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Seasonal Solar Resource Variability and Its Implications for Residential Photovoltaic Design in Selected Tropical Cities

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Abstract

Residential photovoltaic design in tropical cities requires an account of when solar energy is available and when households can use it. Annual irradiation provides an essential measure of resource abundance, but it conceals seasonal shortages, persistent cloudy periods, and mismatches between generation and demand. This article critically synthesizes literature published before 1 May 2023 concerning Singapore, Kuala Lumpur, Jakarta, and Bangkok. It combines local observational and modeling studies with established photovoltaic performance and storage methods, while retaining distinctions between regional evidence, site measurements, and analytical inference. The comparison identifies different design questions within a shared tropical setting: uncertain orientation gains under equatorial cloudiness, spatially differentiated Malaysian seasonality, modeled wet-season exposure in Jakarta, and the interaction of Thailand's monsoon cycle with temperature and demand. A proposed assessment framework separates annual yield, monthly energy adequacy, and chronological supply reliability. An explicitly hypothetical calculation demonstrates that identical annual generation can coexist with substantially different seasonal deficits, and that additional battery capacity cannot sustainably compensate for insufficient charging energy. The resulting design approach evaluates roof geometry, demand timing, array capacity, thermal behavior, and storage against a declared service objective. The contribution is a conditional decision framework rather than a ranking of city performance or a new empirical dataset. It supports residential systems that remain useful across uncertain weather and household operating conditions while identifying the measurements required for defensible city-specific optimization.

Keywords: tropical photovoltaics; solar resource seasonality; residential energy; monsoon; battery sizing; self-consumption

1. Introduction

The usefulness of a residential photovoltaic system depends on the relationship between solar availability and the electricity services a household expects it to supply. Resource assessments commonly begin with annual irradiation or annual electricity production per unit of installed capacity, and these measures are indispensable for estimating overall production. Nevertheless, a household purchases electricity at particular times and may require backup during particular interruptions; neither requirement is represented by an annual energy total. The distinction is consequential in tropical cities, where substantial year-round sunlight coexists with variable cloud cover and seasonally organized rainfall. The central argument developed here is that annual yield must be interpreted alongside seasonal adequacy and the chronology of demand. This approach preserves the value of conventional resource assessment while connecting its results to the actual purpose of a residential installation.

Solar potential has several meanings that should remain separate in design decisions. The Energy Sector Management Assistance Program (ESMAP, 2020) distinguishes the physical resource from technically realizable photovoltaic production and from economic potential. Its internationally comparable assessment is valuable precisely because it makes assumptions about technology and operating conditions explicit. However, an estimate prepared for standardized, large-scale systems cannot establish the performance of a shaded residential roof, and a national average cannot establish a neighborhood's exposure. The appropriate residential inference is therefore conditional: regional assessments establish plausible resource availability, whereas household design requires a further translation through roof geometry, equipment behavior, consumption, and operating constraints. Confusing these levels produces confident capacity recommendations whose apparent precision exceeds the information supporting them.

Singapore, Kuala Lumpur, Jakarta, and Bangkok provide a purposeful comparison of tropical resource conditions rather than a representative sample of all tropical cities. The first two allow attention to equatorial cloudiness and orientation sensitivity, while the Indonesian and Thai cases broaden consideration of seasonally organized atmospheric conditions. Yet geographical proximity does not guarantee identical rainfall timing, irradiance distributions, or household electricity use. Nor does selecting four cities create a controlled experiment when the underlying studies employ different instruments, periods, and models. The comparison consequently asks how evidence from each location changes the questions a designer should investigate. Its value lies in identifying transferable mechanisms and location-dependent uncertainties without manufacturing a common numerical dataset from incompatible sources.

Three questions organize the article. First, which aspects of seasonal solar variability remain relevant after the resource is converted into electricity on a residential roof? Second, how should those aspects change choices about orientation, installed capacity, storage, and operation? Third, what evidence is sufficient to support a city-specific recommendation? These questions connect meteorology with engineering, but answering them fully would require synchronized, multiyear irradiance and household demand records that are not assembled here. The article instead develops a critical synthesis and an auditable analytical demonstration. Its contribution is the integration of published local evidence with an explicit hierarchy of design objectives, enabling readers to distinguish conclusions already supported by literature from propositions requiring further measurement.

Seasonal vulnerability emerges from the interaction between weather and the service expected from a system. The same cloudy interval can produce a manageable increase in electricity purchases for one residence and an unacceptable interruption of essential loads for another. However, this difference cannot be resolved by characterizing the weather more precisely if the household objective remains undefined. The review therefore treats adequacy as a relationship between resource, demand, and operating constraints rather than an intrinsic property of a city. This perspective directs attention toward the choices that convert available radiation into useful

service and explains why a technically productive installation can still disappoint its owner.

2. Review approach and evidential boundaries

This article uses a focused critical literature review with a publication cutoff of 30 April 2023. Searches combined the city names with terms concerning solar radiation, monsoon variability, photovoltaic performance, tilt, haze, self-consumption, battery storage, and resource validation. Publication identity and dates were checked through publisher records, institutional repositories, and dated technical reports; substantive claims were checked against accessible source content. However, the search was neither an exhaustive bibliographic database review nor a statistical meta-analysis, and no screening counts or preregistered protocol are claimed. The appropriate interpretation is a deliberately bounded synthesis whose references can be traced and whose deductions can be assessed independently of claims to comprehensive coverage.

Evidence was selected for its relevance to a physical mechanism, a city or nearby observation site, or an established design method. Local measured studies provide direct information about their instruments and observation periods; regional models provide broader coverage; methodological publications explain conversions from weather to output and from output to household service. These forms of evidence complement one another, but they do not carry interchangeable evidential weight. A satellite estimate at Jakarta cannot be described as rooftop measurement, and a Malaysian station outside Kuala Lumpur cannot establish every roof's exposure within the city. Throughout the comparison, the geographical and methodological boundaries of each source are retained so that a design implication remains proportional to its evidential basis.

