

論文 / 著書情報
Article / Book Information

Title	Geospatial Assessment and Economic Analysis of Rooftop Solar Photovoltaic Potential in Thailand
Authors	Linux Farungsang, Alvin Christopher Varquez, Koji Tokimatsu
Citation	Sustainability, Vol. 17, Issue 15
Pub. date	2025, 8
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Article

Geospatial Assessment and Economic Analysis of Rooftop Solar Photovoltaic Potential in Thailand

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Abstract

Evaluating the renewable energy potential, such as that of solar photovoltaics (PV), is important for developing renewable energy policies. This study investigated rooftop solar PV potential in Thailand based on open-source geographic information system (GIS) building footprints, solar PV power output, and the most recent land use data (2022). GIS-based overlay analysis, buffering, fishnet modeling, and spatial join operations were applied to assess rooftop availability across various building types, taking into account PV module installation parameters and optimal panel orientation. Economic feasibility and sensitivity analyses were conducted using standard economic metrics, including net present value (NPV), internal rate of return (IRR), payback period, and benefit–cost ratio (BCR). The findings showed a total rooftop solar PV power generation potential of 50.32 TWh/year, equivalent to 25.5% of Thailand’s total electricity demand in 2022. The Central region contributed the highest potential (19.59 TWh/year, 38.94%), followed by the Northeastern (10.49 TWh/year, 20.84%), Eastern (8.16 TWh/year, 16.22%), Northern (8.09 TWh/year, 16.09%), and Southern regions (3.99 TWh/year, 7.92%). Both commercial and industrial sectors reflect the financial viability of rooftop PV installations and significantly contribute to the overall energy output. These results demonstrate the importance of incorporating rooftop solar PV in renewable energy policy development in regions with similar data infrastructure, particularly the availability of detailed and standardized land use data for building type classification.



Academic Editor: Alessandro Franco

Received: 6 June 2025

Revised: 29 July 2025

Accepted: 31 July 2025

Published: 4 August 2025

Citation: Farungsang, L.; Varquez, A.C.G.; Tokimatsu, K. Geospatial Assessment and Economic Analysis of Rooftop Solar Photovoltaic Potential in Thailand. *Sustainability* **2025**, *17*, 7052. <https://doi.org/10.3390/su17157052>

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Keywords: rooftop solar photovoltaic; renewable energy; GIS spatial analysis; solar potential assessment; economic analysis; Thailand

1. Introduction

Energy demand is increasing at an unprecedented rate, and renewable energy, such as solar photovoltaics (PV), has grown rapidly in recent years as a result of a rapid cost decline and abundant solar energy potential [1]. In Thailand, the Alternative Energy Development Plan (AEDP2015-2036), which describes the country’s strategy for sustainable renewable energy development, focuses on promoting renewable energy production. The main goal is for renewables to meet 30 percent of the country’s total final energy consumption, with solar energy production set to reach 6000 MW by 2036 [2]. However, to achieve the sustainable development objective of a net-zero scenario in 2050 for greenhouse gas emissions, challenges remain in terms of renewable energy production. Among them is the need to accelerate the development of solar energy and increase cumulative solar PV capacity [3–5].

Considerable advancement has been made in site selection optimization methodology to improve the evaluation and assessment of solar energy potential (e.g., site selection improvement using analytic hierarchy process (AHP) [6,7] and multi-criteria model development combining geographic information systems (GIS) with the ELECTRE-TRI method [8]). However, existing studies predominantly focus on localized or small-scale evaluations [9]. This makes benchmarking difficult since the dataset is inconsistent due to differing methodologies, restrictions, and criteria adopted by each study. In contrast, large-scale assessments often oversimplify data aggregation processes and neglect critical local factors such as building-specific constraints and geographic variability [10]. While harmonized datasets exist for countries like the United Kingdom [11] and the United States [12], Thailand lacks comparable nationally standardized methodologies for rooftop PV assessment, resulting in coverage gaps and inconsistent metadata for regional analyses. These regions have developed rooftop PV assessment frameworks and set solar installation targets based on local datasets and building typologies that differ from those of Thailand. For example, the National Renewable Energy Laboratory (NREL) [12] utilized LiDAR data as their high-resolution building information, which is not yet widely available in Thailand. Directly applying rooftop PV targets or methodologies from other regions without local adaptation may lead to inaccurate results. Several studies have reviewed Thailand's national solar energy situation, mainly focusing on policy and highlighting implementation challenges in the previous year [13–15]. In addition, the existing literature in Thailand typically emphasizes small-scale assessment or site-specific economic analyses, such as car parking areas [16], hospital buildings [17], and university buildings [18].

Consequently, there exists a significant research gap in the development of systematic and replicable frameworks that can effectively integrate comprehensive localized solar PV potential assessments into consistent large-scale evaluations. To the best of our knowledge, while several comprehensive national-level frameworks have been developed for rooftop PV assessments in other regions, including the European Union, and in country-specific studies like China, Thailand lacks a systematic national-level framework capable of integrating detailed rooftop PV assessments into a unified nationwide evaluation [19–21]. Therefore, the lack of an integrated approach restricts policymakers' and stakeholders' ability to effectively plan, prioritize investments, and implement coherent renewable energy strategies at a national scale.

To address this research gap, this study developed a framework for a detailed nationwide assessment of rooftop solar PV potential in Thailand. The framework is designed to ensure consistency, scalability, and replicability across different regions by relying solely on open-source geospatial data. The primary objectives of this study are to (1) develop and apply a systematic GIS-based methodology to quantify rooftop solar PV power generation potential across Thailand; (2) conduct a detailed economic feasibility assessment of rooftop solar PV installations by calculating key financial metrics; and (3) provide insights for policy improvement by analyzing regional and sectoral variations in rooftop solar PV potential and economic viability. By achieving these objectives, this research provides a national-level assessment for Thailand, with crucial baseline data for policymakers and stakeholders.

The remainder of this paper is organized as follows: Section 2 describes the materials and methods, including the PV power generation potential assessment methodology and economic assessment parameters. Section 3 presents the results and discussion, covering GIS analysis outcomes, comparative analysis of rooftop solar PV potential across regions and building types, and detailed economic analysis results with sensitivity testing. Lastly, Section 4 concludes with a summary of the findings and recommendations for future research.

2. Materials and Methods

Overall, this study consisted of three main steps in assessing the feasibility of rooftop solar photovoltaic (PV) installations, including GIS spatial analysis, solar potential assessment, and economic analysis, as illustrated in Figure 1. The first step involved the consolidation of GIS data to identify rooftop areas suitable for solar PV installation. Next, the geographic potential of the identified rooftops was assessed by taking into account the installation and alignment of PV panels, PV power output, and the utilization factor based on building type. Lastly, economic analysis was conducted to determine financial viability and examine how changes in key parameters, such as electricity prices, affect financial outcomes.

