**Chunk 1:** Life on earth is heliocentric as most of its energy is derived from the sun. Climate change and the demand for clean energy sources have aroused global interest in solar energy: the cleanest and most abundant renewable energy source available. Photovoltaic technology is a major sustainable means to produce electrical energy. PV like any solar technology offers an opportunity to exploit the dispersed nature of solar energy and to create a spatially distributed system for electricity production. PV power plants are being increasingly used around the world. There is a need for a manual for successful installation of PV panels. This book fulfills it. The 10 chapters provide details for everything necessary for success in the task of installing a PV system including legal and marketing questions.

**Chunk 2:** Photovoltaics started in 1839 but a new range of possibilities emerged in 1954 when Bell laboratories created the silicon solar cell. The light absorption capacity of silicon is low yet it is the most sought after material for preparing a solar cell because it is the second most abundant element on earth after oxygen. Solar cells are available with efficiency ranging from 10 to 20 per cent. The efficiency is determined by the position of the PV module. Any kind of shading whether direct (antenna adjacent tall building) or self-shading can reduce the annual yield of a PV module between 5 and 10%. Therefore, detailed shading analysis, manual or digital, needs to be done before installing a PV module.

**Chunk 3:** Besides shading factors like location and month deviation from horizontal and ambient temperature can influence the solar irradiance. Solar irradiance is the power generated from incident solar radiation per unit area on the earth’s surface, which directly controls the amount of electricity generated by a PV module. For example, if the temperature of a PV array increases relative to the ambient temperature, that would reduce the energy yield of that particular PV array. The highest energy yield of a PV array is attained when there is optimum inclination.

**Chunk 4:** Accuracy of any forecast depends upon the programming method used in the program. Calculation Programs like NSol! and PV-kalk mainly based on statistical methods are application-oriented and deliver quick results. On the other hand, time-step simulation programs such as Archelios Pro and DASTPVPS use models to predict systems’ behavior based on time series of meteorological input data. Time-step simulation programs are considerably more flexible than calculation programs.

**Chunk 5:** PV panels can be installed on the roof of a single household for its own consumption, or an array can be mounted on the ground. In each case, the process of installation including choice of cables, junction box, inverters, and protective devices will be different. The book provides a model checklist that any PV installer needs to prepare before a client meeting.

**Chunk 1 (Introduction):** Solar power generation is a useful substitute for non-renewable power generation. Singapore has high solar irradiance levels, making it a strong candidate for solar energy generation. The installed capacity of solar PV systems in Singapore has seen significant growth, and while natural gas remains the primary power source, the government has initiated the installation of solar panels on Housing and Development Board (HDB) building rooftops. There is potential to maximize solar generation not only through rooftop PV systems but also integrating into façades of HDB buildings; this would contribute to Singapore's goal of reducing dependence on natural gas.

**Chunk 2 (Background on Solar PV in HDB):** Approximately 1 million flats across 24 towns accommodate 80% of Singapore's population in HDB buildings. The HDB Green Town initiative aims to make these towns more livable and sustainable by 2030. This involves reducing energy consumption, recycling rainwater, and cooling HDB towns. Covered linkways, which provide pedestrian circulation, were initiated by the Land Transport Authority (LTA) to enhance walking experiences. These linkways with horizontal roofs offer an opportunity for installing solar PV panels, which aligns with Singapore's walking and cycling design guide.

**Chunk 3 (Introduction to Research Study):** This research conducted an economic analysis of the potential for applying PV panels to HDB's covered linkways. The study aims to propose a grid-connected solar PV system tailored for this specific use. For a broader context, the paper includes a literature review on solar panel technology, environmental benefits, and an overview of the global PV market. The paper's structure provides a clear roadmap, from the introduction of solar PV in covered linkways in Singapore to the calculations of power generation and cost implications, ending with discussions and conclusions.

**Chunk 4 (Off-grid and Grid-Connected PV Systems):** Off-grid solar PV systems, also known as standalone systems, can function without relying on the grid. Therefore, a storage battery is needed. During the initial design, PV and batteries should be properly sized for efficiency. Additional energy generated when the load is low charges the battery, but improper charging control that results in overcharging can decrease the system's service time and storage capacity. Off-grid systems provide the opportunity to store energy and are expandable as per energy requirements, however, they also involve additional costs for purchasing, maintaining, and replacing batteries.

**Chunk 5 (PV Systems on Building Structures):** Solar PV systems can be mounted on facades or rooftops of buildings, with the latter being more popular. There are potential applications for roof-mounted systems. For example, vacuum-based PV thermal collectors can produce both electrical and thermal energy efficiently while minimizing heat loss. Furthermore, solar PV systems can be combined with other energy sources like wind turbines and fuel cells, utilizing artificial ecosystem optimization to improve performance and system cost and accuracy. They can also be integrated into transmission networks with thermal, hydro, and wind systems to optimize power flow while considering the uncertainty of solar radiation and wind speed.