The synthesis avoids pooling reported irradiation values into a league table because differences in observation period, surface orientation, temporal averaging, and model construction could create misleading rankings. A measured daily mean on a horizontal plane and a simulated annual yield at an optimized tilt are both legitimate quantities, yet their difference cannot isolate a climatic effect. Even apparently comparable annual means may reflect different years or treatment of missing observations. Consequently, numerical findings are used to illuminate their original questions, while comparative conclusions concern mechanisms and assessment priorities. A future harmonized analysis could quantify city differences, but the present review does not substitute heterogeneous published numbers for that analysis.

Reference verification also has limits that should shape the strength of the discussion. A valid bibliographic record establishes that a work exists, whereas an accessible abstract may support only a narrow statement about its methods or principal findings. Detailed numerical claims therefore require readable tables, text, or figures; sources available only through summaries are used conservatively. Similarly, material published after the cutoff cannot become admissible merely because it analyzes earlier weather observations. This separation of publication eligibility, source identity, and claim support gives the review a reproducible evidential boundary. It also explains why some plausible design hypotheses remain explicitly conditional rather than being presented as established local results.

The analytical example later in the article is independently constructed to expose an energy-balance relationship. All of its resource values, household loads, and equipment assumptions are hypothetical, and its calculations are reproducible from the stated equations. Such an example can prove that annual equivalence does not imply seasonal equivalence, but it cannot estimate the size of this effect in any selected city. Its role is explanatory: it identifies which information would be missing from an annual-only design and how that omission can change a capacity decision. The article therefore combines literature synthesis with a transparent demonstration while making no claim to original field measurements or validated city simulations.

3. Physical mechanisms linking seasonality to photovoltaic output

Seasonal solar availability begins with solar geometry, which determines the position of the sun and the radiation incident above the atmosphere. At low latitudes, the sun can pass to either side of the zenith during the year, so

orientation cannot be inferred from a temperate-climate winter design rule without checking the local geometry. However, extraterrestrial availability does not establish radiation received at the roof because clouds, aerosols, and atmospheric absorption modify the incoming energy. The practical synthesis is to treat geometry as a necessary starting condition and atmospheric transmission as a separate, locally variable process. This distinction prevents a shallow latitude-based tilt rule from carrying the weight of a complete tropical resource assessment.

Global horizontal irradiance comprises direct-beam radiation projected onto a horizontal plane and diffuse radiation received from the sky. A tilted roof changes the interception of these components and of ground-reflected radiation; the anisotropic treatment developed by Perez et al. (1990) explicitly addresses the directional structure of diffuse light. Yet adding a sophisticated transposition model does not eliminate errors in the input irradiance or the representation of local obstructions. For residential design, the resulting inference is that tilt comparisons require both a defensible direct-diffuse decomposition and a roof-specific view of shading. Where candidate configurations differ only slightly, uncertainty in those inputs may matter more than the nominal gain reported by the model.

Clouds affect photovoltaic systems through both the amount and the temporal organization of received radiation. A reduction in monthly irradiation lowers the energy available for meeting demand, while an uninterrupted sequence of low-output days can deplete storage even when the monthly total is adequate. Conversely, variable clouds do not imply that output remains continuously low: the sequencing of cloudy and clearer intervals determines opportunities to recharge. The design consequence is that monthly means and time series answer different questions. Monthly means can identify recurring seasonal exposure, whereas chronological data are required to establish whether a particular battery and dispatch rule can carry a household through that exposure without unacceptable interruptions.

Rainfall is informative about atmospheric conditions but is an imperfect substitute for irradiance measurement. A rainy period may coincide with extensive cloud cover, yet the same rainfall total could be produced by short intense storms or by persistent overcast conditions with different solar consequences. Rain can also remove some deposited material from module surfaces, creating a separate effect on optical losses. It follows that rainfall alone cannot quantify either generation reduction or cleaning benefit. The defensible synthesis is to use precipitation as contextual evidence and an operational variable, while deriving production from irradiance and estimating soiling from site observations or appropriately qualified assumptions.

Module temperature creates another distinction between available radiation and electrical output. Faiman (2008) provides a thermal model connecting module temperature with irradiance, ambient conditions, and wind-dependent heat removal. This relationship helps explain why greater incident radiation need not produce a proportional increase in electrical energy. However, thermal coefficients depend on the module and its mounting environment, and an exposed test assembly does not automatically represent a module closely integrated with a roof. A tropical residential design should therefore consider ventilation and mounting geometry as part of the conversion model. Thermal modeling is most useful when it explains a specified installation rather than supplying an apparently universal correction for an entire city.

Atmospheric haze and deposited dirt should also be distinguished because they intervene at different points in the radiation pathway. Urban haze can reduce the radiation reaching a photovoltaic surface, as examined by Peters et al. (2018), whereas surface deposits change how much of the arriving light reaches the cells. Nevertheless, the presence of haze does not establish the magnitude of soiling on a particular roof, and cleaning cannot recover radiation already attenuated in the atmosphere. The operational implication is to diagnose the cause of an observed loss before choosing an intervention. This distinction is especially useful when seasonal low output could plausibly arise from clouds, atmospheric aerosols, dirty modules, or several processes together.

Resource uncertainty persists even when designers use established global data products. Yang and Bright (2020) evaluated eight satellite and reanalysis irradiance products against records from 57 Baseline Surface Radiation Network stations and emphasized verification of distributions alongside aggregate accuracy. Their study supports the value of independent validation, but worldwide performance statistics do not certify the accuracy of a specific tropical urban grid cell. The appropriate synthesis is to examine seasonal bias and low-resource distributions at the nearest credible observations whenever possible. A product that reproduces annual energy satisfactorily may still misrepresent the cloudy sequences that determine storage performance, so the validation criterion should follow the design decision.

