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Challenges, Policies, and Opportunities in Large Scale Solar Energy Adoption for Sustainable Development

Abdullah Aldulli
Mechanical Engineering, University of Sharjah, Saudi Arabia
https://orcid.org/0009-0004-8943-6835

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Abstract

Purpose: Large-scale solar energy is increasingly recognized as a critical pathway for achieving Sustainable Development Goals by meeting rising energy demand while reducing greenhouse gas emissions and strengthening resilient energy infrastructure. This study examines the challenges, policy frameworks, and opportunities associated with deploying large-scale solar photovoltaic systems in commercial buildings, shopping centers, and urban developments, with a focus on their role in supporting sustainable development.

Methodology: The study adopts a qualitative review and comparative policy analysis approach, drawing on peer-reviewed literature, international energy reports, and policy documents. It synthesizes technical, economic, and regulatory perspectives on large-scale solar PV deployment across multiple regions, with particular attention to commercial and urban applications.

Findings: The analysis identifies key technical and infrastructural challenges, including intermittency, grid integration constraints, land availability, and system reliability, alongside economic and institutional barriers affecting project viability. The study further finds that supportive policy instruments, declining technology costs, innovative financing models, and integration of solar PV into the built environment significantly enhance adoption potential in large commercial and urban developments.

Unique Contribution to Theory, Policy and Practice: This study contributes by integrating technical, policy, and urban development perspectives into a unified framework for large-scale solar adoption. It provides transferable policy insights for governments, practical guidance for developers and investors, and strategic recommendations for embedding solar PV into sustainable real estate and urban planning practices.

Keywords: *Large-Scale Solar Energy, Solar Photovoltaic Policy, Sustainable Development, Commercial Buildings, Urban Energy Systems, Renewable Energy Adoption*

1. Introduction

The global energy picture is changing dramatically because of how many government bodies, businesses and cities will address both growing demand for energy and climate change (Wall et al., 2012) One of the fastest growing forms of electricity worldwide is solar energy; especially solar photovoltaics (solar PV), which have evolved to meet the needs of a wide range of geographic and economic environments and are technologically mature, cost effective, and widely applicable. Over the last twenty years there has been rapid growth in the deployment of solar PV on a large scale; and much of that growth has been made possible through advances in manufacturing, increases in system efficiency and favorable policy frameworks. That rapid growth is also representative of a larger trend towards renewable energy systems which can provide low-carbon electricity while providing for long-term economic and environmental sustainability.

There are several ways in which large-scale solar energy deployment supports the achievement of sustainable development goals (Hernandez et al., 2014) First, it reduces greenhouse gas emissions, enhances energy security, and supports the development of resilient infrastructure. Unlike traditional fossil-fuel-based power generation, solar PV does not directly emit gases during operation, and relies upon a virtually limitless supply of an abundant renewable energy source. At a national or regional level, the deployment of large amounts of solar energy can significantly reduce the carbon intensity of electric power systems and contribute to the achievement of climate-mitigation goals and cleaner air (Kibert, 2016) Additionally, large-scale solar deployments can create jobs, promote local economic development and reduce reliance upon foreign fuels.

Beyond utility scale installations, solar energy is becoming increasingly relevant in the built environment particularly in commercial buildings and urban infrastructure. Among the largest consumers of electricity are large commercial facilities such as shopping malls, office buildings and mixed use developments all of which require constant operation to provide light, heating/cooling, ventilation, and digital services (Del Río & Mir-Artigues, 2012) The inclusion of solar PV in these buildings represents a practical and scalable method for reducing the amount of energy consumed by these facilities and the resultant emissions. With rooftop mounted solar systems, solar panels mounted on building facades, and solar-powered parking garages all of which allow for the generation of electricity on site without requiring additional land there are now a number of ways to integrate renewable energy production into the built environment in an efficient manner that supports good urban planning.

Urban infrastructure can also benefit from the widespread implementation of large-scale solar energy through the generation of decentralized energy and the improvement of system reliability. Urban areas continue to experience increased pressure to provide reliable energy services while minimizing their environmental footprint. A flexible form of renewable energy that can be implemented across multiple types of urban assets is provided by solar PV. When combined with energy storage, smart grid technologies and demand response management, solar energy systems can help to reduce peak loads, improve the stability of the electrical grid and increase the overall efficiency of the grid.

Therefore, it is crucial to understand the challenges, policies and opportunities related to the large scale implementation of solar energy. An examination of solar energy's potential deployment in commercial buildings and urban infrastructure emphasizes the strategic significance of incorporating renewable energy into the built environment as part of a comprehensive sustainable development agenda. Therefore, this research examines the function of large-scale solar energy systems to support sustainable development, focusing on the drivers of policy-directed adoption, technical challenges, and opportunities for commercial and urban environments.