**Chunk 6 (Non-Quantifiable Environmental Benefits of Solar PV):** Solar PV systems not only offer financial benefits but also significant environmental benefits. They promote the use of clean energy and reduce the reliance on traditional fossil fuels, which have negative environmental impacts such as air pollution and global warming. Due to its high modularity, no additional resource requirement, and low maintenance, solar PV systems are becoming increasingly popular. In Singapore, a tropical urban city/country, producing clean energy at the point of consumption could significantly improve the environmental, economic, and social aspects of urban sustainability and reduce transmission losses.

**Chunk 7 (Challenges and Quality of Solar PV Systems):** Although solar PV technology provides many benefits in Singapore, challenges related to the transition and implementation process are present due to technical, social, and economic factors. The build quality of solar PV systems is essential for high performance. From an economic perspective, solar PV implementation is influenced by the balance between electricity prices and the upfront cost of solar power. Additionally, weather conditions such as cloud cover and urban shading issues affect the application of solar PV systems in Singapore.

**Chunk 8 (PV Market Worldwide and Singapore's SolarNova Programme):** The global use of solar PV has grown significantly, with an exponential increase in installations over the last decade. China is the leader in cumulative PV capacity, followed by the European Union, USA, Japan, and India. In Asia, while established markets like Japan, China, Taiwan, Korea, and Malaysia show steady development, other markets such as Singapore, Thailand, Indonesia, and the Philippines have seen inconsistent growth. Singapore itself has installed 329.3 MW of solar PV capacity, and the capacity of grid-connected solar PV systems has increased to 350 MWp from 10.1 MWp during 2012 to 2020. The Singapore government has initiated the SolarNova Programme to install solar panels on HDB rooftops as part of its efforts towards a more sustainable future.

**Chunk 9 (Economic Analysis - Payback Period):** When evaluating the economic implications of different system sizes for solar PV installations, it's crucial to consider the payback period. This research identifies that while higher capacity systems (like a 20 kW system) may lead to substantial savings due to higher power generation, they also come with significantly higher initial costs. As electricity tariffs increase, the payback period of these larger systems shortens due to increased savings; however, the initial investment may still deter some potential investors. For covered linkways, finding the balance between system capacity and initial cost is key to optimize the payback period and overall financial benefits.

**Chunk 10 (Discussion - Application of PV in Compact Urban Environments):** Introducing solar PV to HDB’s covered linkways presents a novel and potentially influential approach within the context of Singapore's dense urban landscape. Larger system sizes offer greater energy generation but also bring increased initial and installation costs, which can be a barrier. Nonetheless, technological advancements and the decreasing cost of PV systems may mitigate this issue, leading to more widespread adoption. Moreover, aligning system capacity with energy savings and considering various incentive schemes can enhance the attractiveness of installing PV panels on HDB linkways.

**Chunk 11 (Incentive Schemes and Environmental Benefits):** Singapore's SolarNova programme and other initiatives like electricity buyback schemes support the integration of solar power generation. High-capacity systems can generate excess energy, enabling consumers to benefit financially from selling back to the grid. Similar schemes in Australia and Malaysia incentivize solar PV use and encourage the reduction of greenhouse gases. The consideration of carbon footprint when choosing PV technologies, such as opting for thin film CIGS, also adds environmental advantages to the implementation of solar PV in Singapore's HDB linkways.

**Chunk 12 (Study Summary and Key Findings):** The study concludes with several key findings for viable solar PV systems in HDB linkways in Singapore. An increase in system capacity translates to higher cost savings, although initial costs remain a challenge. With the significant price drop in crystalline silicon modules between 2009 and 2021, the potential for economic gains in the future by implementing solar PV systems in urban environments is promising.

The research presents a grid-connected solar PV system adapted for HDB linkways in Singapore, including an economic analysis to identify the most economically viable option with system sizes ranging from 4 kW to 20 kW. The analysis revealed that the systems with capacities of 4 kW, 5 kW, and 10 kW could not cover the entire electricity demand yearly, but the 10 kW capacity could meet a significant portion of it. It also found that as the electricity tariff increases, the high power generation solar PV systems become more cost-effective. The paper concludes by emphasizing the environmental benefits of solar PV system adoption in reducing CO2 emissions and promoting a more sustainable built environment.

**Chunk 14 (Further Research Directions and Limitations):** The paper suggests that future research should quantify the environmental benefits and provide a detailed study about solar PV in HDB linkways. It mentions the possible extension of economic analysis using additional methods such as net present value, internal rate of return, and profitability index. Furthermore, it calls for sensitivity analysis to investigate the influence of several factors simultaneously.

**Chunk 1:** PV modules should be free from shade. Shading of any single cell of a crystalline silicon PV module will drastically reduce the output of the entire PV module. Thin-film PV modules are more tolerant to partial shading than crystalline silicon PV modules. Typical culprits include shadows cast by tall trees and neighboring buildings.

