Table A4.1, offering a baseline for the challenges explored in this section and highlighting how well-designed regulatory frameworks can accelerate distributed solar deployment. Within the multidimensional trade-off framework proposed in this review, regulatory and institutional factors shape not only technology deployment but also the effectiveness of technical, economic, and social interventions. Despite these advantages, regulatory frameworks strongly influence the feasibility, economics, and scalability of urban DPV systems. Many existing rules were designed for centralized electricity systems and are poorly adapted to distributed, prosumer-driven models.

4.4.1 Outdated grid codes and interconnection standards

In many jurisdictions, interconnection standards for DPV, storage, and EV integration remain outdated or inconsistent (Hasan et al., 2021). Requirements for grid studies, protection systems, and inverter capabilities can be costly, time-consuming, and administratively burdensome, and some utilities impose restrictive caps on DPV penetration.

Version of Record

4.4.2 Complex permitting and administrative procedures

Permitting processes often involve multiple agencies, lengthy inspections, and fragmented responsibilities, increasing costs and discouraging adoption, particularly for small installations (Nuñez-Jimenez et al., 2023). Although streamlined "one-stop shop" permitting models have demonstrated positive results by simplifying administrative procedures and reducing approval times, they remain the exception rather than the rule.

4.4.3 Lack of regulatory support for flexibility and storage

Supplementary Appendix A, Table A4.2 summarizes the principal regulatory and institutional challenges discussed in this subsection, highlighting how regulatory gaps constrain the deployment of enabling technologies. Many regulatory frameworks do not recognize or compensate for the flexibility services provided by storage, V2G, or smart inverters (IEA, 2024b). Without appropriate market mechanisms, investments in these enabling technologies remain unattractive.

4.4.4 Restrictions on collective self-consumption and energy sharing

In several countries, regulations limit energy sharing among residents of multi-apartment buildings or across neighborhoods. These restrictions hinder community solar, cooperatives, and peer-to-peer trading models that could expand access to DPV (Griego et al., 2022).

4.4.5 Utility resistance and institutional inertia

Utilities may be cautious about rapid DPV expansion because of concerns regarding revenue erosion, operational complexity, and cost-recovery mechanisms. These concerns can contribute to institutional resistance toward some forms of DPV deployment, while institutional inertia can slow the adoption of innovative business models such as performance-based regulation or expanded DSO roles (Tan et al., 2024).

4.4.6 Trade-offs in regulatory design

The regulatory and institutional challenges discussed above illustrate that designing effective policies for urban DPV requires balancing competing objectives across multiple dimensions. Regulatory reforms face inherent tensions (Supplementary Appendix A, Table A4.3). Uniform national policies simplify administration but may overlook local grid conditions or heritage constraints. Local rules are more responsive but risk regulatory fragmentation. Streamlined permitting accelerates deployment but may weaken environmental review or community input. Performance-based regulation aligns utility incentives with DPV integration but requires sophisticated monitoring and enforcement capacities that many regulators lack. These multidimensional trade-offs demonstrate that regulatory effectiveness depends not only on simplifying administrative procedures but also on balancing efficiency, flexibility, equity, and long-term institutional adaptability, reinforcing the integrated analytical framework proposed in this review.

Version of Record

5. Enabling solutions: Case studies and best practice

Cities across Europe and beyond have begun addressing the technical, economic, social, and regulatory barriers to on-grid urban solar through policy innovation, integrated planning, and novel financing models. This section presents three illustrative case studies that demonstrate how different governance and technological approaches can address the multidimensional trade-offs identified in Section 4. Each case highlights a different enabling pathway: (1) solar-mobility integration, (2) regulatory reform, and (3) inclusive financing. Together, these examples show that urban DPV challenges are not fixed constraints but can be mitigated through coordinated technological, institutional, regulatory, and community-based strategies.

5.1 Solar-mobility integration: The Netherlands' smart charging ecosystem

The Netherlands offers one of Europe's most advanced examples of coordinated solar-EV integration, combining high rooftop PV penetration with one of the densest public EV charging networks in the EU. Smart charging has been shown to increase PV self-consumption from below 50% to as high as 62-87% (van der Kam & van Sark, 2015), while Amsterdam alone hosts more than 5,000 public charging points (Jos van den Bergh, 2026).

Technical and operational solutions. Smart charging algorithms dynamically adjust EV charging rates based on real-time PV output, grid congestion, and wholesale prices. Pilot projects led by ElaadNL and Liander show that coordinated charging can reduce peak loads by up to 40% (Moorman & Mergelsberg, 2021; Broos et al., 2025), thereby increasing the share of renewable energy used for EV charging while reducing the need for immediate grid reinforcement. Bidirectional charging pilots, such as Utrecht's "We Drive Solar," demonstrate the potential for shared EV fleets to provide frequency regulation and congestion relief, although battery degradation and high bidirectional charger costs remain barriers (Goncearuc et al., 2024).

Regulatory and institutional enablers. Dutch regulation allows DSOs to procure flexibility services from distributed resources, including EV chargers and home batteries (Geerts & Zweistra, 2023). Municipalities also retain authority over charging infrastructure planning through concession models, ensuring alignment with local energy strategies. Dynamic tariffs planned for 2025 will further strengthen the integration of EV charging with solar generation.

Trade-offs addressed. The Dutch model illustrates how coordinated planning and supportive regulation can mitigate several of the multidimensional trade-offs identified throughout Section 4.

- **Technical**: EV batteries act as distributed storage, reducing the need for stationary systems, thereby improving system flexibility and supporting more effective integration of distributed renewable energy resources (Section 4.1.4).

Version of Record

- **Economic**: Smart charging aligns EV demand with PV production, reducing peak loads, increasing self-consumption, and improving grid stability (Section 4.2.4).
- **Regulatory**: National rules provide stability while municipalities retain flexibility to tailor local charging strategies (Section 4.4.5).

Overall, the Dutch experience demonstrates how coordinated technological innovation, supportive regulation, and integrated planning can simultaneously improve renewable energy integration, grid resilience, and electric mobility while mitigating several of the multidimensional trade-offs associated with urban DPV deployment. This case further illustrates that effective implementation depends not only on technological solutions but also on coherent institutional and governance frameworks.