These mechanisms imply that a seasonal performance ratio should be treated as an outcome of interacting losses rather than a fixed property of a tropical climate. Irradiance, temperature, shading, conversion efficiency, and operational availability can vary together, while some losses respond differently to weather. However, increasing model complexity without improving input quality can merely introduce more uncertain parameters. A useful model hierarchy therefore begins with an explicit simple representation and adds detail where a plausible decision could change. The designer should be able to explain why each additional weather variable or loss process is needed, which observations constrain it, and whether its uncertainty affects the recommended system configuration.

4. Comparative evidence from the selected cities

4.1. Singapore

Singapore demonstrates the need to distinguish average climate conditions from weather-related uncertainty. A dated assessment of 2022 attributed unusually wet conditions partly to persistent La Niña and a negative Indian Ocean Dipole, establishing that an individual year can depart materially from a long-term baseline (National Environment Agency, 2023). Rainfall, however, is an imperfect indicator of available solar energy: nighttime rain, brief afternoon storms, and sustained daytime cloud can produce different irradiation outcomes even when precipitation totals match. The design inference is that a residential feasibility assessment should retain measured irradiance as its resource variable and use rainfall and large-scale climate conditions to interpret departures. A designer should compare several weather years and examine the persistence of low-production days, rather than adjust annual output directly in proportion to rainfall. This distinction matters particularly when a household expects the system to cover essential demand during outages, because accumulated energy deficits depend on the sequence of cloudy days as well as the annual total.

Local orientation research also shows why the conventional equation of optimal tilt with latitude is insufficient for Singapore. Khoo et al. (2014) found that an east-facing surface at 10° received 4.1% more irradiation than its west-facing counterpart during June 2012-May 2013; its advantage over the south-facing surface was only 1%, within the stated ±2% measurement uncertainty. Although eastward orientation benefited from the observed daily cloud pattern, these results do not establish one mandatory arrangement for every roof. Their modeled optimum tilt also changed between the three evaluated years. For residential practice, the defensible conclusion is to compare a range of nearly equivalent layouts before purchasing specialized mounting. An existing roof direction may remain attractive if it accommodates additional modules, reduces shading, or simplifies drainage and access. Conversely, an east-facing option warrants explicit evaluation where the roof permits it. Annual resource optimization should therefore supply a feasible range of arrangements whose household benefits can be tested, rather than a single angle presented with unjustified precision.

Haze adds a disturbance that cannot be represented adequately by a fixed wet-season correction. Nobre et al. (2016) evaluated ten Singapore PV systems during the June 2013 haze event and estimated event-related yield losses of 15-25%, using procedures intended to separate haze attenuation from cloud effects. Those estimates are specific to the analyzed event and methodology; they are not annual loss factors. Atmospheric pollution can also alter spectral

conditions, complicating interpretations of performance ratios across module technologies (Liu et al., 2014). A residential design implication is to include a separate adverse-resource scenario where the available evidence supports exposure to smoke episodes. The scenario should specify its assumed duration and attenuation instead of silently reducing all months by a large percentage. Monitoring should compare output with measured or appropriately estimated irradiance so that low generation caused by the atmosphere does not automatically trigger a maintenance diagnosis. The same evidence does not justify recommending a battery solely on the basis of an exceptional historical event.

Thermal behavior further complicates the relationship between abundant sunshine and delivered household electricity. Outdoor testing of nine commercial module technologies in Singapore linked high irradiance with elevated module temperatures and corresponding efficiency penalties (Reindl et al., 2012). Technology, mounting configuration, and observation period limit the transferability of any individual result, and older module comparisons cannot determine the best product for all later installations. The useful design deduction concerns the evaluation method: compare candidates using their temperature response and expected operating conditions, alongside rated power and usable roof area. A tightly integrated roof installation and a ventilated mounting arrangement should not automatically receive identical thermal assumptions. Nevertheless, more ventilation may require additional mounting height or structural provisions, so its energy advantage needs to be assessed together with those practical consequences. For Singapore residences, seasonal resource assessment therefore becomes a joint assessment of irradiation and conversion conditions, with sufficient attention to thermal losses to avoid overstating the benefit of the brightest periods.

4.2. Kuala Lumpur

Kuala Lumpur has a substantial empirical resource foundation, but its station record must retain its geographical and temporal identity. Engel-Cox et al. (2012) reported mean daily global solar radiation of 4.86 kWh/m²/day at Subang using radiation observations from 2006-2009. Subang provides evidence relevant to the Kuala Lumpur area, yet that value is neither a measurement on every urban roof nor an indefinitely valid citywide design constant. Rooftop obstructions, installation geometry, and differences between the observation period and the intended operating period can change the usable resource. Accordingly, the figure is suitable as an independently documented plausibility check against a proposed weather file. It should not replace the file's monthly distribution or the roof's shading assessment. If another dataset gives a substantially different estimate, the designer should first investigate measurement period, spatial resolution, and irradiation definition. Treating disagreement as information about uncertainty is more useful than selecting whichever annual average yields the most attractive economic projection.

The seasonal interpretation for Kuala Lumpur requires particular care because Malaysian climate patterns vary geographically. Engel-Cox et al. (2012) found clearer northeast-monsoon reductions in solar radiation on the peninsula's east coast and in East Malaysia, while other regions had less distinct patterns and Subang exhibited substantial variation between years. A national rainy-season label consequently provides insufficient evidence for assigning Kuala Lumpur a precise annual minimum. A qualitative seasonal description also cannot determine a numerical monthly irradiance profile. The practical synthesis is to derive the city's seasonal profile from the selected local or validated gridded dataset and then examine whether it is stable across years. For a residence, the relevant adverse period may be defined by the largest demand-to-generation imbalance rather than the month with the most rain. This distinction enables a design to respond to actual household exposure without claiming that a broad regional monsoon narrative determines its required array or battery capacity.