**Chunk 2:** Aesthetic and Creative Approaches in Mounting PV Modules: Besides mounting PV modules on the rooftop, customized PV modules can be integrated into the building façade in a creative, aesthetically pleasing manner. They can be mounted on any part of the rooftop or external walls that are well exposed to sunlight, such as skylights, cladding, windows, and external shading devices. They can also be integrated into external structures such as façades and canopies.

**Chunk 3:** Solar PV Output Profile: Solar PV only produces electricity when sunlight is available. The output of a solar PV system varies with its rated output, temperature, weather conditions, and time of the day. The power output profile of a PV installation at a selected test site in Singapore collected over a period from 2002-2004 in terms of its capacity factor shows a high variation of solar PV output.

**Chunk 4:** Solar PV Yield: The amount of electricity you can generate from a solar PV system depends not only on the availability of sunshine but also on the technology you choose to install. For example, a typical 10-kW rooftop solar PV system in Singapore would produce about 11,000 to 12,500 kWh annually using crystalline PV modules and 12,000 to 14,500 kWh annually with amorphous silicon thin-film PV modules.

**Chunk 5:** Cost of a Solar PV System: The cost of your solar PV system will depend on many factors: system configuration, equipment options, labor cost, and financing cost. Prices also vary depending on factors such as whether or not your home is new and whether the PV modules are integrated into the roof or mounted on the roof. The cost also depends on the system size or rating and the amount of electricity it produces.

**Chunk 6:** Therefore, on an overall basis, solar PV-derived electricity is still much more expensive than that from the power grid. However, the cost of solar PV has historically been falling by about 4% a year, and if this continues, solar PV may be competitive within the next 10 years. For incentives on solar PV systems, please refer to Appendix D.

**Chunk 7:** An electrical installation refers to any electrical wiring fitting or apparatus used for the conveyance and control of electricity in any premises. A solar PV system installed within such premises forms part of the consumer’s electrical installation and should comply with the requirements stipulated in the Electricity Act and its regulations, as well as the Singapore Standard CP5 Code of Practice for Electrical Installations.

**Chunk 8:** For non-residential electrical installations with demand exceeding 45 kilo volt ampere (kVA), an electrical installation licence is required from the Energy Market Authority (EMA). For residential installations and non-residential installations with demand below 45kVA, no electrical installation licence is required. The licence mandates that the owner engages a Licensed Electrical Worker (LEW) to take charge of the electrical installation, ensuring safety standards and requirements are met, especially if the solar PV system is to operate in parallel with the power grid.

**Chunk 9:** A grid-connected solar PV system operates in parallel with the power grid supply. The power grid is considered the source, and the electrical installation with the solar PV system connected is viewed as the load. The technical requirement for the installation of a solar PV system is detailed in Section 612 of the Singapore Standard CP5. There are also international product standards that PV modules and electrical components should comply with.

**Chunk 10:** An LEW can advise if there is a need to apply to EMA for an Electrical Installation Licence for the use or operation of the electrical installation at the premises. If required, the LEW will submit the licence application to EMA on behalf of the owner. There is no specific requirement or control by the Urban Redevelopment Authority (URA) on installations like solar PV systems. However, conservation projects or projects within the Central Area are subject to URA’s Urban Design evaluation process.

**Chunk 11:** The standard development control guidelines apply, and architects are advised to refer to URA's guidelines when designing a development with a solar PV system. These guidelines are accessible via URA's website. If there are conflicts with the Urban Design or Development Control guidelines, or if a formal development application is required, queries and applications must be made via a Qualified Person, being a registered architect or engineer.

**Chunk 12:** To ensure safety, measures and steps must be considered when installing a solar PV system onto a new or existing building. For new buildings, the structure's design must account for the loading of the solar PV system. For existing buildings, a professional structural engineer may need to inspect the roof structure and perform calculations to determine if it can withstand the additional load of the solar PV system.

**Chunk 13:** Lightning can pose a threat to solar PV systems and may damage the PV modules and inverters; therefore, proper lightning protection must be provided. Surge arrestors should be installed on both the DC and AC sides, and the structures and PV module frames must be properly grounded to prevent damage from lightning strikes.

**Chunk 14:** A solar PV system designed to supply only a fraction of the electricity load will need to be interconnected with the power grid to meet the remainder of the consumer’s electricity needs. Interconnection is key to the safety of consumers, electrical workers, and to the protection of equipment. LEWs must consult SP PowerGrid (SPPG) on the connection scheme and technical requirements.

**Chunk 15:** Excess electricity generated from a grid-connected solar PV system can be sold back to the power grid. The arrangements to enable this sale depend on whether the consumer is contestable or non-contestable, classified based on average monthly electricity consumption. Contestable consumers are allowed to choose their electricity provider and may sell electricity they generate back to the grid after registering with the Energy Market Company (EMC) to participate in the National Electricity Market of Singapore (NEMS).

