

# Comprehensive Assessment of Land Requirements for 100% Solar Energy Transition in Smart Cities

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**Abstract.** Navigating towards a sustainable future, this paper meticulously reviews diverse studies, exploring the intricate dynamics of transitioning to 100% solar energy in smart cities, whilst particularly scrutinising land requirements. The studies, set against varied geographical and socio-economic backdrops, delve into the technical and economic feasibility, alongside environmental repercussions of a wholesale shift towards renewable energy in urban environments. For example, a detailed exploration of Delhi's multi-sectoral energy transition pathway unveils potential in slashing primary energy and costs, mitigating greenhouse gas emissions, and bolstering the energy job sector. Another study elucidates a methodology for crafting Smart Energy Cities, exemplified by Aalborg's transition within Denmark's 100% renewable energy framework. Additionally, an examination of the economic and environmental performance of renewable energy systems in diverse Chinese residential communities highlights the predominance of solar energy and biomass, revealing disparities in investment recovery and emission reductions. Collectively, these studies illuminate the multifaceted aspects of renewable energy transitions in urban contexts, steering towards a globally sustainable, efficient, and secure energy future.

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## 1 Introduction

Navigating the path towards a sustainable future, the role of cities as epicentres of energy consumption and greenhouse gas emissions cannot be understated. The transition to renewable energy, particularly in urban settings, has become a focal point in global discussions and policy-making. Cities, with their burgeoning populations and economic activities, are pivotal in steering the direction towards a more sustainable energy future. The studies under review provide a multifaceted exploration into the technical, economic, and environmental aspects of transitioning to 100% renewable energy systems in various urban contexts, offering a comprehensive understanding of the myriad challenges and opportunities that such transitions present.

Urbanisation, a defining phenomenon of our times, has seen cities emerge as key players in propelling sustainable development. With the continuous growth of urban populations and the subsequent rise in energy demand and emissions, the role of megacities in the renewable energy transition is particularly noteworthy. The exploration of renewable energy transition pathways, especially in megacities within developing regions, presents a complex yet vital area of study, offering insights into the challenges and opportunities inherent in steering such transitions.

However, the journey towards a comprehensive renewable energy transition is fraught with complexities. While numerous cities and nations have set ambitious targets to transition towards renewable energy, the actualisation of these goals is often impeded by a variety of socio-economic and technical factors. The delicate balance required in these transitions, especially in contexts where there is a heavy reliance on fossil fuels, underscores the importance of meticulous planning and strategic implementation of energy transition pathways.

Local strategies for renewable energy transition must be developed with a broader, more inclusive perspective, ensuring they align and synergise effectively with national and global energy systems. While numerous cities have embarked on crafting strategies for renewable energy transition, a common challenge is ensuring these strategies are in harmony with larger, overarching energy systems. This paper seeks to weave through these complexities, providing a holistic exploration of transitioning to 100% solar energy in smart cities, by reviewing and synthesising insights from various studies across different geographical and socio-economic contexts.

## 2 Navigating the Landscape: A Closer Look at Land Requirements for Solar Energy Deployment

Solar energy, hailed as one of the most promising renewable energy sources, is not without its challenges, and one of the primary concerns is the land requirement for its infrastructure. As the world pivots towards sustainable energy solutions, understanding the spatial footprint of these technologies becomes paramount. The "Solar Future" document delves deep into the intricacies of land requirements for solar energy deployment, offering insights into the acreage needed for both utility-scale photovoltaic (PV) and concentrated solar power (CSP) installations. While the potential of solar energy is vast, its deployment necessitates a significant amount of land, which can have implications for ecosystems, local

communities, and other land uses. The document underscores the importance of optimizing land use, exploring disturbed and contaminated lands as viable options, and understanding the trade-offs and benefits of solar infrastructure placement. As solar energy continues its trajectory of growth, these land considerations will play a pivotal role in shaping its sustainable and harmonious integration into our landscapes [4].