Model-based tilt studies provide a second strand of Kuala Lumpur evidence, with a different evidential status from station measurements. Khatib et al. (2015) examined monthly and seasonal tilt optimization for five Malaysian locations using a Liu-Jordan approach, identifying potential gains from adjustment within the

modeled configurations. Such gains establish an irradiation opportunity, but they do not independently demonstrate an economic advantage for a residential installation. Adjustment hardware, access, maintenance, and the possibility that an array remains in the wrong position introduce practical considerations outside the resource calculation. The resulting design inference is to compare the lifetime value of additional usable electricity with the full cost and reliability consequences of adjustment. A fixed roof-compatible array may offer a defensible compromise even when an adjustable arrangement produces greater modeled irradiation. Where adjustment is considered, its benefit should be recalculated using local weather, the complete feasible orientation range, and household demand, with a sensitivity analysis showing whether the result survives reasonable uncertainty in each input.

The Kuala Lumpur case ultimately supports a design procedure that separates environmental evidence from household assumptions. A measured annual resource or modeled geometric optimum can inform generation estimates, but neither determines when residents consume electricity or how much exported energy is worth. In the absence of household observations, assigning an evening-dominated or daytime-dominated profile would introduce an unverified assumption into an otherwise evidence-based comparison. The appropriate synthesis is to evaluate explicitly stated demand scenarios and identify which design choices remain satisfactory across them. If a larger array produces more surplus under every plausible low-demand scenario, its economic case will depend more heavily on the assumed export arrangement; if flexible demand can move into productive hours, the same capacity may have greater on-site value. These are conditional deductions, not observed Kuala Lumpur household results. Stating the conditions makes the comparison useful to designers while preserving the boundary between the published climate evidence and the residential operating model still required.

4.3. Jakarta

Jakarta illustrates why proximity to the equator does not eliminate seasonality in the usable solar resource. Aldrian and Susanto (2003) identify distinct Indonesian rainfall regimes, placing Java within a southern monsoonal region rather than a uniform national climate. The modeled Jakarta resource in Suri et al. (2017) also varies across the year, with lower mean daily global horizontal irradiation in January and February than in October. However, rainfall classifications cannot establish the magnitude of an irradiance deficit, and this interim resource report explicitly cautions that its results lack local ground-measurement validation. These sources therefore establish a defensible seasonal hypothesis, rather than a precise household production guarantee. The design implication developed here is to preserve the annual cycle when estimating generation and test the household against alternative low-resource sequences. A citywide climate description can identify when closer investigation is needed; the final array and battery specification still requires a roof-specific conversion model and a chronological demand profile.

Locally measured radiation provides an essential check on Jakarta resource estimates because empirical models respond differently to the available meteorological predictors. Nasruddin et al. (2018) compared several estimation approaches against two complete years of Jakarta radiation measurements and found unequal performance among them. Nevertheless, two years are insufficient to characterize the full range of interannual climate variability, and a model that estimates monthly means satisfactorily need not reproduce consecutive cloudy days. The appropriate synthesis is to combine the strengths of local observations and longer modeled records while keeping their uncertainties visible. For a residential project, local measurements can help detect systematic bias, whereas a longer record supplies a wider set of weather sequences for sensitivity analysis. This division of functions also prevents a common inferential error: treating agreement with a monthly average as evidence that a proposed storage system will sustain a specified load through an extended low-generation interval. The latter claim requires a separate chronological test.

Jakarta's solar geometry offers flexibility in roof use, which can make practicable installation more important than small gains from a mathematically optimal angle. Dewi et al. (2023), in city-scale modeling, found Jakarta generation less sensitive to roof slope and orientation than the comparison case of Kyoto. Suri et al. (2017) additionally discuss a practical minimum tilt for rain cleaning even when the irradiation optimum is flatter. These findings do not imply that every roof face performs equally or that rainfall reliably removes all deposited material. Nearby obstructions, mounting constraints, and the timing of demand can still distinguish otherwise similar layouts. The resulting design proposition is to compare feasible roof configurations on usable energy, access, drainage, and lifecycle cost before committing to a geometric optimum. Where the modeled energy difference between orientations is small, an arrangement that accommodates more unshaded modules or simplifies maintenance may provide greater household value, but that advantage must be demonstrated for the particular roof.

The relationship between generation and cooling demand creates a potentially favorable use case for Jakarta residential PV. Dewi et al. (2023) identify persistent cooling demand and its positive relationship with generation as advantages in their urban system analysis. Yet an aggregate city load can conceal substantial differences between households, especially whether cooling occurs during occupied daytime hours or after residents return in the evening. Applying an urban demand profile directly to a dwelling could therefore overestimate direct self-consumption. A useful household analysis should separate daytime cooling, evening cooling, and noncooling loads, then examine their behavior during both brighter and cloudier periods. If daytime demand already absorbs much of the available PV output, additional battery capacity may offer limited energy-shifting value; if evening demand dominates, storage becomes more relevant but its recharge opportunities remain weather-dependent. These conditional implications retain the city study's insight while making the household's measured timing, rather than a generalized tropical cooling assumption, the basis of design.

4.4. Bangkok

Bangkok demonstrates the interaction between seasonal solar geometry and a monsoon-driven atmosphere more clearly than an annual irradiation total can convey. Janjai et al. (2013) associate high March-April radiation across much of Thailand with favorable solar geometry and relatively clear conditions, followed by widespread radiation reductions during June-October as southwest-monsoon cloudiness increases. Bangkok was included in their independent validation network. However, these regional descriptions do not prescribe an identical monthly profile for every Bangkok roof, and relatively clear conditions later in the year coexist with less favorable solar geometry. The design inference is that neither rainfall season nor sun angle alone provides a sufficient calendar for expected output. Residential simulations should use monthly and hourly resource variation together, then evaluate how roof orientation and shading redistribute the resource. A configuration that performs strongly during the clear season should also be inspected during lower-resource intervals, particularly when the household expects the same level of energy service throughout the year.