**Chunk 16 - Appendix A.1 (Zero Energy Building @ BCA Academy):** The Zero Energy Building at BCA Academy features a diverse array of Solar PV technologies designed for zero-energy and advanced academic research. Different mounting techniques are showcased, and the setup demonstrates a comprehensive study of PV performance in various configurations.

**Chunk 17 - Appendix A.2 (Poh Ern Shih - Temple of Thanksgiving):** Poh Ern Shih, a temple, utilizes solar PV arrays mounted with a standing structure to improve performance due to better ventilation. The solar PV system supplies roughly 25% of the building's electricity demand, showcasing the integration of alternative energy sources in religious buildings.

**Chunk 18 - Appendix A.3 (313 Somerset Central):** Located in the heart of Singapore, 313 Somerset Central's solar photovoltaic system incorporates monocrystalline, polycrystalline, and micromorph PV modules to create an accessible and visible renewable energy installation for the public.

**Chunk 19 - Appendix A.4 (Sentosa Cove):** Sentosa Cove utilizes flexible solar laminates that conform to the roof's curvature, highlighting an innovative, lightweight, and aesthetically pleasing approach to integrating PV technology into luxury residential architecture that complies with strict local guidelines.

**Chunk 20 - Appendix A.5 (Marina Barrage - Incomplete Reference):** Details about Marina Barrage's use of a solar PV system are included but incomplete in the excerpt provided.

**Chunk 1 (Executive Summary – Overview):** Since the previous Solar Photovoltaic (PV) Roadmap for Singapore was published in 2014, significant developments have occurred in the PV sector, including advancements in technologies and economics, industry growth, and changes in deployment methods. The update to the Solar PV Roadmap is pivotal for informing future research directions, government regulations, and private sector investments.

**Chunk 2 (Executive Summary – Key Outcomes):** The study provides enhanced projections of solar energy's technical potential in Singapore, updating baseline and accelerated scenarios for solar capacity by 2030 and 2050. It analyzes the updated net usable area for PV deployment based on 3D modeling and revises technical potential figures. The report also includes critical assessments for grid resilience amid increasing solar deployment and intermittency, suggesting mitigation measures.

**Chunk 3 (Background – Project Aim):** The study was commissioned by relevant government agencies to revise the original PV Roadmap’s assumptions and findings, detailing concrete targets and cost-effective pathways for Singapore's solar deployment. It incorporates expertise from Singapore’s most relevant institutions, with a key objective to tackle unique challenges and leverage opportunities specific to Singapore.

**Chunk 4 (Structure of the Document):** The updated PV Roadmap summarizes recent global PV industry developments and revisits the projections from the 2014 roadmap for Singapore’s market. It updates on space availability, energy yield, levelised cost of electricity (LCOE), deployment scenarios, and grid integration. New topics such as re-powering, recycling, renewable energy certificates (RECs), and importation of solar energy are also discussed.

**Chunk 5 (Global Solar PV Developments):** At the end of the year 2018, the cumulative solar PV installed capacity globally surpassed 500 GWp, reaching 512 GWp. Annual deployment reached 103 GWp in 2018 and was expected to grow to 122 GWp in 2019. The top five countries with the highest cumulative capacity were China, the United States, Japan, Germany, and India.

**Chunk 6 (Forecasting Solar PV Installations):** Annual solar PV installations are expected to rise steadily over the next five years, with estimates differing among industry sources. SERIS projects annual capacity additions will gradually increase to around 151 GWp in 2023.

**Chunk 7 (Reduction in PV Module Costs):** The market growth is aligned with a continual decrease in the cost of PV modules, attributed to advancements in technology, economies of scale, and market dynamics. From 1976 to 2018, the "learning rate" for module price reductions was 23.2%, indicating that average module sales prices reduced by this percentage for every doubling of cumulative PV shipments.

**Chunk 8 (Prices of PV Modules):** At the end of 2019, the average spot prices were around USD 0.19-0.20/Wp for low-cost multi-Si PV modules and USD 0.22/Wp for p-type mono-Si PERC PV modules. Higher efficiency modules, such as n-type mono-PERC, were trading at around USD 0.28-0.32/Wp. It is expected that module prices will continue to decrease, although the rate of decline is difficult to predict due to the development of new, higher-efficiency PV module technologies.

**Chunk 9 (Singapore Solar PV Market):** The cumulative installed capacity of solar PV in Singapore has grown steadily over the past years, as depicted in Figure 4.1. The growth rates vary due to the implementation phases of the SolarNova tenders and contributions from both the public and private sectors. Solar PPAs (power purchase agreements), or "solar leasing," have become a popular contractual arrangement, allowing consumers to purchase electricity from developers usually at a discount while the developer maintains the system for about 20-25 years.