## 2.1 General Land Requirements:

- **Utility-scale PV (UPV) and distributed utility-scale PV (DUPV):** These are assumed to require approximately 7.5 acres per installed MW.
- **CSP solar facilities:** Assumed to require approximately 10 acres per installed MW.
- The total U.S. solar development area is about 10.3 million acres by 2050 in the Decarb+E scenario, which has the highest land-use.
- In 2050, ground-based solar technologies require a maximum land area equivalent to 0.5% of the contiguous U.S. surface area.
- The maximum solar land area required is equivalent to less than 10% of potentially suitable disturbed lands.
- Ground-based solar energy is not expected to exceed 5% of any state's land area, with the exception of Rhode Island (6.5%).

## 2.2 Specific Land Requirements Context:

- **2030:** PV will require 3,577,622 acres, which is 2.2% of the total, and CSP will require 18,879 acres, which is less than 0.01% of the total. 39.9% of the land for PV will be contaminated lands.
- **2040:** PV will require 7,437,108 acres (4.5% of the total, 83.0% contaminated lands) and CSP will require 22,017 acres (0.1% of the total, 1.4% contaminated lands).
- **2050:** PV will require 10,291,802 acres (6.2% of the total, 114.9% contaminated lands) and CSP will require 53,280 acres (0.2% of the total, 3.4% contaminated lands).

## 2.3 Mitigation and Alternatives:

- The document suggests that the land requirement could be met using less than 10% of potentially suitable disturbed lands, thus avoiding conflicts with high-value lands in current use.
- Various approaches are available to mitigate impacts on local communities, ecosystems, and agricultural areas.
- Increased efficiency of solar technologies would reduce land requirements.
- Use of non-land-based technologies, such as floating systems or solar cells incorporated into the sides of buildings, could also reduce land requirements.

## 2.4 Additional Notes:

- The document also discusses the potential suitability of contaminated sites for solar development, evaluated using data provided by EPA's Re-Powering America's Land screening tool.

- Siting a financially attractive project in an area without other productive land use opportunities could improve temporary and permanent local economic conditions.
- The life cycle land-use impacts of solar development, including the impacts of mining minerals used in solar technologies, are not well understood.

In conclusion, the land requirements for solar energy deployment present both challenges and opportunities. The "Solar Future" document underscores that while the spatial footprint of solar installations is undeniable, strategic and thoughtful planning can mitigate potential conflicts with existing land uses. By leveraging disturbed and contaminated lands, we can harness solar energy without compromising high-value lands or ecosystems. Moreover, advancements in solar technology efficiency and the exploration of alternative installation methods, such as floating systems, offer promising avenues to reduce land dependencies. As the world continues its transition to renewable energy, it's imperative to approach solar energy deployment with a holistic view, ensuring that land use considerations are at the forefront of decision-making, fostering a sustainable coexistence between our energy needs and the preservation of our landscapes.

### 3 Smart Energy Cities in a 100% Renewable Energy Context

In the face of global climate change and the urgent need to reduce carbon emissions, the transition to renewable energy has become a paramount concern. Various studies have delved into the potential, challenges, and strategies associated with this transition. From exploring the vast potential of solar energy to understanding the role of cities in the renewable energy landscape, researchers are paving the way for a sustainable future.

#### 3.1 Smart Energy Cities in a 100% Renewable Energy Context [2]

The transition towards renewable energy is a global endeavour, with cities and municipalities playing a pivotal role in shaping sustainable futures. The study by Thellufsen et al. (2020) emphasizes the importance of smart energy cities in a 100% renewable energy context, highlighting the necessity to align local strategies with national and global perspectives. The study presents a methodology to design Smart Energy Cities, ensuring they fit within a broader renewable energy context. This approach is not only applicable to the case study of Aalborg, Denmark, but is also framed to be relevant to other global cases, ensuring that local actions do not hinder but rather complement global and national efforts towards a sustainable future [8-10].

##### **Key Points:**

1. **Local and Global Alignment:** The study underscores the importance of cities and municipalities acting locally but acknowledging the national and global context, especially concerning resources, industry, and transport.
2. **Methodology for Transition:** A methodology is presented to transition municipalities like Aalborg to a 100% renewable smart energy system, ensuring compatibility with Danish and European energy systems.
3. **Addressing Challenges:** The study identifies challenges related to defining needs and available resources and proposes a set of principles to ensure that local solutions do not conflict with global strategies.
4. **Guiding Principle:** The principle is that local action should be balanced to match national or global action, ensuring that local strategies are not designed for an isolated energy island but instead form an integral part of the national and global strategies.