Geospatial Assessment and Economic Analysis of Rooftop Solar Photovoltaic Potential

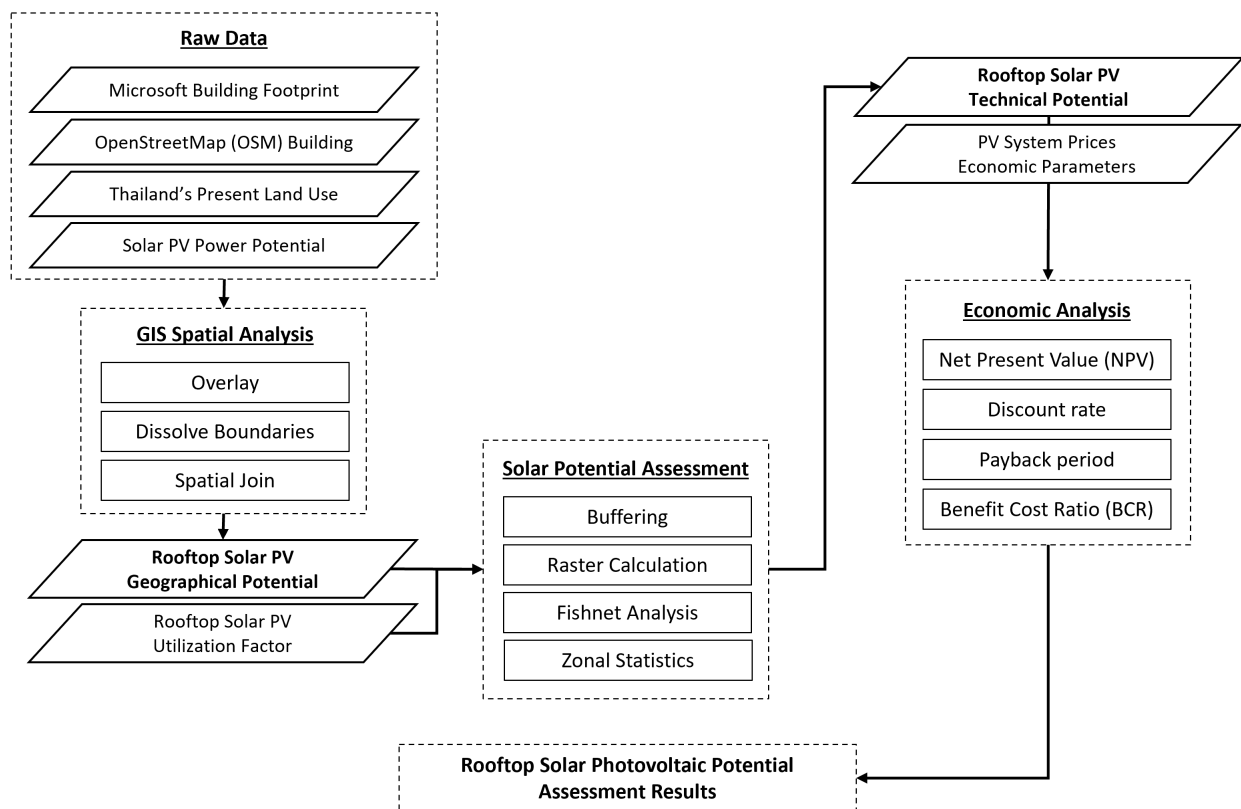


Figure 1. Methodology flowchart for geospatial and economic assessment of rooftop solar photovoltaic potential.

2.1. Data Sources and Study Area

The study utilized various open-source geospatial datasets, including the Microsoft Building Footprint database [22], OpenStreetMap [23], and land use data from the Land Development Department (LDD) of Thailand [24]. These sources provided the foundation for estimating available rooftop areas suitable for solar PV installations. The Microsoft Building Footprint served as the primary spatial data. OpenStreetMap data supplemented building coverage to ensure comprehensive national coverage. The LDD land use dataset enabled systematic building type categorization. The data were subjected to pre-processing to ensure uniformity and consistency. This included the removal of duplicates and correction of any apparent errors in the geospatial datasets.

Thailand is located in Southeast Asia and has a population of approximately 70 million people. The country has a total land area of 513,120 square kilometers, with diverse geographical morphologies. These include northern mountains, a central plain, and a southern peninsular extension. Administratively, Thailand is divided into 77 provinces.

These provinces are commonly grouped into broader regions. Following the categorization from the LDD, this study utilized a five-region classification, as illustrated in Figure 2. This included the Central, Northern, Northeastern, Eastern, and Southern regions. These regions differ in terms of topography, population density, urbanization levels, and economic activities. In addition, the land use data from the LDD were used to classify building types. At the level 1 categorization, this dataset consisted of urban and built-up land, agricultural land, forest land, water body, and miscellaneous land. For this analysis, only the urban and built-up land was selected to represent the building types. This included U1 (city, town, and commercial areas), U2 (villages), and U5 (industrial land), which correspond to commercial, residential, and industrial building types, respectively [24]. This categorization allowed for a more accurate estimation of the solar PV potential specific to each building type in Thailand. All the detailed data information can be seen in Table 1.