**Chunk 10 (Renewable Energy Certificates - RECs):** Another business model involves purchasing "renewable energy certificates" (RECs), providing consumers without sufficient rooftop space another option to meet their renewable energy needs. RECs are discussed more thoroughly in section 6.3.

**Chunk 11 (Review of Projections from the 2014 PV Roadmap):** The 2014 PV Roadmap projected certain parameters that aligned with expectations, such as solar cell efficiencies and area factors for high-end technologies. However, it also observed deviations, with actual energy yields showing a negative divergence, requiring a focus on promoting higher-yielding technologies in Singapore.

**Chunk 12 (PV Module and System Costs, Adoption Rate):** Positive deviations were noted for PV module and system cost, as well as the levelized cost of electricity (LCOE), benefiting from global reductions in prices and the growing domestic market. A slower than anticipated adoption rate for solar PV was observed, with the actual uptake being lower than the projected figures for 2020. This was partly due to unexpectedly low oil prices during 2016/17 and delays in the SolarNova programme.

**Chunk 13 (Space Availability for PV Deployment - General Considerations):** Singapore aims to transition from a "biophilic City in a Garden" to a "City in Nature," integrating nature into the built environment to enhance citizens' connection with nature and resilience against urbanization and climate change. This vision aligns with the deployment of solar PV systems, ensuring that the expansion of solar energy does not compromise green spaces, biodiversity, or the overall paradigm of greening in Singapore. For instance, when deploying PV on buildings, there are existing and future plans for incorporating greenery, specifically for skyrise greenery. Avoiding PV deployment in sensitive areas like the "Central Catchment Nature Reserve" (CCNR) and Kranji Reservoir also preserves critical habitats for migratory birds and the overall environment.

**Chunk 14 (PV Deployment and Public Acceptance):** Most of Singapore's PV installations are currently on rooftops, making them less visible to the public. As PV installations expand to building facades, reservoirs, and over-arching structures for carparks and walkways, public acceptance becomes increasingly important. It's imperative to engage in dialogue regarding the acceptance of more visible solar energy projects within the community.

**Chunk 15 (Safety Considerations for PV Deployment):** Safety is of utmost importance when deploying solar PV systems, particularly for installations on reservoirs used for recreational activities and infrastructures like roads and noise barriers. Fire safety is also critical for solar PV systems on or close to buildings, ensuring protection for structures and inhabitants.

**Chunk 16 (Rooftop PV - Space Assessment):** The assessment of rooftop potential for solar PV deployment is supported by Singapore Land Authority's 3D city model, encompassing around 132,000 buildings after removing those with very small surface areas. The study applied filtering criteria such as minimum irradiation levels, tilt angles, continuous surface area size, and utilization factors varied by building type, recognizing that not all roof surfaces are suitable for PV deployment due to the presence of equipment, water tanks, and other uses.

**Chunk 17 (Façade PV Deployment Assessment):** The façade potential for solar deployment is based on the detailed 3D city model, which allows for both building-added PV (BAPV) and building-integrated PV (BIPV) options. The façade areas suitable for PV are determined by factors such as minimum irradiation thresholds and continuous surface area size, with a window-to-wall ratio serving as the "surface utilization factor" for rooftops.

**Chunk 18 (Façade Areas for BAPV/BIPV on Existing and New Buildings):** Harvesting the technical potential of existing buildings for BIPV requires retrofit measures best carried out during major addition and alteration works, such as façade renovations or cladding changes. The integration of BAPV/BIPV is easier in new buildings since it can be planned from the design phase, making it more cost-effective and not significantly more expensive than conventional façade cladding.

**Chunk 19 (Mobile/Land-Based PV Systems):** Mobile/land-based PV systems are used on land earmarked for development but currently unused, allowing temporary solar PV deployment. JTC's “SolarLand” program is an example, letting operators bid for land with the expectation of redeploying their PV system to another location during its economic life. By 2030, JTC aims to expand SolarLand to approximately 100 MWp of solar capacity.

**Chunk 20 (Assessment of Available Land Plots on Islands):** The assessment of potential land for large-scale PV deployment includes only islands with grid connection potential to the mainland, such as Jurong Island and Pulau Semakau. Jurong Island, Singapore's petrochemical hub, could support notable grid-connected PV installations and already has a ground-mounted system under SolarLand. Pulau Semakau, home to a 1.5 MWp solar PV installation as part of the REIDS testbed, could potentially add more usable land for PV deployment subject to biodiversity considerations.

**Chunk 21 (Assessment of Available Land Plots on the Main Island):** An initial assessment of potential vacant land areas on Singapore’s main island excluded certain areas due to public acceptance issues, conflicting interests, or economic viability. These excluded areas are neighborhood fields, forested/nature areas, unsuitable sundry areas, and newly reclaimed land. The possible areas for mobile-/land-based PV deployment on the main island could add up to approximately 0.38 km².