2. Technical and Infrastructural Challenges in Large-Scale Solar Adoption

The widespread deployment of solar photovoltaics (PV) has experienced rapid growth in the utility, commercial and urban sectors. Although there is a strong foundation of both environmental and economic drivers, there are a number of technical and infrastructural challenges affecting the rate of deployment, reliability and effectiveness of solar deployments. Of particular note are the technical and infrastructural challenges associated with large commercial buildings, shopping centers, and densely populated urban environments. Energy demand patterns, grid restrictions and physical constraints associated with these types of locations require careful management.

2.1 Intermittency/variability of Solar Energy

Intermittent and variable solar energy is an issue that presents itself at the very core of the solar energy problem. Solar PV output is dependent upon solar irradiance; however, solar irradiance varies as a function of diurnal and seasonal cycles, as well as atmospheric and cloud-related conditions (Timilsina, 2021) This results in solar PV output declining precipitously during cloudy weather or after sunset. Large scale systems exhibit increased variability relative to smaller scale systems. The variability of solar PV output complicates energy planning in large scale solar deployments requiring increased dependency on backup generation or energy storage to ensure reliable operation.

Commercial buildings and shopping centers experience operational challenges as a result of the intermittency of solar PV output due to the fact that electricity demands typically exceed the time period of daylight hours. When energy storage or demand side management is inadequate, the excess daytime solar energy generated does not correlate adequately with consumer energy demands resulting in reduced overall efficiency of the installed PV capacity (Timilsina, 2021).

2.2 Grid Integration and Network Restrictions

Grid integration represents a significant infrastructural challenge associated with increased levels of solar penetration into the electric grid. High concentrations of solar PV generate issues related to voltage regulation, frequency stability, and reverse power flow characteristics in distribution networks primarily designed for unidirectional flow of electricity (Asmelash et al., 2020) In

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densely populated urban commercial areas, the grid infrastructure lacks the flexibility or capacity to accept large amounts of distributed solar PV generation (Jia et al., 2020).

Although advanced inverter technologies have improved grid compatibility through the ability to provide voltage support, reactive power compensation and fault ride-through capability, effective integration will depend on coordinated grid planning, accurate solar forecasting and investment in grid modernization. Coordination between the developer, utility, and regulatory agencies will also be important in ensuring that on-site solar PV systems can operate in harmony with the larger electric network in large commercial developments.

2.3 Available Land and Spatial Constraints

Available land represents another significant barrier to the deployment of large scale solar energy, especially in urban and suburban areas. Utility scale solar energy facilities require large tracts of land, which may conflict with agricultural uses, conservation and urbanization. Commercial buildings and shopping centers represent unique spatial barriers, such as roof size and structural loading, shading from adjacent structures and architectural aesthetics. While rooftop and building-integrated PV systems reduce the need for land resources by using existing structures, they are limited by design and available surface area constraints. Large malls and multi-use developments will require careful planning to optimize the available surface area for PV use while providing safe structural support and maintaining architectural integrity.

2.4 System Reliability and Performance Degradation

Long term reliability of large scale solar energy systems is a critical concern, since these systems are expected to operate for several decades. Environmental conditions, such as high temperatures, dust accumulation, humidity and mechanical stresses, will cause performance degradation of solar energy systems and require increased maintenance. Downtime of commercial solar energy systems will directly impact the operational costs and sustainability goals of the commercial facility.

System reliability extends beyond the PV module to include the inverter, mounting structure and electrical connections. Therefore, regular maintenance, robust system design and digital monitoring are necessary to sustain the performance and minimize the lifecycle cost of commercial solar energy systems. In harsh climate zones, reliability becomes a key factor in the choice of technology and the configuration of the system.

2.5 Deployment Challenges in Commercial and Urban Environments

There are unique deployment challenges facing large commercial and urban environments that influence the adoption of solar energy. Project construction schedules, local building codes, fire safety regulations and aesthetic standards may complicate the installation of solar energy systems. Additionally, retrofitting an existing commercial or residential building will require additional structural assessments and potential design modifications, which may increase the complexity and cost of the project. Moreover, the institutional and logistical challenges of coordinating multiple