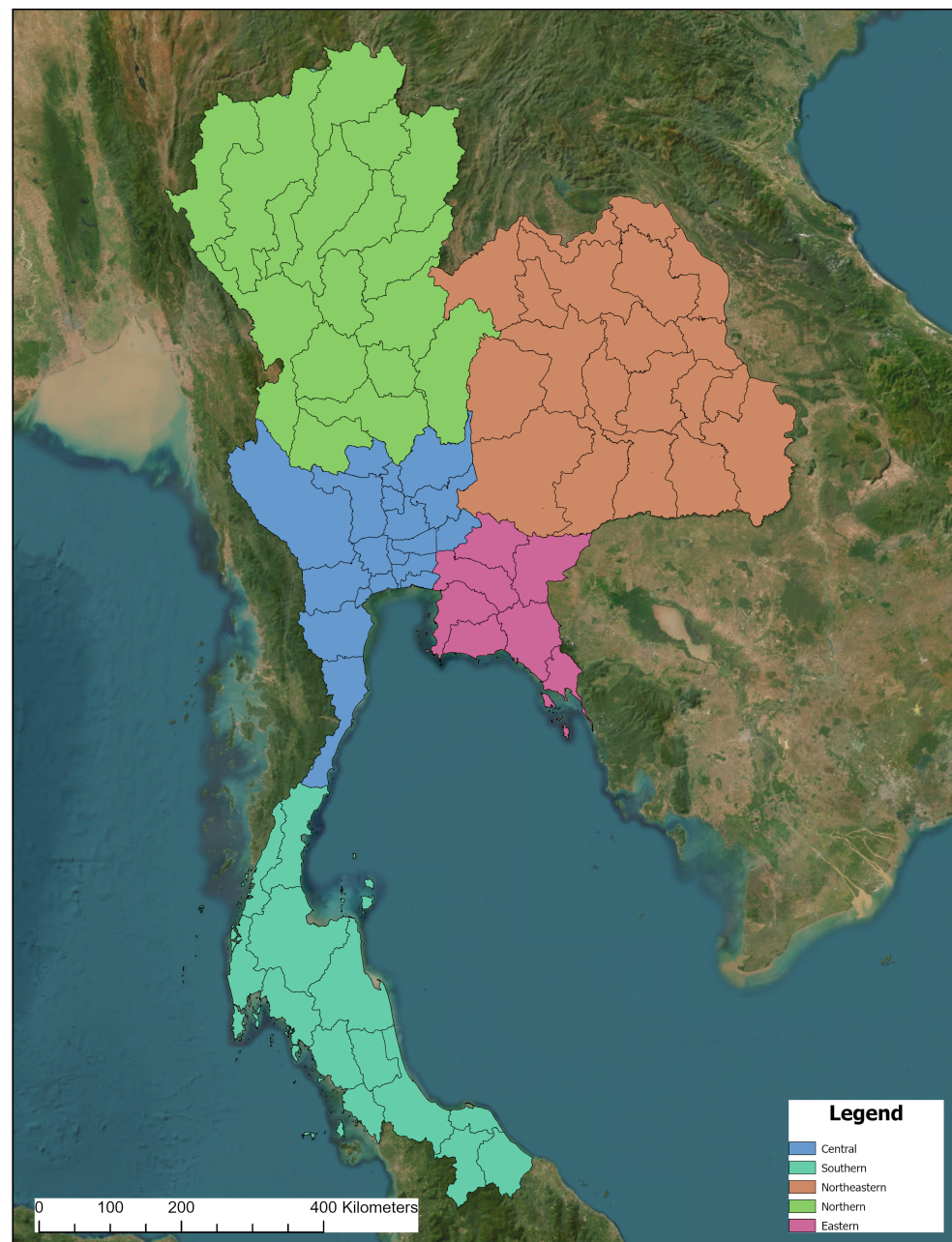


Figure 2. Regional administrative classification of Thailand.

Table 1. Data source information used for rooftop solar PV potential assessment, including building footprint, land use, PV panel assumption, PV installation parameters, PV power output, and PV utilization factors for each building type.

Building Footprint	Thailand's Present Land Use	Solar PV Panel Assumption	Solar PV Installation	PV Power Output	Rooftop Solar PV Utilization Factor
Microsoft Building Footprint [22], Open-StreetMap [23]	Land Development Department of Thailand [24]	Polycrystalline 360 W/panel, Size 1 × 2 m	Buffer 0.05 m between each panel, 20% height, and 1 m within the rooftop area [25]	Global Solar Atlas, World Bank [26]	Commercial: 0.19 [27], Residential: 0.15 [28], Industrial: 0.6 [29]

2.2. Power Generation Potential of Rooftop Solar PV

2.2.1. Overview

The potential power output from solar PV installations was estimated by employing a series of geoprocessing tools to estimate the available rooftop areas. This involved creating theoretical PV panel installations considering rooftop areas, building types, solar PV installation, and alignment criteria with geoprocessing tools in ArcGIS Pro 3.1.0. The ArcGIS ModelBuilder diagram is shown in Figure A1, and the methodology flowchart is outlined in Figure 1. This flowchart outlines the workflow used to analyze building footprints [22,23], land use [24], and PV power output data [26]. The output is rooftop solar PV technical power generation potential, which is used for subsequent economic analysis in Section 2.3.

2.2.2. GIS Data Integration

To prepare the geospatial datasets for analysis, a series of integration and preprocessing steps were performed. The Microsoft Building Footprint and OpenStreetMap datasets were merged into a single feature class. This operation combined all relevant building footprint data from both sources, ensuring comprehensive coverage and minimizing data redundancy. Then, the overlapped building data were removed, and the adjacent or overlapping polygons were consolidated into unified features to reduce the dataset complexity and enhance the efficiency of subsequent analyses.

Lastly, land use information was added using the Spatial Join function. This operation appended land use attributes to each building footprint based on spatial location, allowing the categorization of buildings into residential, commercial, and industrial types, which was crucial for accurately estimating the solar PV potential specific to each building category.

2.2.3. Quality Assurance and Quality Control (QA/QC) for Rooftop Area

The purpose of this process was to verify the accuracy of rooftop availability estimates through the analysis of satellite imagery. This approach enabled the identification of discrepancies between the obtained rooftop area and the actual rooftop area. Visual inspection was conducted to account for factors such as shading from trees and misidentification of rooftops, chimneys, and HVAC systems as non-rooftop areas. A random sampling of 30 buildings from each building type across all regions was conducted to compare the geospatial analysis results with real-world data. This field verification was performed using high-resolution satellite imagery via Google Earth, identifying non-usable rooftop areas such as those affected by shading, HVAC systems, or incorrect rooftop identification. Misclassifications of parking lots, balconies, or vegetated roofs were categorized as incorrect rooftop identification.

In addition, a one-way analysis of variance (one-way ANOVA) statistical test was conducted to evaluate the consistency of the estimation accuracy across building types. The F-value represents the ratio of the variance between the means of different building

types to the variance within each building type. The p-value measures the probability of observing the differences between group means assuming the null hypothesis is true. In this study, the null hypothesis states that there are no statistically significant differences in estimation error rates between building types. A significance level of 0.05 was used as the threshold. If the p-value is less than 0.05, the null hypothesis is rejected, indicating significant differences exist. Otherwise, the null hypothesis is not rejected.

2.2.4. Feature Processing for PV Panel Grid Cell Generation

To account for potential variations in roof types, such as gable roofs (characterized by two sloping sides that form a ridge), hip roofs (sloped on all four sides), flat roofs (with a minimal slope), and other complex configurations that affected rooftop areas for PV installation, the use of three-dimensional (3D) shape data, such as LiDAR (Light Detection and Ranging) or high-resolution imagery, is required. However, due to the unavailability of 3D data in this study area, the building footprint in Shapefile data format from the LDD was used as a proxy for the rooftop area, assuming a flat roof shape for all roof types, and served as the boundary for grid cell generation.

Following this, grid cell generation was performed within each building footprint to establish discrete spatial units for PV module placement. Each grid cell represented a standardized unit capable of accommodating a single PV module installation, thus enabling the quantification of installable solar PV. In addition, solar irradiance, building attributes, and land use data were integrated into the grid cell at the individual module level. This ensured accurate and consistent calculation of maximum installable PV panels across different building types and regions. Since PV modules cannot be installed at the rooftop edges, the effective rooftop area was calculated by removing the 1 m wide area along the building edges. The grid cells were generated according to each building footprint boundary. The size of the grid cells varied depending on the dimensions of the PV modules. In this study, the grid width was set equal to the width of Thailand's standard PV modules, which is commonly around 1 m by 2 m, with the buffer set to 0.05 m between each panel for standard installations. The grid height was set at 1.2 times the height of the module to account for shading effects [30]. As a result, the final dimensions of the PV panel grid cell were 1.05 m by 2.40 m. Finally, any grid cells located outside the usable rooftop area were removed from the dataset.

2.2.5. Rooftop Solar PV Utilization Factor (RSUF)

While the grid cell generation established the theoretical PV module placement, real-world constraints necessitated further reduction of the available area. Rooftop obstacles, including HVAC equipment, ventilation systems, and other structural elements, reduced the usable space for solar installations. Therefore, the total roof area needed to be adjusted to reflect the actual available area for solar PV installation to determine the potential PV power output. The RSUF is defined as the ratio of actual installable PV area, considering obstacles, in proportion to the building's rooftop area. The RSUF varies widely between studies due to differing methodologies, building morphologies, and regional considerations. The RSUF for this study was determined based on the minimum value from the previous literature to ensure conservative estimates and viability under worst-case-scenario conditions [27–29]. A comparison with the literature can be found in Table 2.