5.2 Regulatory reform for distributed solar: Spain's post-2018 self-consumption framework

Spain provides a compelling example of how well-designed regulatory reform can unlock rapid DPV expansion. After years of stagnation under the "sun tax" (Royal Decree 900/2015), the government enacted Royal Decree Law 15/2018 and Royal Decree 244/2019, fundamentally reshaping the DPV landscape (Gallego-Castillo et al., 2021; Prol & Steininger, 2020). This case illustrates how regulatory innovation can address several of the multidimensional trade-offs identified in Section 4, particularly those related to permitting, energy sharing, and market incentives.

Key regulatory innovations. The reforms introduced six complementary regulatory measures designed to reduce administrative barriers, improve investment certainty, and facilitate broader participation in distributed solar deployment:

1. Elimination of the "sun tax," improving project economics.
2. Simplified permitting for systems below 100 kW.
3. Legalization of collective self-consumption.
4. Surplus compensation mechanisms require utilities to pay for exported electricity.
5. Harmonized interconnection standards.
6. Clear legal definitions of prosumer rights and obligations.

These measures directly addressed barriers related to permitting complexity, energy sharing restrictions, lack of compensation, and unclear interconnection rules while improving regulatory certainty for households, businesses, and investors (Section 4.4).

Impact on deployment and market confidence. The regulatory reforms produced rapid and measurable impacts on market development. Annual rooftop installations rose from 262 MW in 2018 to more than 7 GW in 2023 (IEA-PVPS, 2024). Cumulative PV capacity increased more than fivefold in five years. Collective self-consumption expanded rapidly in social housing and condominium buildings, reducing energy bills by 20-30% (Prol & Steininger, 2020). Investor confidence also recovered substantially,

Version of Record

reversing the nearly 70% decline in rooftop solar investment during the "sun tax" period.

Trade-offs addressed. Spain's regulatory reforms illustrate how coherent policy design can mitigate several of the multidimensional trade-offs discussed throughout Section 4:

- **Permitting speed vs. oversight**: Small systems benefited from simplified administrative procedures while maintaining essential technical and safety requirements (Section 4.4.2).
- **Incentives vs. fiscal burden**: Market-based surplus compensation improved investment attractiveness while reducing long-term dependence on direct public subsidies (Section 4.2.2).
- **Equity vs. administrative complexity**: Collective self-consumption extended solar access to distributed solar for the approximately 65% of urban residents living in multi-apartment buildings while introducing additional coordination and governance requirements (Section 4.3.2).

Overall, the Spanish experience demonstrates that coherent and stable regulatory frameworks can substantially accelerate urban DPV deployment by reducing administrative barriers, strengthening investor confidence, and expanding access to collective self-consumption. More broadly, this case illustrates that regulatory innovation is essential for managing the multidimensional trade-offs associated with distributed solar deployment and for creating the institutional conditions necessary for long-term market development.

5.3 Inclusive financing for urban solar: Community and cooperative models

High upfront costs and limited access to credit remain major barriers to DPV adoption, particularly for low-income households, renters, and residents of multi-apartment buildings (Lowitzsch et al., 2025). Several innovative financing models across Europe demonstrate how these barriers can be overcome without relying solely on subsidies. Financial, social, and institutional barriers can be mitigated through alternative ownership structures, cooperative investment, and targeted public support, thereby illustrating practical approaches to managing the multidimensional trade-offs identified in Section 4.

Third-party ownership (TPO) and leasing models. TPO models allow households to adopt solar with zero upfront cost. A third-party developer owns and maintains the system, while households purchase electricity at a fixed rate below utility tariffs (Rakholiya & Neumann, 2026). France's Energy Transition Law of 2015 enabled TPO and collective self-consumption arrangements, expanding access to low and middle-income households. However, TPO extends payback periods and reduces long-term savings, illustrating the trade-off between improving access to solar technologies and maximizing long-term economic returns.

Cooperative financing and citizen investment platforms. Cooperative models pool citizen capital to finance community solar projects. Énergie Partagée in France has

Version of Record

mobilized more than €40 million to support over 300 citizen-led renewable projects (Énergie Partagée, 2022). Similar models in Germany and the UK show that cooperatives enhance local acceptance and long-term stability, though they require strong organizational capacity and trust (Hall et al., 2016). However, their long-term success depends on effective governance and sustained trust among participants.

Municipal programs and social housing integration. Cities such as Lyon, Paris, and Grenoble offer grants, low-interest loans, and technical assistance for condominium PV installations. France's social housing sector (HLM) has deployed thousands of rooftop PV systems, often combined with energy efficiency upgrades. These initiatives directly address equity concerns by reducing energy poverty and stabilizing electricity costs for vulnerable populations.

Trade-offs addressed. These financing mechanisms illustrate how innovative business models and public policies can mitigate several of the multidimensional trade-offs identified throughout Section 4:

- **Accessibility vs. long-term savings**: Multiple financing pathways accommodate different household needs (Section 4.2.5).
- **Equity vs. administrative complexity**: Municipal programs reduce bureaucratic burdens for low-income households (Section 4.3.2).
- **Uniform national frameworks vs. local needs**: Cooperative and municipal models adapt national frameworks to local conditions (Section 4.4.5).

In essence, these examples demonstrate that equitable urban DPV deployment depends not only on financial innovation but also on coordinated institutional support, adaptive governance, and stakeholder participation. Together, these elements help manage the multidimensional trade-offs associated with expanding distributed solar in urban environments.

5.4 Synthesis: Lessons Across Cases

Across the three enabling pathways examined (solar-mobility integration in the Netherlands, regulatory reform in Spain, and inclusive financing in France, Germany, and the UK) several common principles emerge that reinforce the multidimensional trade-off framework proposed in this review:

- **Integrated planning** aligns DPV with mobility, housing, and grid strategies, avoiding siloed approaches.
- **Regulatory clarity and stability** are essential for investor confidence and market growth.
- **Inclusive financing** expands solar access beyond wealthy homeowners.
- **Local autonomy within national frameworks** allows tailored solutions without creating fragmentation.
- **Flexibility markets and digitalization** help mitigate technical trade-offs associated with intermittency, congestion, and distributed resource integration.

Version of Record

Taken together, these cases demonstrate that the challenges identified in Section 4 should not be viewed as fixed barriers. They are multidimensional trade-offs that can be effectively mitigated through coordinated technological innovation, adaptive regulation, inclusive financing, and stakeholder collaboration. Although the cases are not exhaustive, they provide transferable lessons for cities seeking to accelerate on-grid urban DPV deployment while balancing technical, economic, social, and institutional objectives.