Bangkok's research record shows the value of meteorological estimation while also exposing the limits of transferring model accuracy across scales. Waewsak et al. (2014) trained radiation models using Bangkok observations from 2001-2010 and assessed predictions against 2011-2012 observations. Janjai et al. (2013) report a Bangkok mean bias difference of 6.6% for long-term monthly-average daily radiation, even though their nationwide mean bias was only 0.3%. The neural-network assessment of Waewsak et al. and the satellite-model validation of Janjai et al. concern different models and should not be combined into a single error estimate. They nevertheless support a practical requirement: assess the relevant city and temporal scale rather than relying on a national performance statistic. For residential design, a credible uncertainty analysis should distinguish an overall resource bias from errors in the duration and timing of cloudy conditions. The first primarily changes expected energy and financial returns; the second can alter storage operation and unmet demand.

Both deserve attention, but improving one does not establish that the other has been resolved.

Bangkok system sizing must also account for the economic value of energy at the time it is produced. Tongsopit et al. (2019) demonstrate for Thai customers that the relative size of PV and load interacts with the compensation mechanism for surplus electricity. However, their historical scenarios do not establish either present tariffs or a universally profitable system size, and annual financial results cannot independently establish rainy-season adequacy. The synthesis is to evaluate technical and economic performance through the same seasonal generation and demand series. Under a scenario with low export compensation, enlarging the array to reduce a seasonal deficit could create low-value surpluses during brighter periods. Where exported electricity receives substantial value, that same configuration might be more attractive. This conditional comparison is more informative than assuming either that all available roof area should be filled or that all seasonal deficits should be eliminated. The preferred capacity follows from the household objective and explicitly stated compensation assumptions.

Storage and demand management offer distinct responses to Bangkok's generation-demand mismatch. Srikranjanapert et al. (2021) compare residential PV, home energy management, and batteries, showing that the economic case for storage depends on costs and operating assumptions. Jittayasotorn et al. (2023) likewise examine integrated rooftop PV and electric vehicles at the city scale. The city-scale electric-vehicle results do not establish continuous vehicle-battery availability at individual dwellings, and neither study guarantees household reliability. The design implication is to compare accessible flexibility before increasing stationary storage: controllable appliances, cooling schedules, and any vehicle charging must be represented with realistic constraints. Battery capacity should then be selected for a defined service, such as evening self-consumption or essential-load backup, with explicit limits on discharge and recharge. Seasonal cloudiness matters because it changes the energy available to replenish storage; increasing storage capacity alone cannot correct a persistent generation deficit. A useful design therefore specifies both the flexibility resource and the weather-dependent energy supply that makes it effective.

Table 1. Evidence and design priorities in the selected cities

City	Evidence highlighted	Boundary of inference	Priority for residential assessment
Singapore	Small measured orientation differences can approach uncertainty (Khoo et al., 2014).	Observed gains depend on year and installation.	Compare feasible layouts across weather years.
Kuala Lumpur	Subang observations show regional and interannual differences (Engel-Cox et al., 2012).	Nearby station evidence is not a roof-specific profile.	Validate local seasonal inputs and shading.
Jakarta	Published models show seasonal redistribution (Suri et al., 2017).	Local validation of the interim resource report is limited.	Test low-resource sequences and household cooling schedules.
Bangkok	Thai resource maps and Bangkok validation reveal seasonal and local effects (Janjai et al., 2013).	Regional patterns do not specify household outcomes.	Jointly evaluate seasonal production, demand, and export value.

Note. The priorities are deductions of this review. Rows summarize different kinds of evidence and do not constitute a performance ranking.

5. A framework for seasonal residential assessment

The comparative evidence suggests that the first design decision should be the service objective. A grid-connected household seeking lower bills can accept seasonal imports if the investment remains worthwhile, whereas a household seeking backup needs specified loads to remain supplied during an interruption. A fully autonomous residence faces the stricter requirement of balancing supply and demand without routine grid support. These objectives can coexist, but optimizing them requires explicit priorities because a battery held in reserve cannot simultaneously devote its full capacity to daily energy shifting. The framework proposed here therefore begins with a declared objective and acceptable consequences of shortfall. Essential-load backup additionally requires equipment and switching arrangements capable of supplying the selected circuits when the grid is unavailable. Only after the service and hardware requirements are specified can a low-resource month be interpreted as a financial variation, a reserve problem, or a threat to essential service.

Monthly irradiation should be normalized by the number of days before comparing seasonal intensity. Let H_m denote irradiation received on the selected plane during month m, in kWh/m², and d_m its number of days; the mean daily value is $h_m = H_m/d_m$. Raw monthly totals are relevant to monthly energy balances, but they confound seasonal intensity with calendar length. Both representations are therefore needed for different purposes. A descriptive seasonality measure can be defined as $S = (\max h_m - \min h_m)/\bar{h}$, where $\bar{h}$ is the day-weighted annual daily mean. This measure captures amplitude, yet discards sequence and demand; it should describe the resource profile rather than serve as a stand-alone reliability index.

Electricity production requires a second conversion from irradiation to electrical energy. Here E_m denotes alternating-current energy at the photovoltaic inverter output, before storage and household dispatch. A transparent first approximation is $E_m = P_{STC} \times (H_{POA,m}/G_{STC}) \times PR_m$, where P_{STC} is the array's rated direct-current power in kW, $H_{POA,m}$ is monthly plane-of-array irradiation, G_{STC} is the reference irradiance of 1 kW/m², and PR_m is a dimensionless performance ratio incorporating PV and inverter losses but excluding subsequent battery losses. The units produce kWh, and the expression makes losses visible. However, PR_m should not conceal unexamined assumptions about temperature, shading, inverter behavior, and downtime. Detailed approaches such as the model of King et al. (2004) represent these effects more explicitly. The synthesis is to use the simple expression for screening and explanation, then move to chronological modeling when equipment selection or service claims depend on effects the aggregate ratio cannot resolve.

Monthly energy adequacy can be expressed as $A_m = E_m/L_m$, where L_m is household demand during the same month. Values below one identify months in which photovoltaic generation alone cannot cover total consumption even with ideal temporal redistribution, unless energy is carried into the month from elsewhere. Values above one, however, do not prove self-sufficiency because the production may arrive after demand, exceed charging limits, or be exported before an interruption. The minimum monthly ratio is consequently a useful screening indicator with an asymmetric interpretation: insufficiency reveals a balancing requirement, while apparent sufficiency still requires chronological testing. This distinction prevents a favorable monthly total from being mistaken for a guarantee of household supply.