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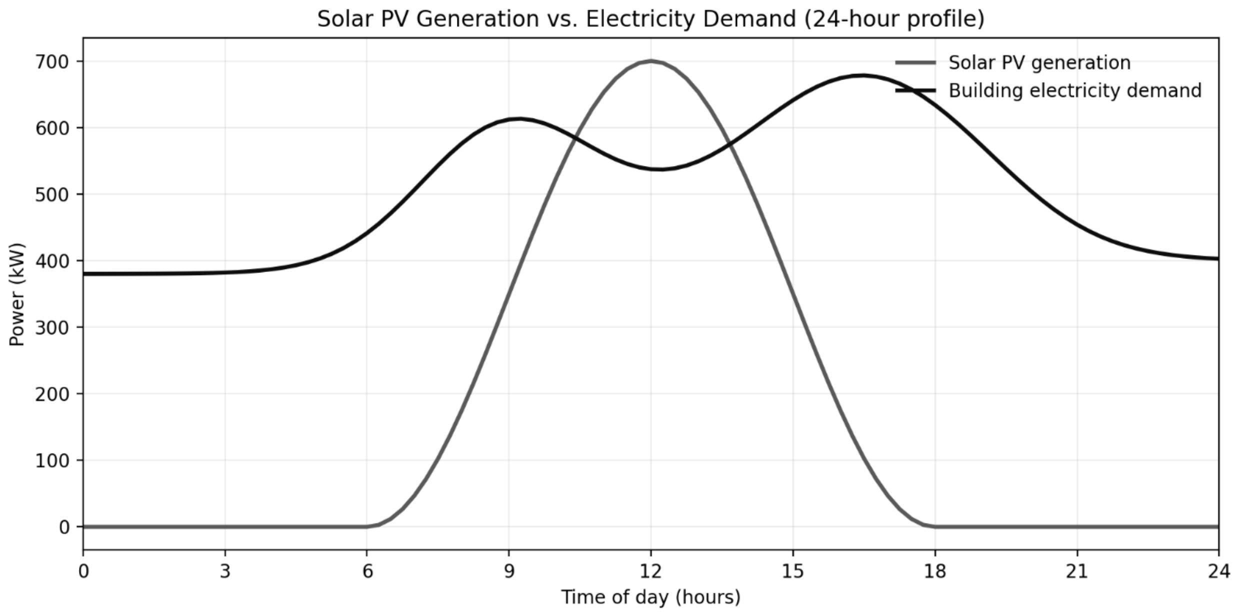
stakeholders, such as the property owner, tenant, utility company, and municipal authority, may hinder the completion of solar energy projects. These institutional and logistical challenges highlight the importance of integrated planning and early consideration of solar energy in commercial and urban development projects.

Figure 1. Daily Solar PV Generation and Electricity Demand Profile in a Large Commercial Building



This figure illustrates the 24-hour profile of solar photovoltaic power generation compared with electricity demand in a large commercial building. Solar PV output peaks during midday hours and declines toward zero in the evening, while electricity demand remains significant beyond daylight hours. The mismatch between generation and demand highlights key technical challenges related to intermittency, grid integration, and the need for energy storage or demand-side management in large-scale and urban solar energy applications (Couture et al., 2010).

3. Policy and Regulatory Frameworks for Solar Energy Deployment

Solar Photovoltaics (PV) Technological Advancements, Cost Reduction, and Policy and Regulation Development

While solar PV technology has evolved and cost reduced, the growth of solar PV from pilot projects to large-scale adoption requires supportive policies and regulations, investment incentives, grid access rules, and clear governance structures. The policies governing large commercial developments and shopping centers and urban areas will affect project bankability, permitting, and long-term revenue stability for all solar PV projects. Section 3 outlines policy and regulatory instruments at the international, national, and local government levels and identifies

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ways to enhance solar PV adoption while identifying some of the reasons why poor regulation has impeded solar PV development.

3.1 Global Policy Drivers and Instruments

Global policy drivers influence national renewable energy policy through shared global climate and sustainability commitments, financing channels, and guidance mechanisms. Many countries have established renewable energy targets as part of their decarbonization strategies and global development finance institutions, multilateral agencies, and clean energy partnerships have provided financing and technical assistance as well as risk management tools to lower the barriers to entry for emerging and developing markets (Del Río & Mir-Artigues, 2014) As such, global policy drivers have shaped national energy strategies particularly in those countries that have identified modernizing their grids, providing universal energy access, and building low carbon infrastructure as priority development objectives.

Furthermore, the development of international standards and best practices for the testing of performance, quality assurance, and environmental compliance for solar PV supports the implementation of consistent standards throughout the world for the procurement of solar PV, the assessment of bankability of solar PV projects, and the long term reliability of solar PV systems.

3.2 National Policy Instruments Supporting Solar Deployment

The most common national policy instruments supporting solar deployment are policy instruments addressing the three fundamental factors: investment risk, revenue certainty, and access to markets. The most common national policy approaches are:

1. Fiscal and Financial Incentives

Many governments have used fiscal and financial incentives to reduce the initial capital costs associated with the installation of commercial-scale PV projects. Tax exemptions, accelerated depreciation, grants, and low interest loans and other types of financial incentives have improved payback periods for solar PV projects and have attracted adoption of solar PV in industries with high electricity usage such as retail and hospitality.