5. **Biomass Utilization:** Aalborg's share of Denmark's total biomass resources in 2050 is considered, ensuring that the available biomass is within the limits of sustainable use, preferably focusing on residual sources.

Thellufsen et al. (2020) delve into the intricate balance required between local actions and global impacts in the transition towards renewable energy. The study is not just a blueprint for creating a renewable energy strategy for a city but also a reflection on how local actions can be harmonized with global strategies. The emphasis on utilizing local resources, such as biomass sustainably and considering the broader impacts on national and global scales, is particularly noteworthy. The methodology and guiding principles presented provide a structured approach for cities to navigate their transition to renewable energy while being mindful of the larger, interconnected energy ecosystem

### 3.2 Energy Transition in Megacities: A Case for Delhi [1]

Ram et al. (2022) embark on a pioneering exploration into the technical feasibility and economic viability of transitioning to 100% renewable energy systems in a global megacity, specifically focusing on Delhi within the North Indian grid region. The research is groundbreaking in its approach, presenting a multi-sectoral, multi-regional, and cost-optimal energy transition pathway for Delhi, a significant hub within the regional energy system. The study not only provides a snapshot of the current and future energy landscapes but also discusses various aspects of an energy transition pathway that could pave the way towards an affordable, efficient, sustainable, and secure energy future for megacities globally.

#### Results and Discussion [5-7]:

- The research explores the technical feasibility and economic viability of transitioning towards 100% renewable energy systems, encompassing power, heat, transport, and desalination sectors, for a global megacity like Delhi within the North Indian grid region.
- The study presents a technology-rich, multi-sectoral, multi-regional, and cost-optimal energy transition pathway for Delhi, positioning it as a hub within the regional energy system.
- The findings indicate that a megacity like Delhi can not only benefit from but also drive a regional energy transition, achieving over 40% reduction in primary energy, over 25% reduction in energy costs, and significant reductions in greenhouse gas emissions, air pollution, and associated health costs.
- The transition also has the potential to create more than three times the number of direct energy jobs across North India and Delhi.

#### Conclusion:

- The research provides insights into the current and future energy landscapes, discussing various aspects of an energy transition pathway that could lead to an affordable, efficient, sustainable, and secure energy future for megacities globally.
- The case of Delhi within the North Indian grid offers snapshots and discussions on several aspects of an energy transition pathway that could guide other global megacities towards a sustainable energy future.

**Table 1.** Key Data from the Study by Ram et al. (2022)

Aspect	Current	Transition	Impact on	Impact on	Job Creation
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	Status	Pathway	Energy Costs	Emissions	Potential
Primary Energy Reduction	-	Over 40%	-	-	-
Energy Cost Reduction	-	Over 25%	Positive	-	-
Greenhouse Gas Emissions	High	Significant Reduction	-	Positive	-
Air Pollution and Health Costs	High	Significant Reduction	-	Positive	-
Direct Energy Jobs	Current Level	More than 3x	-	-	Positive

The study by Ram et al. (2022) provides a comprehensive and detailed insight into the potential pathways through which a megacity, such as Delhi, can navigate towards a 100% renewable energy transition, considering various sectors including power, heat, transport, and desalination. The research underscores the pivotal role that megacities like Delhi can play in driving a regional energy transition, highlighting significant potential benefits such as reductions in primary energy, energy costs, greenhouse gas emissions, and air pollution, along with associated health costs. Moreover, the study illuminates the potential for creating more direct energy jobs, thereby not only contributing to the energy transition but also fostering economic development. This research could serve as a blueprint for other megacities around the world, particularly in developing regions, guiding them towards achieving their renewable energy and sustainability goals.

### 3.3 Exploring Renewable Energy Systems for Residential Communities Across China [3]

In the study conducted by Ling et al. (2021), a meticulous exploration into the design and optimisation of 100% Renewable Energy Systems (RES) for residential communities in various regions of China is presented. The research navigates through the complexities of implementing RES, considering diverse climatic and geographical conditions, and seeks to provide a balanced perspective on the economic and environmental performances of these systems. The study is particularly pivotal in the context of China's ambitious goal to achieve carbon neutrality by 2060 and provides insights that could potentially guide future strategies and investments in the renewable energy sector.