6. Policy and regulatory pathways

Effective policy and regulatory frameworks are central to unlocking the full potential of on-grid urban solar (da Silva et al., 2019). While technological advances and innovative financing models are essential, they cannot overcome structural barriers embedded in legacy regulations, utility business models, and institutional arrangements (Hoehnke et al., 2026). Across Europe, cities and national governments have adopted diverse approaches to reforming permitting, interconnection, tariff design, and market rules. Successful pathways share three characteristics: (1) regulatory clarity and long-term stability, (2) alignment of utility incentives with distributed energy integration, and (3) institutional mechanisms that enable local experimentation within national frameworks. Together, these elements help address the multidimensional trade-offs discussed throughout Sections 3-5 by coordinating technical, economic, social, and institutional objectives.

6.1 Modernizing interconnection standards and grid codes

Several European countries have progressively updated their interconnection standards and grid codes to accommodate the rapid growth of DPV and other inverter-based resources. Germany and Denmark have implemented advanced technical requirements for low- and medium-voltage inverter behavior, including voltage support, frequency response, and fault ride-through capabilities (Sobhy et al., 2015). In the Netherlands, modernization has focused on harmonizing interconnection requirements across DSOs and digitalizing permitting processes. National guidelines issued by Netbeheer Nederland and technical recommendations from ElaadNL streamline interconnection steps, clarify technical requirements, and support voltage management and bidirectional power flows in increasingly congested distribution grids (ElaadNL, 2022; Geerts & Zweistra, 2023). These reforms directly address the technical challenges identified in Section 4.1, particularly voltage fluctuations, reverse power flows, and the need for coordinated inverter behavior.

In contrast, countries with outdated or fragmented grid codes continue to face long permitting timelines, inconsistent technical requirements, and limited visibility for DSOs – factors that slow down distributed PV deployment and increase system integration costs (IEA, 2023). Comparative studies suggest that standardized national interconnection rules, combined with digitalized permitting platforms, can significantly accelerate distributed PV adoption (Nuñez-Jimenez, et al., 2023).

Version of Record

6.2 Enabling collective self-consumption and energy sharing

Regulatory frameworks that allow energy sharing among residents of multi-unit buildings or across neighborhoods have proven transformative. Spain's post-2018 autoconsumo reforms (Gallego-Castillo et al., 2021; Prol & Steininger, 2020), Portugal's Renewable Energy Communities (RECs) (Queiroz et al., 2023), and France's autoconsommation collective (Loi n° 2015-992., 2015; Wokuri et al., 2019) demonstrate how legal recognition of shared generation can expand access to DPV for renters, apartment dwellers, and low-income households. These reforms address the equity challenges discussed in Section 4.3 by enabling broader participation in the energy transition. Experience from these countries suggests clear rules for governance, billing, and dispute resolution, reducing uncertainty for both consumers and developers.

6.3 Aligning utility incentives with distributed solar

Traditional cost-of-service regulation often disincentivizes utilities from supporting DPV, as self-consumption reduces volumetric revenues. The Netherlands has piloted performance-based regulation (PBR), rewarding DSOs for reducing congestion, enabling flexibility markets, and integrating DERs efficiently (Nillesen & Pollitt, 2026). Similarly, the UK has implemented incentive regulation for its electricity distribution networks, with productivity analysis showing the impact of changing incentive mechanisms (Ajayi et al., 2022). These reforms encourage utilities to evolve from passive grid operators toward more active system facilitators, although their effectiveness depends on regulatory capacity, market design, and sophisticated monitoring mechanisms that are not yet present in all jurisdictions.

6.4 Streamlining permitting and administrative procedures

Permitting remains one of the most persistent barriers to urban DPV. Cities such as Berlin, Barcelona, and Copenhagen have implemented "one-stop shop" permitting systems (OECD, 2025) and digital platforms that reduce administrative burdens (OECD, 2025), particularly for small rooftop systems where transaction costs can otherwise outweigh project benefits. However, streamlining permitting introduces trade-offs between deployment speed and oversight. Heritage protection, fire safety, and structural integrity must still be ensured. Successful models apply differentiated pathways: simplified procedures for low-risk installations and enhanced review for complex or sensitive sites (Rakholiya & Neumann, 2026).

6.5 Regulatory and institutional trade-offs

Consistent with the multidimensional trade-off framework proposed in this review, regulatory pathways inevitably involve trade-offs that must be managed transparently and balanced across technical, economic, social, and institutional objectives. Uniform national rules vs. local flexibility: National standards reduce fragmentation but may overlook local constraints. Allowing municipalities limited autonomy has proven effective in Spain and the Netherlands. Permitting speed vs. environmental and heritage protection: Simplified procedures accelerate deployment but risk weakening oversight.

Version of Record

Tiered frameworks mitigate this tension. Utility revenue stability vs. prosumer empowerment: Net metering empowers consumers but can erode utility revenues. Performance-based regulation offers a compromise. Market openness vs. consumer protection: Peer-to-peer trading fosters innovation but requires safeguards against inequitable cost allocation.

6.6 Synthesis: Toward coherent policy architectures

The European experience demonstrates that no single policy instrument is sufficient. Effective DPV integration requires coherent architectures combining modernized interconnection standards, enabling frameworks for collective self-consumption, utility incentive reform, streamlined permitting, and inclusive financing mechanisms. Countries that have adopted integrated approaches (Spain, the Netherlands, and France) have achieved faster, more equitable, and more resilient DPV deployment. These pathways illustrate that many regulatory and institutional barriers are not fixed constraints but design challenges that can be progressively addressed through coordinated, multi-level governance. Rather than relying on isolated policy instruments, successful urban DPV deployment depends on coherent policy architectures that integrate technical, economic, social, and regulatory dimensions.

7. Future research agenda

Despite rapid advances in urban DPV, several unresolved challenges constrain largescale, equitable, and resilient deployment. These gaps represent priority areas for future research, particularly at the intersection of technology, regulation, and social systems. Building on the multidimensional trade-offs framework proposed in this review and the trade-offs identified throughout the preceding sections, three broad research directions emerge.

7.1 Integrated urban energy systems and flexibility solutions

Future research should explore how DPV interacts with electric mobility, storage, heat pumps, and BEMS in dense urban environments. While pilot projects in the Netherlands demonstrate the potential of coordinated solar-EV flexibility, the scalability of these solutions remains uncertain. Key questions include how cities can optimize multi-vector energy flows in real-time, what digital architectures and governance models are required for interoperable flexibility markets, and how unresolved trade-offs, such as cybersecurity risks versus system intelligence, can be managed in practice through coordinated technical, regulatory, and institutional approaches.