Chronological testing must preserve the energy balance of storage. For intervals of duration Δt hours, a simple state equation is $B_{t+1} = B_t + \eta_c C_t \Delta t - D_t \Delta t/\eta_d$, where B is stored energy, C is charging power, D is delivered discharge power, and η_c and η_d are efficiencies. Charging and discharge powers refer to the same household electrical bus, with the efficiencies accounting for the associated conversion losses. This simple equation neglects self-discharge and auxiliary consumption and assumes charging and discharge do not occur simultaneously. State-of-charge bounds and converter power limits constrain the feasible operation. This equation is elementary, but ignoring its initial and terminal conditions can produce fictitious reliability by borrowing energy from an initially full battery without replacing it. Repeated-year simulations should therefore enforce an appropriate cyclic condition or report

the change in stored energy. Outage studies should state the reserve available when the interruption begins rather than assuming unlimited prior charging.

Energy coincidence should also be distinguished from the amount of generation. Following the concepts reviewed by Luthander et al. (2015), useful self-consumption is the share of photovoltaic generation used by the household, while self-sufficiency is the share of household demand met by that generation. Here, battery conversion losses are excluded from useful household supply, and any grid-charged energy is tracked separately. These ratios answer different questions: a very small array can achieve high self-consumption while supplying little of the load, and an oversized array can increase supply coverage while exporting much of its output. The appropriate synthesis is to report both ratios with imported, exported, and unserved energy so that an attractive percentage cannot conceal a weak service outcome.

The time resolution of the assessment should be justified by the output being estimated. Beck et al. (2016) found different resolution requirements for energy sizing and battery-converter power in their German cases, while Ayala-Gilardón et al. (2018) demonstrated aggregation effects on self-consumption and self-sufficiency in a measured Spanish installation. Neither study establishes a universal sampling interval for the four tropical cities. Together, they support a convergence approach: repeat a selected calculation at finer resolution and determine whether the design decision changes materially. Monthly data may suffice for initial seasonal screening, but converter limits and rapid changes in direct household use require finer information. Model resolution is thus an engineering choice to be tested rather than a ritual preference for either coarse or extremely detailed data.

Uncertainty assessment should accompany each stage of this framework. Sengupta et al. (2021) explain why resource comparisons depend on spatial and temporal support, including differences between satellite pixels and point measurements. Yet reporting a single uncertainty percentage does not show whether the preferred design changes under plausible alternative inputs. The proposed extension is to test candidate designs across distinct weather years, resource datasets, demand schedules, and operating assumptions, preserving their identities rather than combining them into an opaque average. A design is comparatively robust when it meets its declared service objective across these credible alternatives at an acceptable cost. This is a decision criterion proposed by the present synthesis, not a measured performance classification assigned to any city.

6. Implications for array configuration and household operation

Roof orientation should be evaluated through the useful electricity it enables within the available building envelope. A configuration with slightly lower irradiation per module can produce more total electricity if it accommodates more modules or avoids an obstruction; alternatively, an orientation that shifts generation toward occupied hours can reduce imports without maximizing annual output. These possibilities are conditional and do not establish that east-west layouts are generally superior. The correct comparison holds roof area, shading constraints, and equipment assumptions visible while allowing demand timing to affect value. For the selected cities, the literature supports testing feasible alternatives rather than assigning one orientation from latitude alone. This approach converts an abstract solar optimum into a residential design decision that can survive practical constraints.

The choice between fixed and adjustable tilt follows the same logic. Seasonal adjustment can improve the interception of radiation, but an irradiation gain becomes valuable only if the resulting electricity can be used or compensated and the adjustment is actually performed. Manual access, mounting complexity, and maintenance effort can erase a small expected benefit even before uncertainty is considered. A sensible comparison therefore includes fixed arrangements matched to the roof and any realistically maintainable adjustable alternative. Where estimated benefits are smaller than plausible errors or operating costs, choosing a simple fixed arrangement can be rational. This conclusion does not deny the geometric advantage of adjustment; it locates that advantage within the costs and behavioral requirements of residential ownership.

Array capacity should be selected against the marginal value of additional production across seasons. Increasing capacity usually raises output during weak-resource periods, but it also increases surplus during favorable periods unless demand or storage can absorb it. A larger array may therefore improve autonomy while reducing the proportion of production consumed on site. Conversely, a system sized only to maximize self-consumption can leave valuable roof area unused and retain substantial grid dependence. The synthesis is to examine a range of array capacities and report how each changes imports, exports, and shortfalls. The preferred capacity should follow the household's objective and the value assigned to these outcomes, rather than an unexplained rule equating annual generation with annual demand.

The array-to-inverter ratio requires a similarly chronological assessment. Additional direct-current module capacity can increase production during lower-irradiance hours, while an inverter with a lower alternating-current rating can limit output during strong production periods. However, the amount of clipping depends on irradiance, temperature, orientation, and equipment characteristics, so a universal tropical oversizing factor is not defensible from the reviewed city evidence. Modeling should compare the value of additional weak-period generation with the cost of modules and the energy lost during constrained hours. The same installation must also meet equipment voltage and current requirements. Seasonal reasoning can inform the economic tradeoff, but it cannot replace electrical compatibility checks based on the selected components.

Storage capacity should be evaluated jointly with array capacity and the operating rule. Weniger et al. (2014) demonstrate this joint sizing logic through residential simulations, although their economic assumptions and climate cannot simply be transferred to Southeast Asia. The underlying relationship remains useful: an enlarged battery provides little additional service when there is insufficient surplus to charge it, while an undersized converter may restrict useful discharge even if the battery contains ample energy. Consequently, residential specifications should distinguish nominal battery energy, usable energy, charging and discharge power, reserve requirements, and expected aging. A statement that a home needs a certain number of battery kilowatt-hours per photovoltaic kilowatt omits too many controlling variables to function as a general seasonal design rule.