2. Tariffs-based Support Schemes

Feed-in tariffs and feed-in premiums have been among the most successful policy instruments in driving early-stage solar markets by ensuring that developers receive a fixed price per unit of renewable electricity produced and injected into the grid. Although many markets are now transitioning from long-term fixed tariffs, the need for developers to have predictable and stable revenue streams remains as significant an issue today as it was during the early days of the solar industry. Today, this issue is addressed in many modern solar markets through auctions, long-term power purchase agreements, and regulated net metering mechanisms (Byrne et al., 2015).

3. Market Design and Procurement Frameworks

Competitive auctions for utility-scale solar projects have become one of the most effective policy tools for reducing the cost of solar energy and attracting private investment. When designed transparently, with bankable contracts and clearly defined responsibilities regarding the connection to the grid, auctions have been able to quickly increase the deployment of solar energy. Corporate power purchase agreements and third-party ownership models for commercial and industrial applications also facilitate the development of solar energy by reducing the financial barriers to entry.

4. Grid Interconnection and Permitting Regulations

When there are adequate financial incentives available to developers, the availability of permits and the ability to connect new solar installations to the grid can still delay or constrain the deployment of solar energy. Standardized procedures for connecting to the grid, defined timelines for permit approvals, and fair cost allocations are necessary to eliminate barriers to the rapid deployment of solar energy. The need for standardized procedures for grid interconnections and defined timelines for permit approvals is particularly acute for large shopping malls and urban developments because of the potential for large-scale solar installations to require upgrades to the distribution network (Owusu & Asumadu-Sarkodie, 2016).

5. Mandatory Renewable Portfolio Standards

Renewable portfolio standards and targets create strong market demand for renewable energy including solar energy by requiring utilities and energy retailers to purchase renewable energy. Renewable portfolio standards and targets can be designed to create both demand for utility-scale solar energy projects and for distributed generation solar energy projects in commercial buildings.

3.3 City Level Policies and Urban Governance Mechanisms

Cities' actions to allow solar installations in densely populated urban areas is a growing area of influence for urban governance. Many municipalities regulate building codes, zoning rules and urban planning to determine if solar systems can be included as part of commercial property developments. At the city level there are many tools (instruments) used to promote solar installations including:

1. Energy efficiency codes for building and solar mandates at the local level.

Many cities have mandated building codes and/or solar installations on all new commercial developments over a certain size. This is the case with many shopping mall and large commercial properties. By requiring commercial property developers to install solar as part of their overall building plans this creates a positive incentive to install solar panels, and it ensures that solar systems are designed into the building as an integral part of the building's design and construction.

2. Simplified permit processes and one stop shop for municipal permits and approvals. Developers in urban locations need to get numerous permits before installing a commercial solar

installation; they need to get electrical permits, structural permits and mechanical permits, as well as meet with engineers and utility representatives. The time required to obtain these permits can delay the start-up date of a commercial solar installation. Municipalities can reduce the amount of time it takes to receive permits for a commercial solar installation by providing a single point of contact for all permitting issues, by providing a template for the designs of solar systems, and by ensuring that inspections occur regularly and predictably.

3. Net-metering and net-billing framework for commercial solar installations.

In many commercial applications, buildings consume electricity during the day and produce excess electricity at night. Therefore, self-consumption of produced electricity is a viable option for many commercial customers. Municipalities can provide incentives for commercial customers to invest in solar by providing a favorable tariff structure for exporting excess generated electricity to the grid.

4. Renewable energy strategies for urban development and public-private partnerships. Municipalities can support the expansion of solar use in urban areas by partnering with private companies to develop solar installations on public buildings, parking garages and transportation facilities. Public-private partnerships help to build credibility for solar in urban areas and will attract additional private investment in the future.

3.4 Policies That Could Limit Solar Installation Development

Regulatory uncertainty is a major barrier to solar investment. Changes in tariffs, delayed subsidies, undefined interconnection responsibilities and uncoordinated permitting processes can deter investors from investing in solar (Byrne et al., 2015) Additionally, restrictive regulatory frameworks for solar installations can limit private sector investment, limit third party ownership options and create limits on the amount of distributed generation allowed, which could hinder solar installation development even though solar technology has reached parity with conventional technologies.

Large commercial property developments, such as shopping centers, may experience similar regulatory barriers related to building codes that do not accommodate building-integrated photovoltaic systems, limited grid capacity to export surplus energy in urban distribution networks and lack of incentives for energy storage in solar installations. These examples illustrate the importance of developing comprehensive policies that address both the needs of expanding the market and the preparedness of the existing infrastructure.