7.2 Regulatory innovation, market design, and institutional capacity

Regulatory reforms have accelerated DPV adoption in Spain, Portugal, and France, yet many institutional trade-offs remain unresolved. Research is needed on adaptive regulatory frameworks that balance national standardization with local autonomy, streamline permitting without weakening oversight, and align utility incentives with prosumer participation. Comparative studies could examine how performance-based

Version of Record

regulation, locational tariffs, and community energy governance models perform under different grid conditions. Another important research priority concerns institutional capacity, particularly how regulators and DSOs can develop the analytical tools, digital capabilities, and governance mechanisms needed to manage high levels of DPV penetration.

7.3 Equity, social acceptance, and inclusive financing

Although inclusive financing models have expanded access to DPV, persistent inequities remain. Future research should investigate how community solar, cooperative ownership, innovative financing mechanisms and social housing programs can be scaled while avoiding dependency on subsidies. Unresolved trade-offs, such as accessibility versus long-term consumer savings, or heritage preservation versus decarbonization, require interdisciplinary approaches combining urban planning, behavioral science, and energy economics. Longitudinal studies assessing how trust, participation, and perceived fairness evolve as DPV becomes mainstream are also needed.

8. Conclusions

Urban DPV hold significant potential to advance decarbonization, strengthen energy resilience, and support more inclusive and sustainable cities. Yet, this review shows that the diffusion of urban DPV depends on the alignment of four interrelated dimensions: technical, economic, social, and regulatory. When these dimensions evolve at different speeds, trade-offs emerge that complicate decision-making and may slow deployment.

The literature synthesis demonstrates that technical challenges (such as intermittency, grid congestion, and cybersecurity) cannot be addressed independently of economic constraints, including high upfront costs, policy uncertainty, and impacts on utility business models. Social and behavioral factors including awareness, equity concerns, aesthetic preferences, and trust influence adoption patterns and shape the distribution of benefits. Regulatory frameworks, often designed for centralized systems, struggle to accommodate prosumer-driven models, flexibility services, and collective self-consumption. These tensions underscore that barriers to urban DPV are not merely technological but deeply socio technical and institutional.

A principal contribution of this review is the development of a multidimensional trade-off framework for analyzing urban DPV deployment. Rather than examining technical, economic, social, and regulatory dimensions separately, this framework emphasizes their dynamic interactions and the tensions that emerge among them. By adopting this integrated perspective, the review extends beyond a conventional synthesis of barriers and opportunities and provides a conceptual framework for understanding the complexity of urban solar transitions.

The case studies of the Netherlands, Spain, and France illustrate that these challenges are surmountable when policy, technology, and community engagement are coordinated. Smart charging ecosystems, enabled by digitalization and flexibility markets, can resolve technical and economic trade-offs. Regulatory reforms in Spain show that

Version of Record

clarity, stability, and streamlined permitting can unlock rapid market growth. Inclusive financing models in France, Germany, and the UK reveal that equitable solar deployment requires financial innovation and strong institutional support. Together, these examples highlight the importance of integrated planning, multi-level governance, and adaptive regulatory design.

A broader insight emerging from this review is that urban DPV should be understood as a dynamic sociotechnical system rather than as a static technological solution. The interaction among technological, economic, social, regulatory, and geopolitical factors creates a constantly evolving environment. Consequently, urban DPV requires continuous adaptation rather than one-time optimization. This stands in contrast to the more ordered and predictable context of legacy electricity systems. As a result, policy outcomes are particularly sensitive to political contestation, shifting discourses, and the relative power of stakeholders, underscoring the need for adaptive governance and sustained institutional learning.

The literature reviewed also provides several broader lessons for urban solar transitions in Europe. First, the deployment of urban DPV varies substantially across Member States due to differences in climatic conditions, urban characteristics, regulatory maturity, investment capacity, and electricity market structures. Second, successful deployment depends not only on solar resource availability but also on stable policies, mature markets, and supportive institutional environments. Third, the evidence suggests that uniform policy approaches may produce heterogeneous outcomes, highlighting the importance of flexible and context-sensitive regulatory frameworks. Together, these findings indicate that successful urban solar transitions require integrated and adaptive policy strategies rather than isolated technological interventions.

Looking ahead, several priorities emerge for research and policy. Future work should examine how flexibility markets, digital twins, and AI-based forecasting can be scaled to support high-density urban DPV. Progress will increasingly depend on hybrid technological approaches combining DPV, stationary storage, V2G, smart inverters, and advanced forecasting. The literature suggests that no single technology can address all operational challenges associated with urban solar systems. At the same time, hybrid socio-technical approaches that integrate economic instruments, social engagement, and adaptive regulation will be essential to address distributional and institutional barriers. More attention is also needed on equity-oriented models that expand access to renters, low-income households, and residents of multi-apartment buildings. Regulatory frameworks must evolve to recognize the value of distributed flexibility, enable energy sharing, and align utility incentives with DPV integration. Finally, interdisciplinary approaches are essential to understand how technical, economic, social, and regulatory dynamics interact to shape the real-world performance of urban solar systems.

This review also has limitations that should guide future work. The analysis synthesizes diverse studies with varying methodologies, geographical scopes, and temporal contexts, which may introduce inconsistencies in evidence quality and comparability.

Version of Record

The focus on European case studies, while analytically rich, limits generalizability to regions with different regulatory, climatic, or socio-economic conditions. Moreover, the rapid evolution of digitalization, storage technologies, and flexibility markets means that some insights may shift as new data and practices emerge. These limitations highlight the need for longitudinal, cross-regional, and empirically grounded research to validate and refine the multidimensional framework proposed here.

Urban DPV will not deliver its full promise without confronting the trade-offs that arise when socio-technical systems transform. By synthesizing these tensions and highlighting practical pathways to address them, this review contributes to a more nuanced understanding of the opportunities and constraints shaping the future of on-grid urban solar. Achieving a resilient, efficient, and inclusive urban energy future will require coordinated action across institutions, technologies, and communities, ensuring that the transition to solar-powered cities is both sustainable and equitable.

Author Contributions (CRediT)

Evaldo Costa: Conceptualization, data curation, formal analysis, investigation, methodology, resources, visualization, writing the original draft.