Demand management can improve the value of an existing resource without increasing annual irradiation. Moving a flexible appliance task into a productive interval can reduce exports and imports, and scheduling can sometimes achieve part of the benefit otherwise sought through storage. Nevertheless, household activities are constrained by occupancy, comfort, appliance availability, and the duration for which a service can be delayed. Air-conditioning demand, in particular, cannot be assumed fully movable simply because cooling is prominent in a tropical climate. The useful synthesis is to classify loads by their actual flexibility and test achievable schedules. Demand management should be evaluated as a practical operating arrangement with explicit limits, not as a mathematical freedom that disappears when residents use the system normally.

Economic appraisal should value electricity according to its destination and timing. For one kWh of photovoltaic surplus sent into a battery, a simplified incremental operating benefit is $\eta_{rt}\,p_{import} - p_{export} - c_{cycle}$, where η_{rt} is round-trip efficiency, p_{import} is the avoided later import price, p_{export} is the forgone export payment, and c_{cycle} represents marginal cycling cost per kWh entering storage. This expression explains why greater self-consumption need not increase economic value. However, it omits capital cost, reserve value, replacement, and other operating effects, so a positive result is not a complete investment case. The design implication is to model financial and reliability objectives separately before combining them. No current tariff or regulatory rule for the four cities is assumed in this article.

Maintenance planning should respond to the process causing seasonal losses. An installation experiencing reduced output during cloudy weather requires a different diagnosis from one experiencing a growing discrepancy between measured irradiance and electrical production. Yet seasonal maintenance schedules inferred solely from rainfall can miss local deposition, inaccessible drainage paths, or equipment faults.

A reasonable monitoring approach compares observed production with weather-adjusted expectations and investigates persistent deviations before prescribing cleaning or replacement. For roof configuration, the same reasoning favors preserving safe access and drainage when evaluating small irradiation gains. These are conditional engineering implications of the reviewed mechanisms; their exact costs and benefits require inspection of the residence and cannot be established from a city-average weather record.

Lifetime adequacy deserves attention because a design with little seasonal margin can become inadequate as equipment performance changes. Jordan and Kurtz (2013) document photovoltaic degradation across a heterogeneous historical evidence base, supporting the need to distinguish initial output from lifetime output. Their review does not supply a guaranteed degradation rate for every humid tropical roof. Instead of adopting one global number as local fact, a residential appraisal should test justified degradation and replacement scenarios for both generation and storage. The resulting question is whether essential service or financial performance remains acceptable later in the project. An apparently adequate first-year wet-season balance should therefore be interpreted alongside plausible future capacity and efficiency changes.

7. Analytical demonstration of the annual energy problem

An idealized calculation isolates the effect of seasonality while holding annual resource constant. Consider two hypothetical irradiation profiles on the array plane over a 360-day model year, comprising twelve equal 30-day periods. Profile A supplies 4 kWh/m²/day throughout the year; Profile B supplies 3 kWh/m²/day for 180 consecutive days and 5 kWh/m²/day for the remaining 180 days. Both total 1,440 kWh/m². These deliberately simplified profiles are not observations, forecasts, or estimates for any selected city. Their purpose is to compare identical annual energy under different temporal distributions, without allowing differences in equipment or total resource to explain the result.

Assume a 5 kWp array, a constant performance ratio of 0.80, and constant household consumption of 16 kWh/day. Under the screening equation above, Profile A produces 16 kWh/day and Profile B produces 12 kWh/day in the lower-resource half-year and 20 kWh/day in the higher-resource half-year. Each produces 5,760 kWh over the model year, equal to total consumption. Nevertheless, Profile B has a 4 kWh/day deficit for 180 days and an equal daily surplus for the other 180 days. Annual equality thus conceals 720 kWh of seasonal energy transfer or external supply. Even Profile A's daily equality does not establish hourly self-sufficiency, because this demonstration deliberately excludes the day-night distribution.

Table 2. Hypothetical profiles with identical annual energy

Profile	Daily irradiation	Annual irradiation	Daily PV output	Low-period energy deficit
A with constant resource	4 kWh/m²/day	1,440 kWh/m²	16 kWh/day	0 at daily resolution
B with seasonal resource	3 then 5 kWh/m²/day	1,440 kWh/m²	12 then 20 kWh/day	720 kWh over 180 days

Note. All values are hypothetical. Both profiles use 5 kWp and a constant performance ratio of 0.80. Demand is 16 kWh/day in a 360-day model year. Daily balance does not establish intraday reliability.

An initially full, ideal, lossless battery with 10 kWh of usable energy cannot eliminate Profile B's seasonal deficit. At a net depletion rate of 4 kWh/day, its energy-equivalent coverage is only 2.5 days, even before power constraints and the timing of household demand are considered. Doubling usable capacity to 20 kWh extends this bound to five days, while leaving the remaining seasonal shortage unresolved. An ideal store would require at least 720 kWh of usable seasonal

transfer capacity to bridge the entire half-year, plus whatever additional capacity the neglected intraday chronology requires. This lossless seasonal store is assumed to begin the low-resource period fully charged from the preceding high-resource period and to regain that state during the next high-resource period. The inference concerns conservation of energy: routine residential storage may shift production effectively within or between days, but increasing capacity alone cannot sustain supply indefinitely when average charging energy remains insufficient.

Adding losses makes the annual equality less favorable. If the idealized 720 kWh seasonal deficit must be delivered through storage with 90% round-trip efficiency, charging requires 800 kWh of surplus generation. Profile B provides only 720 kWh of surplus under the assumptions, so a repeated annual cycle cannot close even with unlimited battery capacity. This calculation assigns all seasonal transfer to storage and ignores additional intraday losses, making it an optimistic bound. Its value is to show why capacity and energy availability must be checked separately. A battery can be large enough to hold a desired reserve while the photovoltaic system remains unable to replenish that reserve over the relevant operating cycle.