Table 2. Rooftop solar PV utilization factor (RSUF) values for different building types, as reported in the literature and adopted in this study.

Researchers	Commercial Building	Residential Building	Industrial Building
Gutschner et al., 2002 [31]	0.4	0.4	0.4
Lehmann & Peter, 2003 [32]	0.9	0.9	0.9
Denholm & Margolis, 2008 [33]	0.60–0.65	0.22–0.27	n/a
Yue & Huang, 2011 [34]	0.66	0.58	0.63
Peng & Lu, 2013 [35]	0.55	0.55	0.55
Schallenberg-Rodríguez, 2013 [29]	n/a	0.35–0.48	0.6–0.9
Dehwah, Asif, & Rahman, 2018 [28]	n/a	0.15–0.44	n/a
Boulahia, Djiar, & Amado, 2021 [36]	n/a	0.18–0.35	n/a
Ghaleb & Asif, 2022 [27]	0.19–0.56	n/a	n/a
RSUF used in this study	0.19 [27]	0.15 [28]	0.6 [29]

2.2.6. Solar Energy Potential Calculations

The potential power output (PVOUT) from solar PV installations was estimated using technical specifications from the World Bank’s Global Solar Atlas [26]. The PVOUT data have a spatial resolution of 30 arcsec (nominally 1 km), considered at optimum tilt angle, providing spatially distributed values across Thailand. The referenced solar PV panel data based on the Thailand market was uniformly applied at 360 Watt-peak (Wp) capacity. These data enable the estimation of potential energy generation and provide a realistic estimate of the annual energy output for the proposed solar PV system. The calculation was performed using the following equation:

$$E_{\text{annual}} = \text{PVOUT} \times P_{\text{system}} \quad (1)$$

where E_{annual} is the estimated annual energy production (in kilowatt-hours per year, kWh/year), PVOUT is the specific photovoltaic power output for the location (in kilowatt-hours per kilowatt-peak, kWh/kWp), and P_{system} is the total installed capacity of the solar panels (in kilowatt-peak, kWp).

2.3. Economic Assessment

2.3.1. Economics Feasibility Assessment Parameters

To conduct an economic evaluation of investment in rooftop solar PV, standard economic metrics, including the net present value (NPV), internal rate of return (IRR), payback period, and benefit–cost ratio (BCR), were calculated to assess the financial viability of solar PV installations across different regions and building types. The procedure was undertaken by incorporating the annual energy generation potential obtained from the geospatial analysis with economic inputs and assumptions in Table 3.

In this study, the cash flow for rooftop solar PV was estimated by combining the annual energy generation potential obtained from the geospatial analysis with investment costs and economic parameters following the Metropolitan Electricity Authority (MEA) of Thailand and the National Survey Report of PV Power Applications [37]. Operation and maintenance (O&M) costs were set at 1% of the initial capital expenditure (CAPEX) per year. The annual cash inflow was calculated by multiplying the PV electricity generation potential (in GWh/year) by the electricity price of USD 0.083/kWh and was adjusted for system performance degradation by applying a 0.5% annual reduction in output. In general, PV degradation rates vary by manufacturer, technology, and installation conditions. As such, the degradation rate of 0.5% per year was selected based on the median value reported by the National Renewable Energy Laboratory (NREL, Golden, CO, USA) [38], which accounted for a variety of PV module brands and installation environments.

All the economic metrics were calculated following standard equations. First, the NPV was calculated as the sum of discounted net cash flows over a 25-year project lifetime. The IRR was obtained as the discount rate that yielded an NPV of zero. The payback period was determined as the year in which the cumulative net cash flows became positive. Finally, the BCR was calculated as the ratio of total benefits to total costs. In this study, the benefit was measured as the total monetary value of electricity generated by the rooftop solar PV system based on the estimated annual energy output. This represents the cost savings from offsetting grid electricity usage with solar generation. The cost included CAPEX, O&M, and the degradation rate over the project lifetime. The CAPEX values were derived from the PV system installation costs reported in the National Survey Report of PV Power Applications in Thailand [37]. The discount rate was set at 6.3145%, reflecting the 2022 Bank of Thailand policy rate. In all calculations, the annual PV output was reduced by 0.5% each year, following the degradation rate. All parameter values and assumptions are summarized in Tables 3 and 4.

Table 3. Inputs and assumptions used for economic metrics calculations, including PV module capacity, system type, lifetime, operation and maintenance, degradation rate, and discount rate.

Parameter	Value
PV Module Capacity	360 W capacity per module
PV Systems Type	On-grid, self-consumption, no private power purchase agreement
PV Lifetime (years)	25
Operation and Maintenance	1%
Degradation Rate	0.50%
Discount Rate	6.3145%

Table 4. Capital expenditure for rooftop PV systems by building type (units: USD per PV panel).

Building Type	Minimum System Price (USD)	Maximum System Price (USD)	Average System Price (USD)
Residential	349.68	450.98	400.33
Commercial	251.64	300.66	276.15
Industrial	251.64	300.66	276.15

Data are derived from the National Survey Report of PV Power Applications [37]. Currency exchange rate calculated as 1 USD = 36 THB [39].

2.3.2. Sensitivity Analysis

To evaluate the robustness of the economic feasibility of rooftop solar PV installations, a sensitivity analysis was performed on key financial parameters. This process examines how changes in key parameters, including electricity prices, PV system costs, and discount rates, impact the BCR, NPV, IRR, and payback period. In general, electricity prices influence the value of offset energy (defined as the electricity generated by the solar PV system, thereby creating cost savings from grid electricity purchases). PV system costs determine capital expenditure. Discount rates reflect the time value of money and investor risk preferences. In this study, the key parameters varied from the base case value at $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$. This provided insight into which factors the investment is most sensitive to regarding economic feasibility.

3. Results and Discussion

3.1. GIS Analysis Results

Figure 3 visualizes the total number of buildings used in this study, classified by five regions and three building types, namely commercial, residential, and industrial buildings. In total, the number of commercial, residential, and industrial buildings used in this study was 1,749,558, 9,244,385, and 267,056, respectively. Regarding the QA/QC process, one-way ANOVA was conducted to test differences in rooftop area estimation error

rates between building types. The results indicated no statistically significant differences for any building type ($F = 1.14, p = 0.35$) when comparing ground truth and obtained building footprint data. This illustrated consistency across data sources and validated the methodological reliability of GIS spatial analysis.