Peter Wells: Conceptualization (supporting), methodology, writing (review and editing).

Declaration

The authors declare no conflicts of interest. During the preparation of this work, ChatGPT was used to provide language feedback and identify opportunities to improve clarity and brevity. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the final publication.

Data Availability Statement

Data sharing is not applicable to this article as no new data were analyzed or created in this study.

References

Alimi, O. A., Meyer, E. L., & Olayiwola, O. I. (2022). Solar photovoltaic modules' performance reliability and degradation analysis—A review. Energies, 15(16), 5964.

Almadhor, A., Mallikarjuna, K., Rahul, R., Chandra Shekara, G., Bhatia, R., Shishah, W., Mohanavel, V., Suresh Kumar, S., & Thimothy, S. P. (2022). Solar Power Generation in Smart Cities Using an Integrated Machine Learning and Statistical Analysis Methods. *International Journal of Photoenergy*, *2022*.

Ajayi, V., Anaya, K., & Pollitt, M. (2022). Incentive regulation, productivity growth and environmental effects: the case of electricity networks in Great Britain. Energy Economics, 115, 106354.

Allam, Z., & Soomauroo, Z. (2025). How the Green New Deal can transform urban landscapes and promote health equity. Cities & health, 9(3), 410-414.

Version of Record

Andrade-Arias, A. S., Kabir, G., Mirmohammadsadeghi, M., Gunasekaran, A., & Elizondo-Noriega, A. (2025). Exploring public perspectives on solar energy adoption in Mexico. *Renewable and Sustainable Energy Reviews*, *212*, 115410.

Azzuni, A., & Breyer, C. (2018). Definitions and dimensions of energy security: a literature review. *Wiley Interdisciplinary Reviews: Energy and Environment*, *7*(1), e268.

Best, R., Burke, P. J., Nepal, R., & Reynolds, Z. (2021). Effects of rooftop solar on housing prices in Australia. *Australian Journal of Agricultural and Resource Economics*, *65*(3), 493–511.

Boehm, S., Schumer, C., & Grier, E. et al. ,. (2023). *Tracking Climate Action: How the World Can Still Limit Warming to 1.5 Degrees C.* . USA.

Bommana, B., Kumar, J. S. V, Nuvvula, R. S. S., Kumar, P. P., Khan, B., Muthusamy, S., & Inapakurthi, R. (2023). A Comprehensive Examination of the Protocols, Technologies, and Safety Requirements for Electric Vehicle Charging Infrastructure. *Journal of Advanced Transportation*, *2023*.

Broos, P., Geerts, F., Refa, N., van den Brink, H., van Kaathoven, E., & Zweistra, M. (2025). Guide to smart charging solutions. ElaadNL Foundation, Netherlands, retrieved on Jun 9, 2026, at: https://elaad.nl/wp-content/uploads/2025/06/SC_Solutions_20_Digitaal.pdf

Byrne, R. H., Nguyen, T. A., Copp, D. A., Chalamala, B. R., & Gyuk, I. (2017). Energy management and optimization methods for grid energy storage systems. *Ieee Access*, *6*, 13231–13260.

C40 Cities (2016). Wuhan - Research center built with green design principles. C40 Cities Climate Leadership Group. Retrieved May 27, 2026, from https://www.c40.org/case-studies/cities100-wuhan-research-center-built-with-green-design-principles/

Chen, S., Zhang, Z., Wang, C., Tan, L., Liu, H., Yuan, H., Zhang, R., & Hu, R. (2024). Evaluation Model of Distributed Photovoltaic Utilization in Urban Built-Up Area. *Buildings*, *14*(4), 943.

Chowdhury, M. S., Rahman, K. S., Chowdhury, T., Nuthammachot, N., Techato, K., Akhtaruzzaman, M., Tiong, S. K., Sopian, K., & Amin, N. (2020). An overview of solar photovoltaic panels' end-of-life material recycling. *Energy Strategy Reviews*, *27*, 100431.

Costa, E., Teixeira, A. C. R., Costa, S. C. S., & Consoni, F. L. (2022). Influence of public policies on the diffusion of wind and solar PV sources in Brazil and the possible effects of COVID-19. *Renewable and Sustainable Energy Reviews*, *162*, 112449.

Costa, E., Wells, P., Wang, L., & Costa, G. (2022). The electric vehicle and renewable energy: Changes in boundary conditions that enhance business model innovations. *Journal of Cleaner Production*, *333*, 130034.

Costa, E., Fontes, M., & Bento, N. (2023). Transformative Business Models for decarbonization: Insights from prize-winning start-ups at the Web Summit. *Sustainability*, *15*(18), 14007.

Costa, E., Vicente, P., & Reis, E. (2025). Driving Innovation Through Cross-Sector Collaboration with Higher Education Institutions. *INTED2025 Proceedings*, 2045–2053.

Costa, E., & Mercier-Laurent, E. (2025). Technological Challenges, Energy Poverty and Other Barriers to the Expansion of Energy Communities in Europe. In IFIP International Workshop on Artificial Intelligence for Knowledge Management (pp. 283-292). Cham: Springer Nature Switzerland.

Version of Record

Costa, E., & Pereirinha, P. G. (2025). Exploring the Socio-Technical Integration of Electric Vehicles and Solar Systems from a User-Centered Perspective. In 2025 IEEE Vehicle Power and Propulsion Conference (VPPC) (pp. 1-6). IEEE.

Cuervo, F. I., Arredondo-Orozco, C. A., & Marenco-Maldonado, G. C. (2021). Photovoltaic power purchase agreement valuation under real options approach. *Renewable Energy Focus*, *36*, 96–107.

da Silva, P. P., Dantas, G., Pereira, G. I., Câmara, L., & De Castro, N. J. (2019). Photovoltaic distributed generation–An international review on diffusion, support policies, and electricity sector regulatory adaptation. Renewable and sustainable energy reviews, 103, 30-39.

Diagne, M., David, M., Lauret, P., Boland, J., & Schmutz, N. (2013). Review of solar irradiance forecasting methods and a proposition for small-scale insular grids. *Renewable and Sustainable Energy Reviews*, *27*, 65–76.