3.5 Implications for Large Commercial Properties and Urban Development Projects

Solar PV policies play a significant role in the development of shopping centers and urban development projects due to the nature of large commercial property developments, including large capital expenditures, extended operational life cycles, and multi-stakeholder involvement. Clarity regarding regulatory policies related to connecting to the electric grid, paying for exported energy, complying with safety standards, and meeting building code requirements enable developers to plan for the inclusion of solar systems in project development early on and to optimize the design of the solar systems (Hernandez et al., 2014) On the other hand, ambiguity in regulatory policies can result in delays in project development, higher costs, and reduced utilization of available solar resources (Asmelash et al., 2020).

Therefore, effective solar policy development requires the alignment of national objectives, utility company planning and local government policy implementation (Panwar et al., 2011) When coordinated, the national and local government policies can drive large-scale solar adoption, support sustainable development goals, and enhance the competitiveness and environmental sustainability of commercial and urban infrastructure(Kempener et al., 2015).

Figure 2. Relative Influence of Key Policy Instruments on Large-Scale Solar PV Adoption

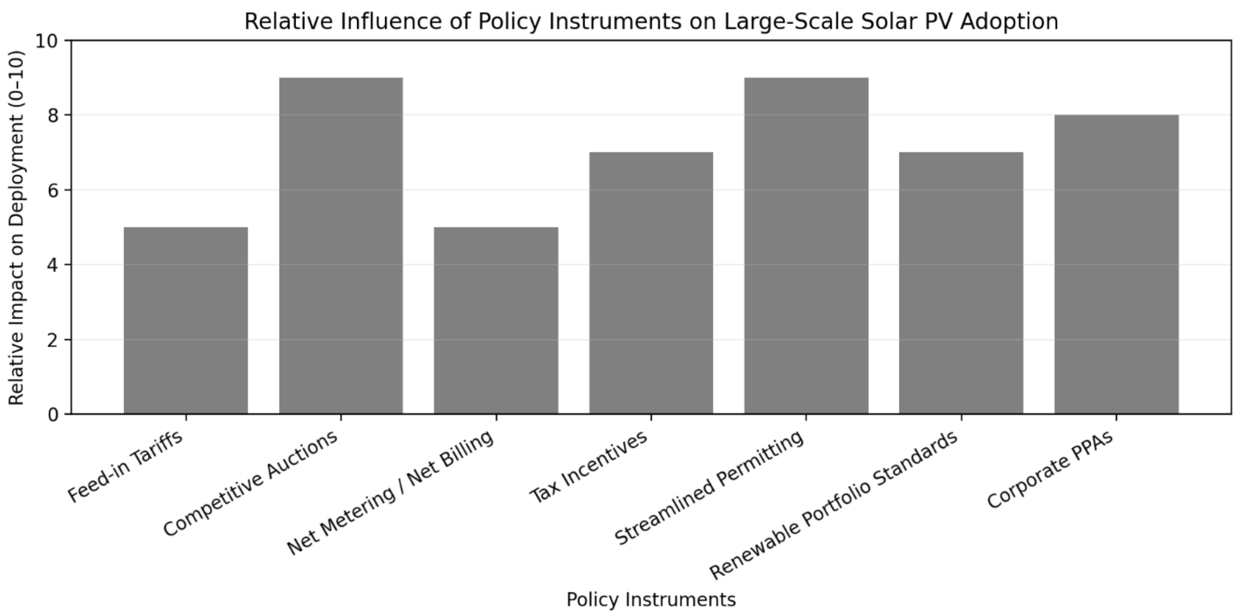

Figure 2. Relative influence of key policy instruments on large-scale solar photovoltaic deployment. Competitive auctions, streamlined permitting, and corporate power purchase agreements (PPAs) exhibit the highest relative impact, while tax incentives and renewable portfolio standards provide moderate support. Feed-in tariffs and net metering or net billing mechanisms show moderate influence, depending on market maturity and regulatory context.

4. Opportunities for Solar Energy in Commercial Buildings and Urban Developments

The commercial building industry and the implementation of large-scale urban development projects are some of the most viable and impactful ways to promote and accelerate the deployment of solar photovoltaics (PV). The electric demands of shopping malls, office complexes, mixed-use developments and municipal-scale infrastructure are significant because of their need to cool, light, vertically move people and equipment, and provide digital services. There are numerous advantages of integrating solar PV into the properties that are used for these purposes across economic, environmental, and operational perspectives specifically when the solar PV systems are sized to meet the load profile of the property and when they are supported by the latest energy management techniques.

4.1 Advantages Economic

Lowering of the cost of electricity; hedging of possible tariff rate increases.

Commercial buildings, especially those located in hot climate zones, have high electrical bills primarily due to the amount of money spent on cooling (Wall et al., 2012) Solar PV will offset the cost of purchasing electricity from the grid when the demand for electricity is highest in the day. Not only will this help lower the cost of operation, it will provide a hedge against future tariff rate increases and/or the volatility of fuel prices contained within the cost of electricity.