**Chunk 22 (Floating PV):** Floating PV installations on water bodies, such as fresh water reservoirs or near-shore marine waters, are considered within Singapore's territorial waters with a focus on inland water bodies due to space constraints at sea. The assessment included inputs from various agencies to determine the theoretical maximum deployable solar PV capacity on in-land water bodies, leading to an estimation of about 2.5 km² of net PV area on reservoirs.

**Chunk 23 (Floating Solar on 'Dead Sea Spaces'):** Floating PV installations can also be considered for 'dead sea spaces', which are areas in maritime waters not suitable for other purposes or already affected by the main industrial use of the area. A high-level assessment indicates approximately 2.12 km² of such near-shore spaces around Singapore's coastal waters. These sites may also harbor biodiversity, and thus an assessment for environmental and biodiversity impacts would be necessary.

**Chunk 24 (Infrastructure-Based PV Options):** Singapore has the option to utilize existing infrastructure by combining them with solar PV systems in an opportunistic manner. Prioritized land options include existing land with potential for vertical expansion, PV noise barriers along expressways and railways, flood canals, and existing roads.

**Chunk 25 (Specific Applications for Solar PV Systems):** Specific applications for solar PV systems include the use of existing land by adopting dual land use, implementing solar PV noise barriers as seen in several European countries, and exploring the potential of overbuilding flood canals and existing roads with solar PV systems while ensuring safety and minimal disruption to existing functions.

**Chunk 26 (Obstacles and Considerations for Infrastructure PV):** Several considerations and potential challenges for infrastructure-based PV systems include grid interconnection, visual impact on drivers, integration with street lighting, and fire safety requirements. These concerns require in-depth evaluation and collaboration between relevant government agencies.

**Chunk 27 (Summary of Net Usable Areas for PV Deployment in Singapore):** The assessment of net usable areas for PV deployment in Singapore, summarizing potential areas from rooftops, façades, mobile/land-based PV, floating PV, and infrastructure PV, leads to a technical potential for PV in Singapore that is somewhat smaller than previously estimated in the 2014 PV Roadmap due to observed space utilization in real-world installations.

**Chunk 28 (Lifecycle Cost Comparison for BIPV Façades):** Figure 5.9 compares the lifecycle cost (LCC) of a conventional cladding façade and a colored BIPV façade, indicating that though BIPV façades have higher initial capital expenditures (capex), they become more cost-effective over time through electricity generation. Additional benefits not reflected in this calculation might include reduced solar heat gain, potentially lowering the building's cooling load. Different annual insolation values, such as 750 and 500 kWh/m2/year, change the payback period, which is important for determining the economic viability for building owners.

**Chunk 29 (Scenarios for PV Deployment):** Similar to the original PV Roadmap, a scenario-based approach is used to describe various possibilities for PV deployment. Two scenarios, "Baseline" and "Accelerated," differ in the extent of adoption, technological advancements, and projected installed capacity. The Baseline scenario assumes a conservative uptake, primarily driven by government-led projects, while the Accelerated scenario expects a substantial contribution from the private sector and novel PV applications, alongside high-efficiency technologies.

**Chunk 30 (Managing PV Grid Integration - Global Developments):** To manage the variability from solar PV, a fundamental concern for large-scale adoption in Singapore, this section discusses global experiences with high penetration of variable renewables. The literature survey includes Japan, Germany, Hawaii, Australia, and California, each facing unique grid integration challenges. The survey covers the current power system status and the penetration levels for solar PV with a focus on addressing the variable and distributed nature of solar PV and the associated challenges.

**Chunk 31 (Grid Mitigation Measures for PV):** The challenges in grid integration due to solar PV's variable nature are addressed through various mitigation measures and technologies, categorized into supply & demand-side management, grid infrastructure modifications, energy storage, and curtailment or load shedding. The cheapest option commonly represents system balancing through coordinated control or incentivizing user response to system needs.

**Chunk 32 (Table Overview of PV Penetration and Power Grid Status):** Table 5.10 provides an overview of the power grid status and solar PV penetration in countries that have high rates of variable renewable energy adoption, summarizing the common issues and highlighting the differing severity of these challenges across distinct power systems.

**Chunk 33 (Grid Mitigation Technologies and Smart Grids for PV Integration):** The ADDENDUM to the “Update of the PV Roadmap” provides a detailed overview of various mitigation technologies and their current implementation status globally. It also discusses the benefits and importance of Smart Grids, Internet of Things (IoT), and cybersecurity for the integration of solar PV into the grid. As solar PV deployment increases, the role of Smart Grids and related innovative technologies becomes more critical in managing grid stability and optimizing energy distribution.

**Chunk 34 (Grid Impact Assessment of PV in Singapore):** Singapore's most viable renewable energy option is solar PV, which is inherently variable and non-dispatchable. The tropical climate conditions and frequent changes in cloud cover result in highly variable solar output. PV installations, mostly dispersed and connected to the low-voltage distribution network, could present visibility and control challenges over a large generation fleet embedded in the distribution network. Addressing these challenges is essential for the safe and efficient integration of distributed PV systems into Singapore's energy grid.