ElaadNL. (2022). Smart charging in the Netherlands: Pilot results and policy implications. ElaadNL Foundation, Netherlands, retrieved on Jun 12, 2026, at: https://elaad.nl/en/publications/

Etukudoh, E. A., Nwokediegwu, Z. Q. S., Umoh, A. A., Ibekwe, K. I., Ilojianya, V. I., & Adefemi, A. (2024). Solar power integration in Urban areas: A review of design innovations and efficiency enhancements. *World Journal of Advanced Research and Reviews*, *21*(1), 1383–1394.

Fathoni, H. S., & Boer, R. (2021). Battle over the sun: Resistance, tension, and divergence in enabling rooftop solar adoption in Indonesia. *Global Environmental Change*, *71*, 102371.

Fthenakis, V. M., & Kim, H. C. (2011). Photovoltaics: Life-cycle analyses. Solar Energy, 85(8), 1609-1628.

Gallego-Castillo, C., Heleno, M., & Victoria, M. (2021). Self-consumption for energy communities in Spain: A regional analysis under the new legal framework. Energy Policy, 150, 112144.

Geerts, F., & Zweistra, M. (2023). Accelerating national scale up of Smart Charging in the Netherlands. In 36th International Electric Vehicle Symposium and Exhibition (EVS36).

Gholami, H. (2024). A holistic multi-criteria assessment of solar energy utilization on urban surfaces. Energies, 17(21), 5328.

Gómez-Navarro, T., Brazzini, T., Alfonso-Solar, D., & Vargas-Salgado, C. (2021). Analysis of the potential for PV rooftop prosumer production: Technical, economic and environmental assessment for the city of Valencia (Spain). Renewable Energy, 174, 372-381.

Goncearuc, A., De Cauwer, C., Sapountzoglou, N., Van Kriekinge, G., Huber, D., Messagie, M., & Coosemans, T. (2024). The barriers to widespread adoption of vehicle-to-grid: A comprehensive review. Energy Reports, 12, 27-41.

Griego, D., Mehta, P., & Nuñez-Jimenez, A. (2022). Solar Energy Communities in the Urban Environment. In The Palgrave Encyclopedia of Urban and Regional Futures (pp. 1–8). Springer.

Hall, S., Foxon, T. J., & Bolton, R. (2016). Financing the civic energy sector: How financial institutions affect ownership models in Germany and the United Kingdom. Energy Research & Social Science, 12, 5-15.

Version of Record

Hasan, M. K., Mahmud, M., Habib, A. K. M. A., Motakabber, S. M. A., & Islam, S. (2021). Review of electric vehicle energy storage and management system: Standards, issues, and challenges. *Journal of Energy Storage*, *41*, 102940.

Hemetsberger, W. , A. D. , S. M. (2023). *EU Market Outlook for Solar Power 2023-2027*. Belgium.

Hoang, A. T., & Nguyen, X. P. (2021). Integrating renewable sources into energy system for smart city as a sagacious strategy towards clean and sustainable process. *Journal of Cleaner Production*, *305*, 127161.

Hoehnke, H., Wussow, M., Zanocco, C., Carley, S., Konisky, D., & Neumann, D. (2026). Structural barriers and policy pathways for a just clean energy transition. Nature Reviews Clean Technology, 1-21.

Huy, T. H. B., Dinh, H. T., Vo, D. N., & Kim, D. (2023). Real-time energy scheduling for home energy management systems with an energy storage system and electric vehicle based on a supervised-learning-based strategy. *Energy Conversion and Management*, *292*, 117340.

ICNIRP (2020). Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz). International Commission on Non-Ionizing Radiation Protection, Health physics, 118(5), 483-524.

IEA (2023). Electricity grids and secure energy transitions: Enhancing the foundations of resilient, sustainable and affordable power systems. International Energy Agency, France, retrieved on Jun 12, 2026, at: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions

IEA. (2024a). *Renewables 2023*. International Energy Agency, Paris, France, retrieved on January 20, 2024, at: https://www.iea.org/reports/renewables-2023, License: CC BY 4.0.

IEA. (2024b). *Global EV Outlook 2023*. International Energy Agency, Paris, France, retrieved on January 20, 2024, at: https://www.iea.org/reports/global-ev-outlook-2023.

IEA-PVPS. (2024). National Survey Report of PV Power Applications in Spain 2023. International Energy Agency Photovoltaic Power Systems Programme, Spain, retrieved on June 10, 2026, at: https://iea-pvps.org/wp-content/uploads/2024/12/IEA-PVPS-2023-National-Survey-Report-Spain.pdf

Énergie Partagée. (2022). Bilan d'activité 2022: Les coopératives citoyennes d'énergie renouvelable. Énergie Partagée, France, retrieved on Jun 11, 2026, at: https://energie-partagee.org/wp-content/uploads/2023/04/Rapport-dactivite-2022.pdf

Fthenakis, V. M., & Kim, H. C. (2011). Photovoltaics: Life-cycle analyses. Solar Energy, 85(8), 1609-1628.

Jin, S., Zhang, H., Huang, X., Yan, J., Yu, H., Gao, N., Jia, X., & Wang, Z. (2023). Solar Energy Utilization Potential in Urban Residential Blocks: A Case Study of Wuhan, China. *Sustainability*, *15*(22), 15988.

Jos van den Bergh, 2026. Amsterdam with 10,000th charging point one step closer to clean air, Electric Drivers Association, Netherlands, retrieve on Jun 8, 2026 at: https://www.evrijders.nl/nieuws/10000ste-laadpunt-in-amsterdam

Judson, E., & Zirakbash, F. (2022). Investigating the potential of solar energy for low-income communities in Australia to reduce hardship, debt and inequality. *Energy Research & Social Science*, *84*, 102386.

Version of Record

Khan, S. U.-D., Wazeer, I., Almutairi, Z., & Alanazi, M. (2022). Techno-economic analysis of solar photovoltaic powered electrical energy storage (EES) system. *Alexandria Engineering Journal*, *61*(9), 6739–6753.

Kobashi, T., Jittrapirom, P., Yoshida, T., Hirano, Y., & Yamagata, Y. (2021). SolarEV City concept: Building the next urban power and mobility systems. *Environmental Research Letters*, *16*(2), 024042.

Korsnes, M., & Throndsen, W. (2021). Smart energy prosumers in Norway: Critical reflections on implications for participation and everyday life. *Journal of Cleaner Production*, *306*, 127273.

Liew, P. Y., Varbanov, P. S., Foley, A., & Klemeš, J. J. (2021). Smart energy management and recovery towards Sustainable Energy System Optimisation with bio-based renewable energy. In Renewable and Sustainable Energy Reviews (Vol. 135, p. 110385). Elsevier.