Increased predictability of savings and improved bankability of projects.

Because solar PV produces relatively stable and predictable amounts of energy over its useful life, the value of on-site solar production can be determined and included in the financial analysis of large facilities that have similar daily energy demand (Kibert, 2016) This increased predictability of savings will improve the ability of the owner/developer to obtain funding for their project and will also improve the availability of funding, if they include a contractual agreement, such as a Power Purchase Agreement (PPA), to ensure a stable revenue stream (Knight, 2015).

Value of the asset to the developer/investor; increased attractiveness of the property to the tenant/institutional investor.

When a commercial property incorporates solar into the construction of the property, it has the opportunity to increase its sustainability rating and decrease the annual operating expense of the property. As such, the value of the asset will likely increase and the property will be more attractive to both tenants and institutional investors (de Wild-Scholten, 2013) Increasingly, institutional investors are requiring that companies report on environmental performance and incorporate sustainability into all aspects of the company, including the company's portfolio of commercial properties (Couture et al., 2019) Therefore, the incorporation of on-site solar PV into the commercial property can be considered a valuable addition to the real estate portfolio of an institution.

Flexibility of business models available to encourage the adoption of solar PV.

There are several models that can be utilized to encourage the adoption of solar PV in commercial applications, including direct ownership, third party ownership, leasing and Corporate Power Purchase Agreements (CPPAs). The flexibility of business models will assist in overcoming the

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barriers of capital and allow the owner/developer of the commercial property to select the model that best fits the financial strategy and risk tolerance of the project.

4.2 Advantages Environmental

Reduction of greenhouse gas emissions associated with the operation of the facility. By utilizing solar PV to generate electricity instead of relying on grid supplied electricity that may be generated using fossil fuels, the carbon intensity of the electricity being consumed is reduced. Due to the size of the electrical load of shopping malls and large commercial facilities, solar PV can significantly reduce the greenhouse gas emissions of these facilities over the course of their useful lives.

Efficiency in the use of existing surfaces to minimize land impact.

Rooftop mounted PV, facade mounted PV and solar carports can transform existing built surfaces into energy generating surfaces. Compared to utility-scale solar PV projects, this will result in less land area impacted due to the fact that existing surfaces are being utilized to generate energy, particularly in urban areas where land is either very expensive or limited.

Compliance with green building certifications and sustainable urban planning.

Solar PV will assist with meeting the requirements of green building certifications and sustainable urban planning initiatives (de Wild-Scholten, 2013) By providing renewable energy credits, assisting in achieving energy performance targets, and supporting low-carbon development objectives, solar PV will assist in improving the environmental certification outcomes of large developments and improve the sustainability reporting of large developments.

4.3 Advantages Operational

Potential for high self-consumption rates in commercial facilities.

Due to the high peak demand of shopping malls and commercial facilities, particularly during daytime hours due to cooling, lighting and other operational needs, there exists a strong correlation between the solar PV generation profile and the peak demand profile of these facilities. As a result, these facilities can realize high levels of self-consumption and eliminate the need for export compensation mechanisms. Improved self-consumption will improve the economics of solar PV and reduce grid strain.

Peak load reduction and demand management.

Utilizing solar PV to reduce peak load demand, particularly in conjunction with operational strategies such as moving certain loads to daytime hours, can assist in reducing peak demand charges and improve load management. Additionally, solar PV will contribute to improving the overall efficiency of the power system at the facility level.

Smart energy management and storage – integration of solar PV.

Monitoring and control capabilities via digital platforms, Building Energy Management Systems (BEMS) and energy storage systems will enable commercial sites to optimize the utilization of solar PV. Storage systems can shift solar energy generated during the day to evening demand periods, provide backup power during grid disturbances, and improve reliability for critical loads. Smart controls will also enable rapid fault detection and improved maintenance planning.

Business continuity and resiliency benefits.

Large shopping centers and commercial hubs are vulnerable to significant economic loss and operational disruption in the event of power outages. Commercial PV systems integrated with storage and properly controlled will provide backup power for critical systems and provide a higher level of operational resiliency.

In summary, the integration of solar PV into commercial buildings and urban development projects represents a unique combination of cost savings, emissions reduction, operational efficiencies and strategic asset value. When solar PV systems are integrated into commercial buildings and urban development projects during the design and development phase, rather than retrofitting them after the fact, these advantages will be realized at a greater magnitude.

5. Comparative Policy Experiences and Strategic Insights

The adoption of solar energy differs significantly across regions due to variations in policy design, market maturity, grid infrastructure, institutional capacity, and financing mechanisms. Comparative policy analysis is valuable because it identifies which strategies have successfully scaled solar deployment and which barriers have slowed progress. These insights can be translated into best practices and practical recommendations for large-scale real estate and urban development projects (Knight, 2015).