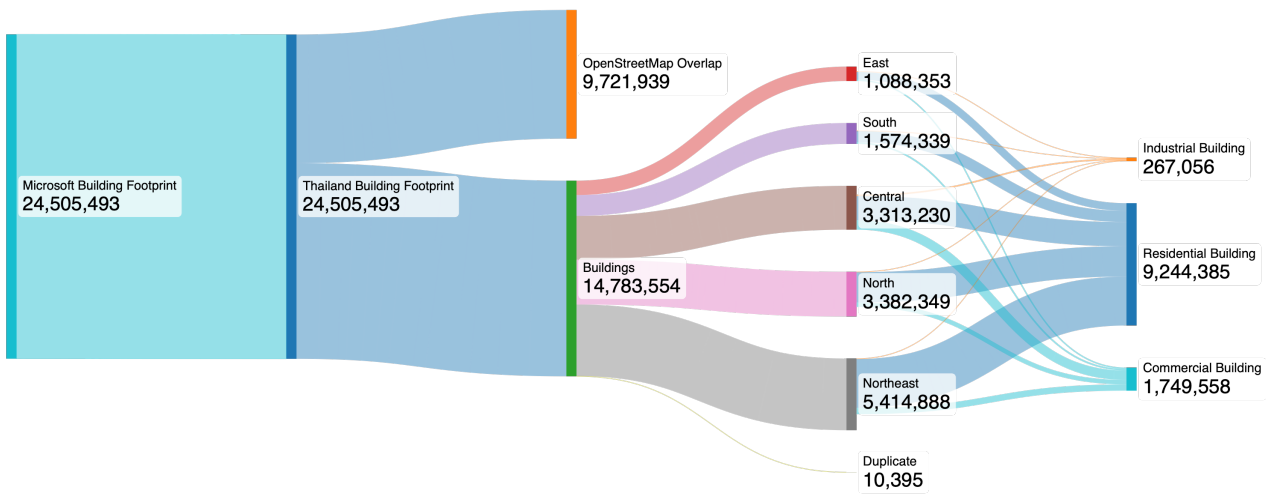


Figure 3. The number of buildings used in this study.

3.2. Comparisons and Analysis of Rooftop Solar Photovoltaic Potential

The findings are presented in Tables A1–A3 and Figure 4, revealing a total rooftop solar PV potential of 50.32 TWh/year, equivalent to an installable capacity of 33,972.98 MW (Tables A1 and A2). This potential is highly significant in the national context for two key reasons. First, it could satisfy 25.5% of Thailand’s 2022 electricity demand [40]. Second, the total rooftop PV installable capacity is significantly greater than the AEDP’s 6000 MW solar energy target set for 2036 [2]. This substantial gap between the current national target and the installable capacity indicates a strong growth potential for rooftop solar PV in Thailand.

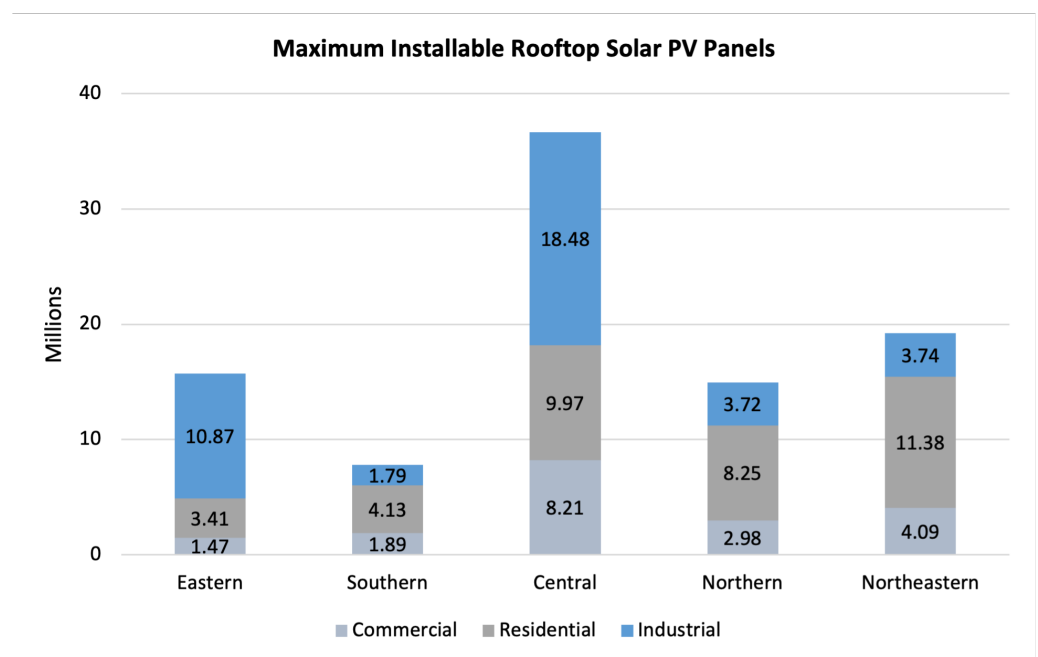


Figure 4. Regional maximum installable rooftop solar PV panels.

In terms of spatial distribution, Figure 5 visualizes the rooftop PV potential distribution across Thailand. The provincial ranking system (Rank 1–5) was applied for visualization

using a quantile classification function in ArcGIS. Consequently, the ranking was assigned based on the total rooftop solar PV potential per province, where Rank 1 represents the highest potential provinces and Rank 5 represents the lowest potential provinces. This visualization facilitates the identification of high-potential provinces for targeted renewable energy development. At the regional level, the Central region showed the highest potential, contributing 19.59 TWh/year with 36.66 million PV panels, due to its higher building density and larger building footprint area compared to other regions (Figure 4 and Table A3). Subsequently, the Northeastern region contributed 10.49 TWh/year, with 19.21 million PV panels, followed by the Eastern region (8.16 TWh/year, 15.75 million PV panels), Northern region (8.09 TWh/year, 14.95 million PV panels), and Southern region (3.99 TWh/year, 7.81 million PV panels). Furthermore, the analysis revealed that residential and industrial building types contribute a significant number of PV panels (37.14 million and 38.60 million, respectively). This means that the residential and industrial sectors are the primary drivers of this potential, containing a combined capacity of over 27,000 MW.