#### Key Findings from the study [11-14]:

- The study aimed to investigate the economic and environmental performance of 100% Renewable Energy Systems (RES) for residential communities across different areas in China.
- 30 typical cities were chosen based on climate characteristics and the availability of renewable energy resources.

- The genetic algorithm was utilized to obtain the optimal design of 100% RES in each area, considering minimum total annual cost and minimum CO<sub>2</sub> emissions as optimization objectives.
- Results indicated that 100% RESs were predominantly powered by solar energy and biomass.
- When optimized for economic performance, investments could be recovered in 8 years in most areas, but the payback period extended when optimized considering environmental performance.
- Emissions could be reduced by 86-99% for CO<sub>2</sub> and 64-97% for NO<sub>x</sub>.

Ling et al. (2021) provide a robust framework for understanding the feasibility and implications of implementing 100% RES in residential communities across various Chinese regions. The study underscores the potential of solar energy and biomass as primary RES power sources and brings to light the economic and environmental trade-offs that come with optimising for either economic or environmental performance. The findings could be instrumental in shaping future policies and investment strategies in China's journey towards achieving its carbon neutrality goal.

## 4 Additional Insights

### 4.1 Land Requirements and Solar Energy Transition

A study published in [Nature](#) provides a detailed analysis of the potential land requirements and related land-use change for solar energy transitions. The study introduces a novel method that dynamically accounts for the land occupation of solar energy, depending on geographical location and year of installation, within an Integrated Assessment Model (IAM) that links energy, land, socioeconomic, and climate systems. The model simulates a range of electricity mix penetration scenarios for solar energy technologies and bioenergy for comparison. The results indicate that land occupation by Utility-Scale Solar Energy (USSE) could range from 0.5 to 2.8% of total territory in the EU, 0.3 to 1.4% in India, and 1.2 to 5.2% in Japan and South-Korea, depending on the penetration rates of solar energy in the electricity mix.

### 4.2 Vulnerabilities and Limits in Solar Energy Transition

Another study titled "Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios" which can be found [here](#) and [here](#), explores the land-use requirements associated with a transition to a 100% solar-powered economy. The study indicates that this transition may be physically unfeasible for countries like Japan and most of the EU-27 member states due to the extensive land-use requirements. This could be a pivotal point to explore, especially in the context of smart cities where land use is a critical factor.

### 4.3 Harnessing Pedestrian Power in Urban Areas

In the quest for innovative solutions to enhance energy sustainability, particularly in urban environments, some intriguing advancements have been made in the realm of pedestrian

power. A notable development in this area is the creation of high-tech tiles that generate energy from human footsteps, which can be placed in various locations, such as indoor spaces or city streets, to harness energy from daily pedestrian traffic ([source](#)).

Moreover, the concept of integrating transparent solar cells into the infrastructure of smart, energy-sustainable buildings is gaining traction. Researchers in South Korea, for instance, have developed a hybrid transparent voltaic (TPVs) device that is not only efficient in generating electricity but also utilizes a unique combination of materials to optimize its energy generation capabilities. This technology can potentially be applied to windows in buildings, contributing to the creation of smart cities by enabling structures to generate their own solar energy. Furthermore, these TPVs have demonstrated the ability to generate electricity even under low-light conditions, such as during cloudy or rainy days, which is crucial for maintaining a consistent energy supply ([source](#)).

In another innovative approach, Japan has witnessed a significant increase in the installed capacity of rooftop solar, jumping from fewer than 5 gigawatts to over 20 gigawatts in the past decade. The nation is also exploring intelligent energy grids to manage the burgeoning adoption of solar cells in urban settings. With a local government mandate that all new dwellings in Tokyo be installed with rooftop solar from 2025, there is a pressing need to revamp how energy in the local and national grid is managed to ensure stability of supply and prevent outages and failures. This involves rethinking the architecture of the grid and establishing new standards for how this new energy mix is distributed and managed ([source](#)).

These instances underscore the potential of integrating innovative technologies into urban planning and development to facilitate the transition towards more sustainable and energy-efficient cities. The incorporation of technologies that leverage pedestrian movement for energy generation, the application of transparent solar cells in building design, and the strategic management of energy grids to accommodate increased solar capacity represent promising avenues for future research and development in the realm of sustainable urban planning. This could potentially fill the knowledge gaps in understanding how to effectively integrate various renewable energy sources into a cohesive and reliable urban energy system.