5.1 Comparative Strategies across Regions

Policy stability and long-term visibility as a key success factor.

Regions with rapid solar growth typically provide long-term policy clarity through stable incentive programs, predictable procurement schedules, and consistent grid access rules. Policy volatility, on the other hand, creates investment uncertainty, increases financing costs, and delays project pipelines.

Competitive auctions and large-scale procurement.

Many markets have achieved rapid utility-scale solar expansion through competitive auctions with transparent rules and bankable power purchase agreements. Auctions reduce costs and attract private capital, but their success depends on reliable contract enforcement, clear permitting processes, and defined grid interconnection responsibilities.

Distributed generation support in cities and commercial sectors.

Urban solar growth is strongly linked to enabling policies for distributed generation, including streamlined permitting, building code support, and fair compensation mechanisms. Regions that support commercial rooftop PV often implement net billing or self-consumption incentives that align economics with actual building load profiles (Kibert, 2016).

Corporate and private-sector procurement pathways.

In markets with mature electricity frameworks, corporate power purchase agreements and third-party ownership models have accelerated deployment. These mechanisms allow private developers and large commercial electricity consumers to adopt solar PV without relying solely on government subsidies.

5.2 Best Practices for Large-Scale Real Estate and Urban Projects

1. Integrate solar requirements into building codes and permitting.

One of the most effective strategies for increasing solar PV adoption in commercial developments is embedding renewable readiness or PV inclusion into building codes. This ensures early-stage integration, optimizes design choices, and reduces retrofitting costs.

2. Streamline urban permitting and interconnection.

Cities that simplify approval pathways, reduce bureaucratic steps, and provide clear interconnection timelines tend to see faster commercial PV deployment. For mall developments, streamlined permitting reduces construction delays and supports predictable project delivery.

3. Promote self-consumption oriented tariff structures.

Policies that reward self-consumption, rather than depending heavily on export tariffs, support more sustainable market growth for commercial buildings. Large malls often have daytime demand, making self-consumption a particularly effective deployment strategy.

4. Encourage storage and smart grid readiness.

Regions that support storage adoption and grid modernization can integrate higher shares of solar PV without compromising reliability. Incentives for storage, demand response, and smart meters improve solar value and reduce curtailment risk.

5. Ensure transparent procurement and bankable contracts.

For large-scale projects, procurement mechanisms must be transparent, with clear risk allocation and enforceable long-term contracts. Bankable power purchase agreements reduce financing costs and support scaling of solar infrastructure in both utility and commercial contexts.

5.3 Transferable Lessons for Commercial and Urban Solar Adoption

The following are the main conclusions from the analysis across all regions. The first conclusion is that investors require both regulatory clarity and policy stability in order to establish their trust in the investment market and therefore sustain the growth of the market. The second conclusion is that for large-scale adoption to occur, the policies adopted by government must be aligned with the capabilities of the grid systems (including but not limited to interconnectivity rules and operational flexibilities) (Wall et al., 2012) The third conclusion is that the early adoption of solar photovoltaics will increase through policy incentives that provide developers and owners with an economic incentive to include the use of solar PV into the building design and development process at the earliest possible stage; promote self-consumption economics and provide incentives to invest in enabling technology such as energy storage and digital energy management.

Incorporating these conclusions into the implementation of strategies for large-scale commercial and urban real estate projects (such as shopping malls or mixed-use urban development projects) results in specific actions that can be taken to ensure that the solar PV becomes a central element to achieving sustainable development in commercial and urban infrastructure (Hernandez et al., 2014). These include, but are not limited to, incorporating solar PV into the design and delivery process of new construction projects; utilizing business models that minimize the amount of upfront capital required to install solar PV and utilizing solar PV configurations that are optimized based upon available incentives and grid operating conditions.

6. Future Outlook and Strategic Recommendations

Large scale solar energy has the potential to make a significant contribution to achieving the United Nations' Sustainable Development Goals (SDGs). The growth of solar energy is being driven by several factors, including the need to reduce greenhouse gas emissions, the rapid pace of technological improvements in solar panels and inverters, and the increasing demand for green and sustainable infrastructure (Del Río & Mir-Artigues, 2012).

The challenges related to deploying large-scale solar energy have shifted from technical feasibility to implementing the technology, ensuring effective governance, and integrating it into existing energy systems. Therefore, large-scale solar energy is expected to provide a number of benefits for sustainable development, including supporting low-carbon electricity generation, enhancing energy security, and providing resilient urban and commercial infrastructure.