Liu, J., Wu, H., Huang, H., & Yang, H. (2023). Renewable energy design and optimization for a net-zero energy building integrating electric vehicles and battery storage considering grid flexibility. *Energy Conversion and Management*, *298*, 117768.

Loi n° 2015-992 (2015). Relative à la transition énergétique pour la croissance verte. (2015). Journal Officiel de la République Française, France, retrieved on Jun 11, 2026, at: https://www.vie-publique.fr/dossierlegislatif/JORFDOLE000029310724

Loumakis, S., Giannini, E., & Maroulis, Z. (2019). Merit order effect modeling: The case of the Hellenic electricity market. Energies, 12(20), 3869.

Lowitzsch, J., Bucha, M., & Lonscher, S. (2025). From access to ownership: Energy communities & social inclusion in the EU's energy transition. Friedrich-Ebert-Stiftung, Competence Centre Climate and Social Justice.

Lyu, Y., Fairbrother, A., Gong, M., Kim, J. H., Gu, X., Kempe, M., Julien, S., Wan, K.-T., Napoli, S., & Hauser, A. (2020). Impact of environmental variables on the degradation of photovoltaic components and perspectives for the reliability assessment methodology. *Solar Energy*, *199*, 425–436.

Ma, R., Cai, H., Ji, Q., & Zhai, P. (2021). The impact of feed-in tariff degression on R&D investment in renewable energy: The case of the solar PV industry. *Energy Policy*, *151*, 112209.

Moorman, S., & Mergelsberg, S. (2021). Lessons learned: Smart charging in Nederland 2015-2020*. Nationale Agenda Laadinfrastructuur (NAL), Netherlands, retrieved on June 9, 2026, at: https://elaad.nl/wp-content/uploads/downloads/lessons-learned-smart-charging-in-nederland.pdf

Murray, C. (2022). Acciona Energia sets up ‘first’ V2G network in Spain, retrieved on January 20, 2024, at: https://www.energy-storage.news/acciona-energia-sets-up-first-v2g-network-in-spain/.

Nillesen, P. H., & Pollitt, M. G. (2026). Incentive regulation and distribution network performance: a Dutch case study (2000–2024). Journal of Regulatory Economics, 69(1), 15.

Notton, G., Nivet, M.-L., Voyant, C., Paoli, C., Darras, C., Motte, F., & Fouilloy, A. (2018). Intermittent and stochastic character of renewable energy sources: Consequences, cost of intermittence and benefit of forecasting. *Renewable and Sustainable Energy Reviews*, *87*, 96–105.

Notton, G., Ouédraogo, S., Faggianelli, G. A., Voyant, C., & Duchaud, J. L. (2024). Profitability and performance improvement of smart photovoltaic/energy storage

Version of Record

microgrid by integration of solar production forecasting tool. In Intelligent Learning Approaches for Renewable and Sustainable Energy (pp. 73–102). Elsevier.

Nuñez-Jimenez, A., Mehta, P., & Griego, D. (2023). Let it grow: How community solar policy can increase PV adoption in cities. Energy Policy, 175, 113477.

OECD (2025), Diagnostic Toolkit for Reducing Regulatory Barriers to Solar, Wind and Pumped Hydro Storage in the European Union: Empowering Policymakers at National, Regional, and Local Levels, OECD Publishing, Paris, https://doi.org/10.1787/15f4aed4-en.

Pascaris, A. S., Schelly, C., & Pearce, J. M. (2020). A first investigation of agriculture sector perspectives on the opportunities and barriers for agrivoltaics. *Agronomy*, *10*(12), 1885.

Petrou, K., Procopiou, A. T., Gutierrez-Lagos, L., Liu, M. Z., Ochoa, L. F., Langstaff, T., & Theunissen, J. M. (2021). Ensuring distribution network integrity using dynamic operating limits for prosumers. *IEEE Transactions on Smart Grid*, *12*(5), 3877–3888.

Petrucci, A., Barone, G., Buonomano, A., & Athienitis, A. (2022). Modelling of a multi-stage energy management control routine for energy demand forecasting, flexibility, and optimization of smart communities using a Recurrent Neural Network. *Energy Conversion and Management*, *268*, 115995.

Prol, J. L., & Steininger, K. W. (2020). Photovoltaic self-consumption is now profitable in Spain: Effects of the new regulation on prosumers' internal rate of return. Energy Policy, 146, 111793.

Queiroz, H., Lopes, R. A., Martins, J., Silva, F. N., Fialho, L., & Bilo, N. (2023). Assessment of energy sharing coefficients under the new Portuguese renewable energy communities regulation. Heliyon, 9(10).

Rabiee, A., Nikkhah, S., Salehi, D., Holttinen, H., Helistö, N., Göransson, L., ... & Yasuda, Y. (2026). From electricity to economy-wide Net-Zero: Comparative analysis of global energy pathways. *Renewable and Sustainable Energy Reviews*, *231*, 116771.

Raimi, D., Davert, E., Neuenfeldt, H., Van Zanen, A., & Whitlock, Z. (2024). The energy transition and local government finance: new data and insights from 10 US states. *Environmental Research: Energy*, *1*(3), 035003.

Rakholiya, Keyur & Neumann Rainer (2026). Solar PPA vs ownership: Third-party financing for commercial solar, India, retrieved on Jun 11, 2026, at: https://www.surgepv.com/hub/commercial-solar/ppa-ownership

Rangarajan, S. S., Raman, R., Singh, A., Shiva, C. K., Kumar, R., Sadhu, P. K., Collins, E. R., & Senjyu, T. (2023). DC microgrids: A propitious smart grid paradigm for Smart Cities. *Smart Cities*, *6*(4), 1690–1718.

Ren, H., Ma, Z., Chan, A. B., & Sun, Y. (2023). Optimal planning of municipal-scale distributed rooftop photovoltaic systems with maximized solar energy generation under constraints in high-density cities. *Energy*, *263*, 125686.

Rezaee, E., & Silva, S. R. P. (2026). Solar energy in 2025: Global deployment, cost trends, and the role of energy storage in enabling a resilient smart energy infrastructure. Energy & Environmental Materials, 9(3), e70199.

Rezaei, H., Abdollahi, S. E., Abdollahi, S., & Filizadeh, S. (2022). Energy management strategies of battery-ultracapacitor hybrid storage systems for electric vehicles: Review, challenges, and future trends. *Journal of Energy Storage*, *53*, 105045.