#### 4.4 Implications

- **Innovative Urban Energy Harvesting:**The incorporation of energy-harvesting tiles and transparent solar cells into urban infrastructure presents a novel avenue for cities to generate their own power. This not only contributes to energy sustainability but also reduces dependency on traditional power grids.
- **Architectural Integration:**The integration of transparent photovoltaic devices into building designs (e.g., windows, facades) necessitates a re-evaluation of architectural and engineering practices to ensure optimal energy generation without compromising aesthetic and functional aspects of structures.
- **Grid Management and Stability:**With the increased adoption of localized energy generation methods, such as rooftop solar installations, there is a critical need to develop intelligent and adaptive energy grid management systems that can handle fluctuating energy inputs and demands, ensuring stability and reliability in energy supply.
- **Policy and Regulation Development:**The implementation of policies that mandate the incorporation of renewable energy technologies in new buildings, as

seen in Tokyo, implies a need for clear guidelines and regulations that can facilitate compliance while also considering economic and social factors.

- **Economic Considerations:**The economic viability and return on investment of implementing technologies like energy-harvesting tiles and transparent solar cells in urban environments need to be thoroughly evaluated, considering factors like installation costs, maintenance, and energy savings.
- **Social and Behavioural Aspects:**Understanding and addressing the social and behavioural aspects related to the adoption of new energy technologies, such as public acceptance, usability, and impact on daily life, are crucial for the successful implementation of these innovations in urban settings.
- **Environmental Impact:**While the adoption of renewable energy technologies aims to reduce environmental impact, it is vital to assess and mitigate any potential negative effects associated with the manufacturing, installation, and operation of these technologies, ensuring a truly sustainable approach.
- **Scalability and Adaptability:**Research into how these innovative technologies can be scaled and adapted to various urban contexts, considering the diverse geographic, climatic, and socio-economic conditions across different cities and regions, is imperative to ensure widespread applicability and effectiveness.
- **Interconnected Energy Networks:**Investigating and developing interconnected energy networks that allow for the sharing and distribution of locally generated energy between different urban areas could enhance energy security and provide a buffer during periods of low energy generation.
- **Technological Advancements and Research:**Continuous research and development into improving the efficiency, durability, and cost-effectiveness of renewable energy technologies, such as enhancing the energy conversion rates of transparent solar cells or increasing the durability of energy-harvesting tiles, are vital for ensuring the long-term success of these initiatives.

In light of these implications, future research and development in the realm of urban energy sustainability could explore the multifaceted challenges and opportunities presented by the integration of innovative energy technologies into our cities. This involves a holistic approach that considers technological, economic, social, and environmental aspects, ensuring that the transition towards sustainable urban energy systems is not only feasible and efficient but also inclusive and equitable.

## 5 Future Scope of Research

Navigating through the intricate pathways towards fully embracing renewable energy in urban landscapes has opened a myriad of possibilities for further exploration. The multifaceted nature of energy shifts, particularly within the bustling and varied terrains of global megacities, unveils a rich domain where additional research can interweave further insights, strategies, and innovations, fortifying the journey towards sustainable urban futures.

### Key Points:

- **Exploring Regional Dynamics:** Investigate the distinct challenges and opportunities presented by various geographical and climatic conditions across different regions.

- **Impact on Society and Economy:** Delve into the socio-economic repercussions of adopting a complete renewable energy model in megacities, focusing on aspects like employment, economic development, and social equality.
- **Policy and Governance Insights:** Research the role of policy-making, governance structures, and regulatory frameworks in either facilitating or impeding the transition to a fully renewable energy model in diverse urban contexts.
- **Innovation and Technology:** Investigate the potential of emerging technologies and innovations in enhancing the efficiency and reliability of renewable energy systems in urban settings.
- **Engaging Communities and Stakeholders:** Explore the role of community participation, public perception, and stakeholder engagement in shaping and propelling the renewable energy transition in cities.
- **Strategic Urban Planning:** Investigate how urban planning and design strategies can be optimised to facilitate more effective renewable energy transitions, considering aspects like spatial organisation, infrastructure development, and resource distribution.