One of the key emerging trends in the large-scale solar energy market is the greater integration of solar photovoltaic (PV) systems with energy storage systems. Solar-plus-storage solutions enable load-shifting and peak demand reduction as well as provide improved reliability through the ability to store excess energy generated during the day for use at night or during periods when solar radiation is lower than average. This trend is particularly relevant for large commercial buildings and shopping centers, where electrical demand can extend into evening hours.

As the cost of energy storage continues to decrease and regulatory frameworks evolve to recognize the economic value of energy storage, hybrid solar-plus-storage systems are likely to become a common feature of all large-scale solar deployments.

There are now many new investment opportunities in large-scale solar energy across multiple segments, including utility scale solar projects, commercial rooftop solar installations and urban renewable energy infrastructure (Couture et al., 2019) Long-term power purchase agreements, third party ownership models and corporate purchasing arrangements for renewable energy are each helping to create new financing options for large-scale solar projects by decreasing financial risk associated with uncertain revenues.

For real estate developers, incorporating large-scale solar energy into their project development processes may help increase the value of their assets, reduce operating expenses and support the ability of their clients to meet the growing expectation for sustainable and environmentally friendly products and services.

Effective governance will be essential for promoting the widespread adoption of solar energy while maintaining the reliability of electric grids and preserving the environment. Effective governance requires stable regulatory environments, clear and transparent interconnection processes, and reasonable timeframes for obtaining permits and approvals. Establishing these types of governance environments will be crucial for creating an investment climate that supports the development and deployment of large-scale solar energy projects.

In urban areas, aligning solar policy with local building codes and zoning ordinances as well as with regional and national development plans will help to ensure that renewable energy is integrated into the design process at the earliest possible stage of development, thereby avoiding unnecessary retrofitting costs and time-consuming deployment delays.

To strategically advance solar energy adoption, both government agencies and private sector companies should focus on developing solar energy capabilities in large commercial and urban settings where there is a high level of demand for electricity and/or abundant underutilized surface area (de Wild-Scholten, 2013) To optimize self-consumption and operational resilience, combining solar PV with smart energy management systems and/or energy storage systems can help maximize the amount of solar-generated electricity consumed within the premises of the building. Additionally, investments in grid modernization, including advanced inverters and digital control systems, will be necessary to ensure that electric distribution systems can support increased levels of solar penetration.

Ultimately, future success will depend on adopting circular economy principles, responsible sourcing of materials, and effective end-of-life management for solar technology. By pairing technological innovation with supportive governance and forward-thinking investment strategies,

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the development and deployment of large-scale solar energy has the potential to grow and continue making a meaningful contribution to the achievement of SDG's.

Conclusion

The large scale adoption of solar energy offers a great deal of potential for environmental sustainability, economic development, and operational improvements to energy systems, commercial buildings and urban infrastructure. The purpose of this paper was to review the major technological, infrastructural, and institutional factors which determine the rate of adoption of solar energy; with particular attention to the major obstacles to increasing the scale of the deployment of solar photovoltaic (PV) systems, as well as the opportunities that exist for overcoming them. While issues related to the intermittency of solar power, its connection to the grid, spatial limitations on where it may be deployed, and the long-term reliability of PV systems continue to represent important challenges to widespread adoption, they are increasingly capable of being overcome by advances in the design of PV systems, the incorporation of energy storage into PV systems, and the use of digital energy management systems.

This study's examination of the roles of policy and regulatory frameworks for promoting the widespread adoption of solar energy suggests that stable, consistent, and well coordinated governance arrangements play a significant role in determining the success of such efforts. At the international level, national incentives, local government plans and other elements of governance arrangements at all levels of jurisdiction have the ability to shape investor confidence in solar energy investments, the speed of their deployment, and the performance of the systems deployed. The comparison of the policy experiences of different jurisdictions reveals that countries whose governments have established long term policy clarity regarding the promotion of solar energy, have streamlined permitting processes, and have established clear guidelines for accessing the electric grid have achieved higher rates of solar penetration than those that do not.

For shopping centers, large commercial properties, and urban developments, the integration of solar PV into building design and construction from the outset provides the greatest potential for achieving environmental and financial objectives. In addition to providing a source of clean renewable energy, solar PV technology also presents an opportunity to develop new business models and operating strategies that provide additional sources of revenue, enhance asset values and create new forms of employment.

Continued decline in costs of solar PV technology, the increased availability of hybrid solar-plus-storage technologies, advancements in digital technologies and the emergence of the principles of a circular economy will all contribute to making solar energy a larger part of the strategy for achieving environmentally sustainable development. As has been demonstrated in a number of jurisdictions around the world, the combination of technological innovation, supportive public policies, effective governance, and thoughtful planning in the development of the built environment can accelerate the widespread adoption of solar energy, while creating a more sustainable future for our cities and commercial spaces.

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