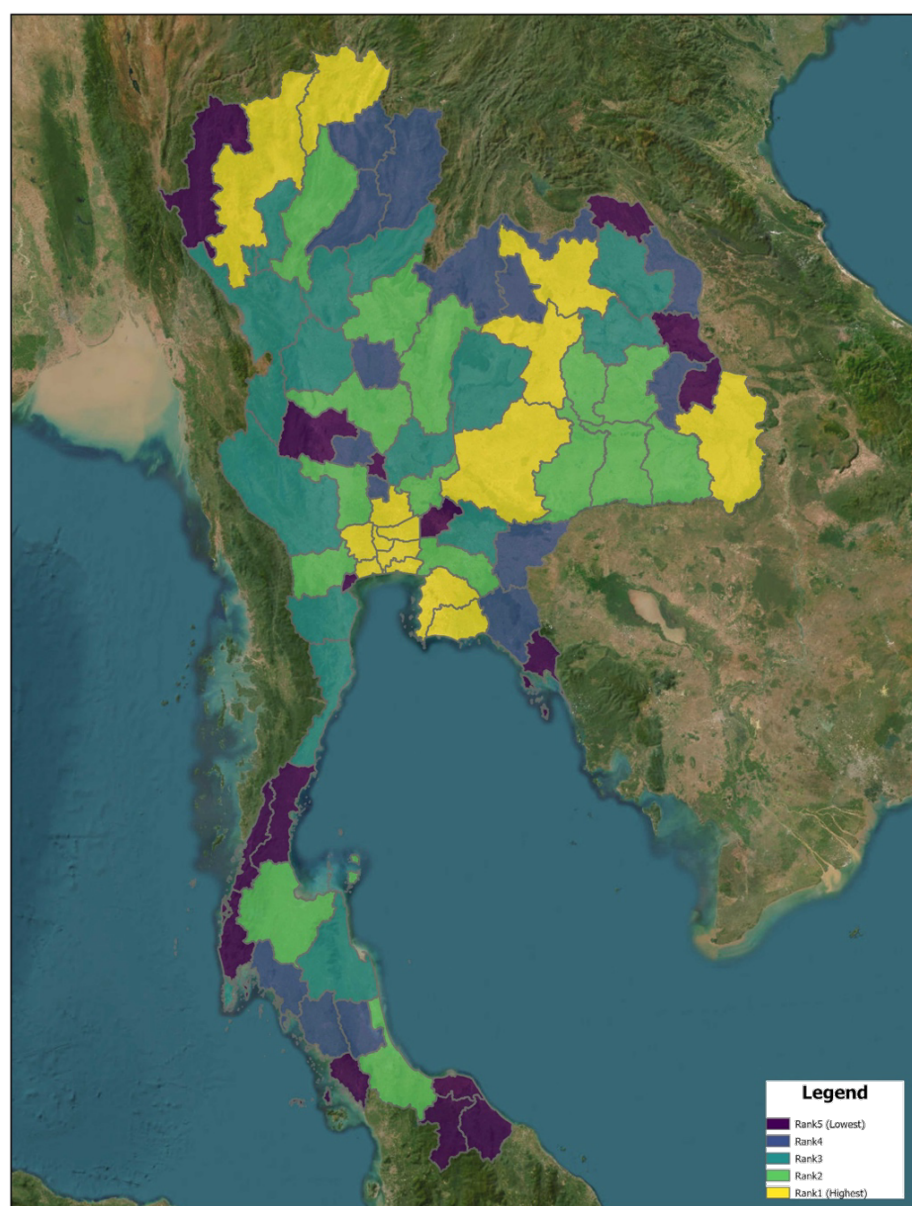


Figure 5. Spatial distribution of Thailand's rooftop solar PV potential.

3.3. Economic Analysis Result

3.3.1. Benefit–Cost Ratio (BCR), Net Present Value (NPV), Payback Period, and Internal Rate of Return (IRR)

Tables 5 and 6 show the economic feasibility of rooftop solar PV installations across different regions and building types in Thailand. The NPV, IRR, BCR, and payback period were calculated using the information from the GIS analysis in the previous section, summarized in Table A3, and the economic assumptions from Tables 3 and 4. The analysis revealed significant variation in economic viability based on both geographic and building-type factors. The baseline at the national level indicates an NPV of USD 1237.12 million, an IRR of 13.66%, a BCR of 1.75, and a payback period of approximately 8 years. These baseline data are used for the comparison of regional and sectoral variations. In terms of NPV, the Central region exhibited the most favorable financial outcomes, with the NPV reaching USD 1913.23 million for the commercial sector, USD 1330.20 million for the residential sector, and USD 4502.28 million for the industrial sector. In contrast, the Southern region showed a low NPV, at USD 413.45, 446.84, and 385.24 million for the commercial, residential, and industrial sectors, respectively. This lower economic viability in the Southern region is primarily due to its substantially smaller rooftop area and PV power output. This indicates that without additional financial incentives or technological advancements, the Southern region may not be as economically favorable in comparison to other regions. For sectoral variations, residential rooftop PV installations, while more expensive, offered positive NPVs in all regions. The Northeastern region, with an NPV of USD 2343.85 million, demonstrated the highest potential for residential solar PV expansion due to the high rooftop PV area.

Table 5. Identified minimum and maximum PV system costs (in million USD) for commercial, residential, and industrial buildings by region.

Regions in Thailand	Commercial (Min)	Commercial (Max)	Residential (Min)	Residential (Max)	Industrial (Min)	Industrial (Max)	Total Cost (Min)	Total Cost (Max)
Eastern	369.40	441.36	1193.01	1538.65	2734.53	3267.23	4296.94	5247.24
Southern	474.34	566.74	1444.58	1863.11	450.87	538.70	2369.79	2968.55
Central	2065.08	2467.37	3487.71	4498.17	4649.26	5554.97	10,202.06	12,520.50
Northern	750.16	896.29	2883.85	3719.36	935.83	1118.13	4569.84	5737.78
Northeastern	1029.12	1229.60	3978.53	5131.18	941.87	1125.35	5949.52	7486.13
Total	4688.10	5601.36	12,987.69	16,750.48	9712.36	11,604.37	27,388.14	33,956.21

Table 6. Economic analysis results for rooftop solar PV installations by region and building type, showing net present value (NPV, million USD), internal rate of return (IRR, %), payback period (years), and benefit–cost ratio (BCR).

Region	Building Type	NPV (Million USD)	IRR (%)	Payback Period (Years)	BCR
Eastern	Commercial	329.30	15.02	7	1.89
	Residential	393.91	9.74	10	1.33
	Industrial	2447.84	15.05	7	1.90
Southern	Commercial	413.45	14.84	7	1.87
	Residential	446.84	9.54	10	1.31
	Industrial	385.24	14.68	7	1.85
Central	Commercial	1913.23	15.34	7	1.93
	Residential	1330.20	10.25	9	1.38
	Industrial	4502.28	15.71	7	1.97
Northern	Commercial	743.55	15.92	7	1.99
	Residential	1120.47	10.32	9	1.39
	Industrial	933.61	15.98	7	2.00
Northeastern	Commercial	1034.02	16.04	6	2.00

Table 6. Cont.

Region	Building Type	NPV (Million USD)	IRR (%)	Payback Period (Years)	BCR
	Residential	1615.93	10.49	9	1.41
	Industrial	946.97	16.05	6	2.01
Overall		1237.12	13.66	8	1.75

3.3.2. Sensitivity Analysis Result

Figure 6 shows overall sensitivities of $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$ compared to the baseline scenario, which were calculated using the geospatial analysis results and economic parameters described in the previous section. The sensitivity analysis indicated that the economic viability of rooftop solar PV installations in Thailand is most sensitive to changes in electricity prices and PV system costs. Tables A4 and A5 show that higher electricity prices enhance revenue from energy savings, with the NPV increasing by up to 53% with a 20% change in electricity price. Furthermore, PV system costs contribute to overall improvements in all economic parameters. A 20% reduction in PV system costs improves the overall BCR to 2.22 (27% increase) and the IRR to 17.88% (31% increase), and it reduces the payback period to 5.93 years (23% decrease). While changes in PV system cost significantly affect all the financial metrics, the magnitude of the impact is less pronounced than that of electricity price changes. Table A6 shows that NPV is sensitive to the discount rate, varying by 31% with a 20% change. However, the discount rate does not affect the payback period or IRR because these metrics are independent of discounting; the payback period is based on actual cash flows, and the IRR is the discount rate that sets the NPV to zero.