## 6 Knowledge Gaps

While the existing research provides invaluable insights into the pathways towards fully embracing renewable energy in urban contexts, several knowledge gaps remain, calling for further exploration. These gaps, spanning various dimensions from technological to socio-economic and policy-oriented aspects, present opportunities for deeper inquiry, enabling a more nuanced understanding and strategy formulation for renewable energy transitions in megacities and urban environments.

### Key Points:

- **Analysis of Interlinked Systems:** A profound understanding of how various energy systems (power, heat, transport, etc.) interact and can be optimally integrated in a megacity context is vital.
- **Detailed Data and Local Studies:** A need for more detailed data and localised studies that delve into the specificities of different urban contexts, considering local resources, demands, and challenges.
- **Cultural and Behavioural Exploration:** Investigate how cultural and behavioural aspects influence the adoption and integration of renewable energy technologies and practices in different urban environments.
- **Solution Scalability:** Investigate the scalability of proposed renewable energy solutions and strategies from case studies and pilot projects to wider urban and regional contexts.
- **System Resilience and Reliability:** Explore the resilience and reliability of fully renewable energy systems in megacities, especially in the face of growing urbanisation, climate change impacts, and other potential disruptions.
- **Comprehensive Sustainability Assessment:** Understanding the comprehensive sustainability of renewable energy transitions, considering not just the environmental, but also the social and economic sustainability, is crucial.
- **Harmonising Global and Local Dynamics:** More research is needed into how local renewable energy strategies can be aligned and harmonised with broader national and global energy perspectives and policies.

These pointers for future research and identified knowledge gaps could serve as a foundation for further studies, enabling a more comprehensive, nuanced, and effective approach towards understanding and facilitating renewable energy transitions in megacities and urban environments globally.

## 7 Conclusion

Embarking on a journey to thoroughly explore the prerequisites for a full transition to solar energy within intelligent urban environments has unveiled a myriad of insights and potential pathways, intertwining technological, economic, and environmental aspects. Through a detailed review of various studies, we have traversed through different geographical and socio-economic landscapes, exploring the complex nature of energy transitions in urban settings. The following key findings emerge as crucial in shaping the discourse and future trajectories of implementing complete solar energy systems in intelligent urban landscapes:

- **Technical and Economic Aspects:**The studies underscored the technical feasibility and economic viability of adopting comprehensive solar energy solutions in major urban areas, such as Delhi, revealing possibilities for substantial reductions in primary energy, costs, and greenhouse gas emissions.
- **Inclusive, Multi-Sectoral Strategies:**An inclusive, multi-sectoral strategy that envelops power, heat, transport, and desalination sectors is vital to sculpt effective and sustainable energy transition pathways, ensuring all aspects of urban energy demand are comprehensively addressed.
- **Alignment of Local and Global Strategies:**Ensuring local energy strategies are in harmony with national and global contexts is pivotal, ensuring cities act with regard to local demands but also align their strategies with broader, interconnected energy systems.
- **Impact of Geographical and Climatic Conditions:**The design and operation of comprehensive solar energy solutions are significantly influenced by geographical and climatic conditions, necessitating strategies and technologies that are optimally suited to the specific conditions of different areas.
- **Significance of Policy and Regulation:**The crucial role of policy and regulation frameworks in facilitating and guiding the transition towards complete solar energy solutions in urban settings has been highlighted, indicating the need for clear, supportive, and actionable policies.
- **Adoption of Innovative Technologies:**Integrating innovative technologies, such as transparent solar cells and energy-harvesting tiles, into urban infrastructures presents a novel avenue for enhancing localised energy generation, with considerations for architectural, economic, and social aspects.

These findings weave into our discourse, elucidating that the pathway towards a full solar energy transition in intelligent urban environments is not linear but a dynamic, multi-dimensional endeavour that requires a harmonious blend of technological, economic, social, and environmental elements. The insights from the reviewed studies not only illuminate the possibilities but also the complexities and challenges that lie ahead, offering a nuanced perspective that can inform, guide, and inspire future research, policy-making, and practice in the realm of sustainable urban energy transitions. This seamlessly aligns with our initial abstract, subtly echoing the imperative for a comprehensive, multi-faceted exploration and

assessment of land requirements and strategies for actualising a full solar energy transition in our vibrant, pulsating urban entities.

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