Increasing the array can address the mean seasonal imbalance, although it creates a different tradeoff. Meeting the assumed 16 kWh/day demand during Profile B's 3 kWh/m²/day period at a performance ratio of 0.80 requires 20/3 kWp, or approximately 6.67 kWp. The following totals use the unrounded capacity. This is a 33.3% capacity increase, producing 7,680 kWh annually and a 1,920 kWh annual surplus relative to demand in the idealized calculation. Yet balancing the lower-resource daily mean still does not guarantee supply through every cloudy day or overnight interval. The resulting design choice concerns the relative value of extra generation, storage, load reduction, and grid support. Seasonal array sizing is therefore an economic and service decision that should be evaluated explicitly, rather than treated as an automatic correction factor.

The example also illustrates why the same annual resource can support different residential recommendations. A household with reliable grid access and modest export compensation may tolerate seasonal imports instead of purchasing enough equipment for autonomy; another household may prioritize a smaller essential-load circuit during outages. However, neither choice can be inferred solely from the irradiance profiles because it depends on costs, interruption exposure, and service preferences that the example leaves unspecified. The synthesis is a bounded analytical result: annual energy equality is insufficient evidence of adequacy, while the preferred remedy remains context-dependent. Applying the result to Singapore, Kuala Lumpur, Jakarta, or Bangkok requires the local resource and household records identified by the review.

8. Discussion and research priorities

The four-city comparison supports a common assessment structure without supporting a single regional design prescription. Singapore's orientation evidence draws attention to the scale of a gain relative to measurement uncertainty; Kuala Lumpur's station evidence cautions against transferring a national monsoon calendar; Jakarta's resource studies emphasize local estimation and validation; Bangkok's literature connects a monsoon-sensitive resource with demand and compensation assumptions. These differences identify useful starting questions, but they do not rank the cities by photovoltaic suitability. A household's roof, demand, and service objective can outweigh the climatic distinction highlighted by a city-level comparison. The practical contribution is therefore a sequence of questions that remains consistent across cities while allowing the evidence used to answer them to differ.

An important implication is that the best design may be a stable compromise across uncertain conditions. Optimizing a single weather year can identify a precise orientation or capacity, but a small advantage may disappear under another year, another credible resource product, or a changed occupancy schedule. Conversely, a configuration that performs acceptably across these alternatives may be more useful even if it never achieves the highest modeled annual yield. A future comparative study should quantify this tradeoff by reporting both expected performance and the sensitivity of design choices. Such

analysis would turn uncertainty from a concluding disclaimer into a testable part of the recommendation, particularly where additional mounting or storage has substantial cost.

Typical meteorological years remain useful for routine comparisons, but their limitations become important when the objective is reliability. Wilcox and Marion (2008) explain that typical-year datasets are constructed to represent typical conditions and are unsuitable for designing to worst-case weather; Dobos (2014) similarly cautions against interpreting simplified typical-weather output as guaranteed actual production. These methodological cautions do not imply that typical-year tools should be abandoned. The appropriate synthesis is to use them for initial configuration comparisons and then test selected designs against actual multiyear sequences or clearly defined adverse scenarios. An assessment should state whether it estimates expected energy, historical shortfall exposure, or a specified outage service, since those are different evidential claims.

A reproducible empirical extension would begin with common variable definitions and a documented period across the four cities. Irradiance components, ambient temperature, wind, and equipment configuration should be recorded together with household demand, while rooftop shading and data-quality flags should remain available for inspection. However, harmonization must not erase local evidence by forcing every city into the same poorly validated data source. A useful study would compare a common gridded product with the best available local observations and disclose where that comparison is weak. It would then calculate annual yield, daily-normalized monthly profiles, and chronological household outcomes using the same equations and service definitions. This design would make city differences interpretable without presuming that model uniformity guarantees empirical accuracy.

The most informative hypotheses concern decisions, rather than merely correlations between weather variables. One hypothesis is that a configuration maximizing annual irradiation can differ from the one minimizing household imports; another is that a small change in the distribution of low-output sequences can alter storage requirements more strongly than a similar change in annual irradiation. These propositions are physically plausible and consistent with the framework, but the present review does not estimate their frequency or magnitude in the selected cities. They should be tested using controlled comparisons that hold equipment and demand assumptions constant, followed by sensitivity analyses that vary them. Publishing both successful and unsuccessful cases would establish where seasonal detail materially improves a design and where a simpler assessment already suffices.

The review's main limitation is that its evidence does not form a harmonized experiment. Some studies measure local radiation, others model regional availability, and still others evaluate economic scenarios whose demand and price assumptions differ. Consequently, the article cannot supply a validated city-specific battery size, a universal optimal tilt, or comparable household payback periods. These limitations identify the observations needed to move from a design framework to validated local specifications. The defensible contribution is an original synthesis of the decision logic, supported by traceable literature and an explicit energy-balance example. Further empirical work should test that framework with local records rather than treating the framework itself as a substitute for measurement.

9. Conclusion

Seasonal solar resource variability changes residential photovoltaic design through its interaction with conversion losses, demand timing, and the service expected from the system. The evidence from Singapore, Kuala Lumpur, Jakarta, and Bangkok supports attention to these interactions while resisting a uniform tropical prescription. Annual irradiation remains essential for production assessment, but it cannot establish the weakest-season energy balance or the ability to supply a household through consecutive low-output intervals. The appropriate synthesis is to evaluate annual yield, monthly adequacy, and chronological reliability as related but distinct outcomes. Orientation, capacity, and storage choices become defensible when each is connected to the outcome it is intended to improve.

The practical recommendation is to begin with a clear household objective, use locally qualified resource evidence, compare feasible roof configurations, and evaluate generation and storage together against chronological demand. The hypothetical demonstration establishes why an annually balanced system may still require substantial seasonal imports or additional generation; it does not establish the magnitude of that requirement in any selected city. This boundary is central to the article's contribution. Tropical residential photovoltaic design becomes more credible when favorable resource averages are translated into explicit, testable service claims, and when uncertainty is used to assess the stability of a recommendation rather than hidden within a single optimistic estimate.

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