**Chunk 35 (Methods for the Grid Impact Study):** For the Grid Impact Study, the focus was on assessing demand profile and ramp rate impacts, distribution network impact, as well as inertia and reserve requirements and protection system changes. The assessment was performed for both the Baseline (BAS) and Accelerated (ACC) PV deployment scenarios, with relevant input data summarized to facilitate the evaluation of potential consequences and necessary adaptation measures within Singapore’s power system framework.

**Chunk 36 (Demands and Penetration Level Projections):** The projected scenarios for 2030 and 2050 depict varying degrees of PV penetration levels and their potential impact on the demand profile. PV peak power during mid-day and the assumed system peak demand are integral parts of defining the penetration level. Penetration level is the ratio of installed PV capacity to system peak demand, which is a significant indicator in assessing solar PV's role in the overall energy mix and planning for necessary infrastructure enhancements.

**Chunk 37 (Grid Impact Study and Fault Ride-Through Requirements):** Singapore's power system, in its current state, is expected to accommodate up to 2 GWp of PV by 2030 without significant concerns. However, for higher levels of PV penetration, factors such as power factor and ramp rates require monitoring, and appropriate mitigation measures should be deployed to manage power and voltage fluctuations. While only negative impacts of high PV penetration are addressed here, it's important to note that there are also potential positive impacts on the grid, such as providing ancillary services for voltage support. In addition, smart grid and IoT technologies will increasingly play important roles in grid condition monitoring and management.

**Chunk 38 (New Topics in PV Roadmap for Singapore – Re-powering):** Re-powering refers to the replacement of aging power generation equipment with the latest technologies to achieve higher efficiencies and performance, and it is already established in the wind industry. With improvements in PV efficiencies and drastic reductions in solar module prices over the past years, PV system owners are now considering re-powering, particularly in tropical climates like Singapore where increased system losses due to degradation or soiling are more common. The economic and technical considerations are numerous because re-powering involves replacing not just PV modules but also inverters and possibly cabling. This action is often considered when inverters are due for replacement.

**Chunk 39 (Recycling of PV Modules):** The exponential global growth in PV installations and the aging of panels underscore the escalating need for PV module recycling. Adequate management of PV waste is crucial both for environmental reasons and to uphold the technology's clean reputation. Regulations are critical in this area, with the EU currently leading in PV recycling policies through the WEEE Directive. On the technological front, improving recycling technologies for PV components is an ongoing effort, even as the actual recycling rate for end-of-life PV modules remains around 10% globally.

**Chunk 40 (Policy Regulations and Technological Improvements in PV Recycling):** The development of recycling solutions for solar PV is approached through policy regulations and technological advancements. Europe provides a structured legal framework, whereas other countries with rapidly expanding PV markets still rely on general regulations for waste management. As a result, specific legislations need to be crafted for end-of-life PV modules to ensure effective and efficient recycling practices.

**Chunk 41 (PV Module Recycling Innovations and E-Waste Management in Singapore):** There are more than 120 patents from various countries for recycling PV modules, with the largest share coming from China. Researchers and corporations are competing to improve the efficiency, energy consumption, economics, recovery, and recycling rates, as well as the environmental performance of recycling processes. Despite the anticipated large volume of module waste worldwide, there are only a few dedicated recycling companies. In Singapore, most PV systems are leased with end-of-life (EoL) take-back services provided by the developers. From 2021, an Extended Producer Responsibility (EPR) system will be implemented, requiring producers of PV panels to offer free take-back services for EoL panels. The recycling need in Singapore's relatively young market will become more significant in 5-10 years, especially as "re-powering" older systems may lead to earlier decommissioning of installations.

**Chunk 42 (Renewable Energy Certificates (RECs) and Their Role in Singapore):** RECs are proof that electricity was generated from renewable energy sources and are typically transacted in megawatt-hour (MWh) units, though some platforms in Singapore allow for smaller (kilowatt-hour) trades to accommodate residential demand. Bundled and unbundled RECs offer flexibility for consumers and organizations to document their renewable energy usage and fulfill sustainability goals. In Singapore, a number of registries and platforms monitor and verify RECs transactions.

**Chunk 43 (Drivers for RECs Adoption in Singapore's Market and Policy Incentives):** Factors driving the adoption of RECs in Singapore include membership in the RE100 consortium, sustainability reporting mandates for companies listed on the Singapore Exchange (SGX), and the Building and Construction Authority’s (BCA) Green Mark scheme for Super Low Energy Buildings (SLEB). These elements, alongside government encouragement for higher levels of energy efficiency, are galvanizing the REC market and could play a significant role in offsetting a building's energy consumption.