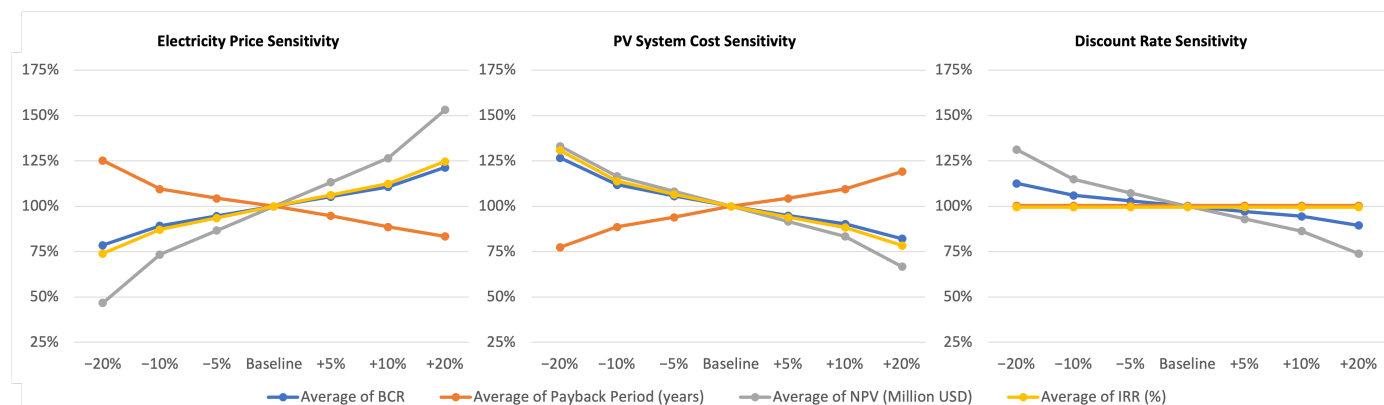


Figure 6. Sensitivity analysis of electricity price, PV system cost, and discount rate within the range from -20% to $+20\%$.

Tables A7–A9 show the financial viability differences of rooftop PV across different regions and sectors. The significance of regional variations can be seen in the Central region. Under the baseline conditions, the Central region’s NPV is 2581.90 million USD, significantly higher than the Southern region’s (415.18 million USD). For sectoral variations, the residential sector demonstrates the highest sensitivity. Reducing PV system costs can significantly improve the financial outcomes of the residential sector with 59% improvements from the baseline in comparison to 23–24% improvements from commercial and industrial sectors. This indicates that stakeholders should focus on the residential sector when it comes to the PV system cost reduction program.

3.3.3. Limitations and Assumptions

It is important to acknowledge a limitation of this study concerning the interpretation of rooftop area. The current methodology utilized the constant value method, in which key

parameters were held fixed across all regions and building types based on 2022 market conditions and technical specifications, including minimum RSUF, PV panel specifications, and economic parameters. The constant-value method has the advantage of providing a conservative baseline for national-scale policy planning and ensuring that estimated potentials represent a reliable lower bound. Nevertheless, this made the calculations restricted and unable to capture the actual spatial availability of the rooftop area. Moreover, the geometric simplifications in the GIS modeling assume uniform roof conditions and do not account for complex architectural features, varying roof orientations within individual buildings, or site-specific shading from adjacent structures. To overcome these limitations, further investigation of minimum, average, and maximum RSUF values is needed in order to strengthen the assessment results.

The economic analysis is based on several assumptions and market conditions that may change over time. Factors such as fluctuations in PV module prices, changes in electricity tariffs, and evolving government policies can influence actual economic outcomes. As such, the calculated NPV, IRR, payback period, and BCR represent a snapshot rather than a long-term forecast, which may differ as these market parameters evolve. Nevertheless, this study demonstrates a geospatial analysis framework that relies solely on open-access data, allowing for its global applicability in future work. This successful assessment of rooftop solar PV technical output in Thailand demonstrates the effectiveness and viability of this approach.

4. Conclusions

Understanding the power generation potential of rooftop solar PV is crucial for Thailand's future sustainable energy policies. In this study, detailed geospatial analysis was combined with economic evaluation to assess rooftop solar PV potential, determine financial feasibility, and examine the differences across regions and building types. The developed methodology successfully quantified Thailand's national rooftop solar PV potential, revealing a significant technical output of 50.32 TWh/year, which could satisfy 25.5% of the country's 2022 electricity demand. The economic analysis confirmed the financial viability of such installations, particularly in the commercial and industrial sectors, with a national average payback period of approximately 8 years.

This study's primary contribution is its systematic and replicable methodological framework. Similar large-scale rooftop PV assessments can be adopted in other countries, particularly in developing regions where high-resolution proprietary data is often unavailable. For Thailand specifically, this work provides detailed national baseline data for energy planning. An installable capacity of 33,973 MW is quantified, accounting for over five times the government's AEDP 2036 solar target. This result provides concrete evidence that rooftop PV can play a significant role in the country's decarbonization strategy. While Thailand's overall solar targets are specified in the AEDP, rooftop PV policy remains fragmented and faces key barriers, such as subsidy uncertainty and complex permitting processes [14,15]. Our findings offer critical baseline data to support more coordinated and effective rooftop PV policy development. Finally, from a data perspective, open-source datasets were utilized across all procedures. This means that evidence-based energy analysis at a national scale is possible and can be replicated in other countries.

These findings have direct policy implications. Regional disparities suggest the need for region-specific policies rather than a one-size-fits-all approach. Incentive programs could be tailored to unlock potential in the Southern region. Furthermore, the sensitivity analysis reveals that while residential installations are viable, their financial attractiveness is highly sensitive to initial capital costs. This suggests that financing mechanisms for the residential sector could accelerate adoption. Lastly, policymakers should recognize that the 50.32 TWh/year potential identified here represents a conservative baseline. This

means the true installable capacity is likely even greater, thus reinforcing the significant opportunity for expansion and supportive PV policies and highlighting further possibilities for rooftop PV installations beyond our conservative estimate.

While providing a conservative lower-bound estimate, this study acknowledges its limitations, primarily the use of the RSUF. Future research should prioritize developing regional-specific RSUF values for Thailand to refine the accuracy of the potential assessment. Furthermore, as high-resolution 3D building data become more accessible with the growing development of “Digital Twins”, incorporating them into this framework would allow for more precise calculations of roof orientation and shading effects. This would allow a deeper understanding of the rooftop solar PV situation and facilitate Thailand’s transition toward a sustainable energy future.

Author Contributions: Conceptualization, L.F., A.C.G.V. and K.T.; methodology, L.F.; validation, L.F.; formal analysis, L.F.; investigation, L.F.; data curation, L.F.; writing—original draft preparation, L.F.; writing—review and editing, L.F., A.C.G.V. and K.T.; supervision, A.C.G.V. and K.T. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by a Grant-in-Aid of the Academy of Energy and Informatics, Institute of Science Tokyo.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AEDP	Alternative Energy Development Plan
BCR	Benefit–Cost Ratio
CAPEX	Capital Expenditure
GIS	Geographic Information Systems
IRR	Internal Rate of Return
LDD	Land Development Department of Thailand
MEA	Metropolitan Electricity Authority of Thailand
NPV	Net Present Value
OSM	OpenStreetMap
PV	Photovoltaic
PVOUT	Photovoltaic Power Output
QA/QC	Quality Assurance and Quality Control
RSUF	Rooftop Solar PV Utilization Factor
THB	Thai Baht
TWh	Terawatt-hour
USD	United States Dollar
Wp	Watt-peak

Appendix A

Table A1. Geospatial assessment results of annual rooftop solar PV energy generation potential by region and building type in Thailand (units: GWh/year).