Rzepucha-Hlubek, K. (2026). The easy way of participating in energy transition—Investigating the purchase intention for plug-in solar devices using an extended theory of consumption values. Energy Research & Social Science, 136, 104742.

Version of Record

Samaniego-Rascón, D., da Silva, M. C. G., Ferreira, A. D., & Cabanillas-Lopez, R. E. (2019). Solar energy industry workers under climate change: a risk assessment of the level of heat stress experienced by a worker based on measured data. Safety science, 118, 33-47.

Sánchez, A., Zhang, Q., Martín, M., & Vega, P. (2022). Towards a new renewable power system using energy storage: An economic and social analysis. *Energy Conversion and Management*, *252*, 115056.

Shand, J., Glakpe, E., & Ivey, C. (2025). Policy implications of implementing residential PV solar energy systems in developing regions. *Energy Policy*, *196*, 114414.

Sheng, C., & Liu, J. (2023). A systematic analysis of stakeholder interaction and the barriers towards upscaling urban residential solar PV: The case of Shanghai, China. *Energy Strategy Reviews*, *50*, 101259.

Sierro, F., & Blumer, Y. (2024). Material energy citizenship through participation in citizen-financed photovoltaic projects. Energy, Sustainability and Society, 14(1), 33.

Sobhy, T., Hemdan, N., Hamada, M., & Wahab, M. (2015). German grid code aspects discussion: low voltage ride-through of converter based decentralized generation. Int. J. Distrib. Energy Resour. Smart Grids, 11, 129-141.

Sovacool, B. K., Evensen, D., Kwan, T. A., & Petit, V. (2023). Building a green future: Examining the job creation potential of electricity, heating, and storage in low-carbon buildings. *The Electricity Journal*, *36*(5), 107274.

Stauch, A., & Vuichard, P. (2019). Community solar as an innovative business model for building-integrated photovoltaics: An experimental analysis with Swiss electricity consumers. Energy and Buildings, 204, 109526.

Stauch, A. (2021). Does solar power add value to electric vehicles? An investigation of car-buyers' willingness to buy product-bundles in Germany. Energy Research & Social Science, 75, 102006.

Strupeit, L., Bocken, N., & Van Opstal, W. (2024). Towards a circular solar power sector: Experience with a support framework for business model innovation. *Circular Economy and Sustainability*, *4*(3), 2093–2118.

Su, C. W., Umar, M., & Khan, Z. (2021). Does fiscal decentralization and eco-innovation promote renewable energy consumption? Analyzing the role of political risk. *Science of the Total Environment*, *751*, 142220.

Taminiau, J., Byrne, J., Kim, J., Kim, M., & Seo, J. (2021). Infrastructure-scale sustainable energy planning in the cityscape: Transforming urban energy metabolism in East Asia. *Wiley Interdisciplinary Reviews: Energy and Environment*, *10*(5), e397.

Tan, B., Chen, S., Liang, Z., Zheng, X., Zhu, Y., & Chen, H. (2024). An iteration-free hierarchical method for the energy management of multiple-microgrid systems with renewable energy sources and electric vehicles. *Applied Energy*, *356*, 122380.

To, T., Heleno, M., & Valenzuela, A. (2022). Risk-constrained multi-period investment model for distributed energy resources considering technology costs and regulatory uncertainties. Applied Energy, 319, 119210.

Tolmasquim, M. T., de Barros Correia, T., Porto, N. A., & Kruger, W. (2021). Electricity market design and renewable energy auctions: The case of Brazil. *Energy Policy*, *158*, 112558.

Ufa, R. A., Malkova, Y. Y., Rudnik, V. E., Andreev, M. V., & Borisov, V. A. (2022). A review on distributed generation impacts on electric power system. International journal of hydrogen energy, 47(47), 20347-20361.

Version of Record

Van Der Kam, M., & Van Sark, W. (2015). Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study. Applied energy, 152, 20-30.

Vargas-Salgado, C., Aparisi-Cerdá, I., Alfonso-Solar, D., & Gómez-Navarro, T. (2022). Can photovoltaic systems be profitable in urban areas? Analysis of regulation scenarios for four cases in Valencia city (Spain). *Solar Energy*, *233*, 461–477.

Verbeek, J., Oftedal, G., Feychting, M., van Rongen, E., Scarfì, M. R., Mann, S., ... & van Deventer, E. (2021). Prioritizing health outcomes when assessing the effects of exposure to radiofrequency electromagnetic fields: A survey among experts. Environment international, 146, 106300.

Vimpari, J., & Junnila, S. (2017). Evaluating decentralized energy investments: Spatial value of on-site PV electricity. *Renewable and Sustainable Energy Reviews*, *70*, 1217–1222.

Widén, J. (2014). Improved photovoltaic self-consumption with appliance scheduling in 200 single-family buildings. *Applied Energy*, *126*, 199-212.

Wells, P. (2023). Business model innovation for the circular economy: Market, multi-stakeholder, or circular vertical integration? In Strategic Management and Sustainability Transitions (pp. 35-54). Routledge.

Wirfs-Brock, J. (2015). Lost in transmission: How much electricity disappears between a power plant and your plug? Inside Energy. Inside Energy, retrieved on May 27, 2026 at: https://insideenergy.org/2015/11/06/lost-in-transmission-how-much-electricity-disappears-between-a-power-plant-and-your-plug/

Wokuri, P., Yalçın-Riollet, M., & Gauthier, C. (2019). Consumer (co-) ownership in renewables in France. In Energy Transition: Financing Consumer Co-Ownership in Renewables (pp. 245-270). Cham: Springer International Publishing.

Xue, Y., Temeljotov-Salaj, A., & Lindkvist, C. M. (2022). Renovating the retrofit process: People-centered business models and co-created partnerships for low-energy buildings in Norway. Energy Research & Social Science, 85, 102406.

Yoldaş, Y., Önen, A., Muyeen, S. M., Vasilakos, A. V, & Alan, I. (2017). Enhancing smart grid with microgrids: Challenges and opportunities. *Renewable and Sustainable Energy Reviews*, *72*, 205–214.

Zhang, W., Yan, C., Xu, Y., Fang, J., & Pan, Y. (2022). A critical review of the performance evaluation and optimization of grid interactions between zero-energy buildings and power grids. *Sustainable Cities and Society*, 104123.

Version of Record