**Chunk 44 (Importing Solar Energy as An Alternative for Singapore):** Due to land constraints for deploying PV in Singapore, importing renewable energy from other countries has become an option. This includes direct electricity imports through cable connections or solar-derived fuels like hydrogen. Although the focus is on solar power imports, other renewable energy sources such as wind power and hydropower are also under consideration. This section of the roadmap outlines technical concepts for solar energy imports without addressing geopolitical, legal, or financial risks.

**Chunk 45 (Trans-border Cable Connections and Pan-Asian Power Grid Vision):** The concept of installing solar PV systems in neighboring countries and linking them to Singapore's grid is explored. Such connections could be made through dedicated trans-border cables or existing grid interconnections. The idea leverages the geographic smoothing effect, reducing the variability of solar PV output across a larger area. Longer-term visions for a Pan-Asian super grid are also discussed, which could enable significant regional utilization of renewable energy sources, thus contributing to a sustainable energy supply system for the region by mid-century.

**Chunk 46 (Policy & Regulations for Future Solar Technologies):** Future government tenders, such as those from the SolarNova programme, should specify higher system efficiency or area factors for solar PV installations. Additionally, Performance Ratios (PR) that influence energy yields should be enhanced, as installations with PR values over 80%, and in certain cases even reaching 90%, have been achieved at not significantly higher costs.

**Chunk 47 (Novel 'Urban Solar' Applications):** There is significant potential to develop cost-effective solutions in areas where Singapore has good deployment potential and where no global market solutions are available off-the-shelf. Innovations could include:

* Standardized "plug & play" solutions for rooftops and facades
* Co-locating PV with greenery
* Colored BIPV modules
* Prefabrication of BIPV
* "Transparent" PV windows
* Ultra-light BIPV elements
* PV-powered media walls.

These solutions, once developed and tested, could be useful in other megacities looking to increase their PV deployment and may present export opportunities.

**Chunk 48 (Evolving Technologies - Tandem Solar Cells):** Tandem solar cells represent a promising future research direction. Specific attention is given to perovskites-on-silicon tandem solar cells, capitalizing on Singapore's past investment in major R&D centers focusing on both perovskites and crystalline silicon solar cells. The research aims to increase efficiencies, durability, reliability, and establish an industrial pilot line for relevant research on this tandem technology.

**Chunk 49 (Policy & Regulations to Encourage Urban PV Development):** Policies fostering novel urban solar developments include allowing for test-bedding of new technologies, such as PV noise barriers, and opening opportunities for their deployment. Additional encouragement could involve mandating solar PV on buildings, possibly through the BCA Green Mark scheme, to support the SLE/ZEB/PEB building agenda.

**Chunk 50 (PV Grid Integration and Identified RD&D Areas):** At higher PV penetration rates, Singapore's current power system may struggle with variable solar generation. Identified areas for RD&D include operational solar forecasting, demand response alternatives, energy storage systems, and smart inverters that allow for the provision of ancillary services despite the distributed nature of PV systems.

**Chunk 51 (Addressing Recycling and Circular Economy for PV):** The need for effective PV module recycling practices is clear, considering the future volume of module waste. RD&D efforts focus on on-site recycling, developing cost-effective methods, and moving towards a circular economy, where mobile solar systems could represent significant progress.

**Chunk 52 (Urban Heat Island Effect and Solar Development Database):** Urban solar solutions must prioritize optimizing solar energy harvesting while considering the associated social, economic, and environmental impacts. A city-wide database of solar potential could support researchers, developers, and policymakers in managing the Urban Heat Island (UHI) effect and facilitating efficient PV deployment.

**Chunk 53 (Projections for Capital Expenditure Reductions of PV Systems):** By 2050, capital expenditure (capex) for various solar PV applications is expected to decrease by approximately 45% from 2019 levels. This reduction is projected across all PV system applications, with large ground-mounted, rooftop PV (1 MWp+), and floating PV inland systems forecasted to have the lowest installed costs. However, these figures do not account for potential grid connection costs that may be necessary if systems are constructed farther from the main grid or new substations are needed.

**Chunk 54 (Forecasted Levelized Cost of Electricity for PV Systems):** The current and projected levelized cost of electricity (LCOE) for 2030 and 2050 for different types of PV systems in Singapore is presented in Table B.3. The table illustrates the LCOE based on two different weighted average cost of capital (WACC) scenarios (5% and 9%) to represent diverse financing alternatives. Ground-mounted PV installations are expected to achieve the lowest LCOE, closely followed by large rooftop PV systems (>1 MWp). After 2030, LCOE for floating PV on reservoirs is foreseen to become the second lowest-cost option.

**Chunk 55 (Summary Table of LCOE Projections):** Table B.3 shows the LCOE projections for various PV system applications with WACC at 5% and 9%, representing the range of financial conditions for PV system owners. LCOE trends from 2019 to 2050 suggest a continuous decline, with the most significant drops observed for larger installations, reflecting the cost reductions in capex and potential improvements in operations and maintenance (O&M) efficiencies.