Region	Commercial	Residential	Industrial	Total
Eastern	759.29	1769.35	5631.13	8159.77

Table A1. *Cont.*

Region	Commercial	Residential	Industrial	Total
Southern	965.41	2111.72	909.74	3986.87
Central	4318.49	5354.77	9921.28	19,594.54
Northern	1618.25	4448.64	2042.92	8091.81
Northeastern	2234.26	6208.83	2045.47	10,488.56
Total	9895.69	9893.32	20,532.55	50,321.56

Table A2. Geospatial assessment results of rooftop PV installable capacity by region and building type in Thailand (units: MW, percentage of the national total).

Region	Commercial (MW)	Residential (MW)	Industrial (MW)	Total Installable Capacity (MW)	Total Percentage
Eastern	528.47	1228.24	3912.12	5668.83	16.22%
Southern	678.61	1487.24	645.03	2810.88	7.92%
Central	2954.39	3590.68	6651.41	13,196.48	38.94%
Northern	1073.20	2969.00	1338.83	5381.03	16.09%
Northeastern	1472.30	4095.99	1347.47	6915.76	20.84%
Total	6706.97	13,371.14	13,894.87	33,972.98	100%

Table A3. Geospatial assessment results of rooftop PV panels and PV potential by region and building type in Thailand (units: PV panels, TWh/year, and percentage of the national total).

Region	Commercial	Residential	Industrial	Yearly Output (TWh)	Total Percentage
Eastern	1,467,979	3,411,772	10,866,990	8.16	16.22%
Southern	1,885,016	4,131,210	1,791,762	3.99	7.92%
Central	8,206,625	9,974,118	18,476,152	19.59	38.94%
Northern	2,981,119	8,247,212	3,718,973	8.09	16.09%
Northeastern	4,089,725	11,377,752	3,742,972	10.49	20.84%
Total	18,630,464	37,142,064	38,596,849	50.32	100%

Table A4. Sensitivity analysis results indicating the impact of electricity price variations on BCR, payback period, NPV, and IRR for the national baseline scenario.

Electricity Price (USD/kWh)	BCR	Payback Period (Years)	NPV (Million USD)	IRR (%)
−20%	1.37	9.60	579.20	10.11
−10%	1.56	8.40	908.16	11.92
−5%	1.65	8.00	1072.64	12.80
Baseline	1.75	7.67	1237.12	13.66
+5%	1.84	7.27	1401.60	14.52
+10%	1.94	6.80	1566.08	15.37
+20%	2.12	6.40	1895.04	17.05

Table A5. Sensitivity analysis results indicating the impact of PV system cost variations on BCR, payback period, NPV, and IRR for the national baseline scenario.

PV System Cost (%)	BCR	Payback Period (Years)	NPV (Million USD)	IRR (%)
−20%	2.22	5.93	1647.62	17.88
−10%	1.96	6.80	1442.37	15.56
−5%	1.85	7.20	1339.75	14.57
Baseline	1.75	7.67	1237.12	13.66
+5%	1.66	8.00	1134.50	12.84
+10%	1.58	8.40	1031.88	12.08
+20%	1.44	9.13	826.63	10.72

Table A6. Sensitivity analysis results indicating the impact of discount rate variations on BCR, payback period, NPV, and IRR for the national baseline scenario.

Discount Rate (%)	BCR	Payback Period (Years)	NPV (Million USD)	IRR (%)
−20%	1.97	7.67	1624.36	13.66
−10%	1.85	7.67	1421.71	13.66
−5%	1.80	7.67	1327.28	13.66
Baseline	1.75	7.67	1237.12	13.66
+5%	1.65	7.67	1068.65	13.66
+10%	1.56	7.67	914.60	13.66
+20%	1.43	7.67	679.13	13.66

Table A7. Detailed sensitivity analysis of BCR by region and sector under varying PV system costs, electricity prices, and discount rates.

	Central			Eastern			Northeastern			Northern			Southern		
	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res
PV System Cost (%)															
−20%	2.44	2.49	1.76	2.40	2.40	1.69	2.54	2.54	1.79	2.52	2.53	1.77	2.37	2.35	1.67
−10%	2.15	2.20	1.55	2.12	2.12	1.49	2.24	2.24	1.58	2.23	2.23	1.56	2.09	2.07	1.47
−5%	2.03	2.08	1.46	2.00	2.00	1.41	2.12	2.12	1.49	2.10	2.11	1.49	1.98	1.96	1.38
Baseline	1.93	1.97	1.38	1.89	1.90	1.33	2.00	2.01	1.41	1.99	2.00	1.41	1.87	1.85	1.31
5%	1.83	1.87	1.31	1.80	1.80	1.26	1.90	1.90	1.33	1.89	1.90	1.33	1.78	1.77	1.26
10%	1.74	1.78	1.24	1.71	1.71	1.20	1.81	1.81	1.27	1.80	1.80	1.27	1.69	1.67	1.18
20%	1.58	1.62	1.13	1.56	1.56	1.09	1.65	1.65	1.15	1.64	1.64	1.14	1.54	1.52	1.07
Electricity Price (USD/kWh)															
−20%	1.52	1.55	1.08	1.49	1.49	1.04	1.58	1.58	1.10	1.57	1.57	1.09	1.47	1.46	1.02
−10%	1.72	1.76	1.23	1.69	1.69	1.18	1.78	1.78	1.25	1.79	1.79	1.24	1.67	1.66	1.17
−5%	1.82	1.86	1.31	1.79	1.79	1.26	1.89	1.89	1.33	1.89	1.89	1.31	1.77	1.76	1.25
Baseline	1.93	1.97	1.38	1.89	1.90	1.33	1.99	2.00	1.41	1.99	2.01	1.41	1.87	1.85	1.34
5%	2.03	2.07	1.46	1.99	2.00	1.40	2.11	2.11	1.48	2.10	2.10	1.48	1.97	1.95	1.38
10%	2.13	2.18	1.53	2.09	2.10	1.48	2.22	2.22	1.56	2.20	2.21	1.54	2.07	2.05	1.45
20%	2.34	2.39	1.68	2.29	2.30	1.62	2.43	2.43	1.71	2.41	2.42	1.69	2.27	2.25	1.60
Discount Rate (%)															
−20%	2.17	2.22	1.56	2.13	2.13	1.50	2.26	2.26	1.58	2.24	2.25	1.58	2.11	2.09	1.47
−10%	2.04	2.09	1.46	2.01	2.01	1.43	2.13	2.13	1.49	2.11	2.12	1.49	1.98	1.97	1.43
−5%	1.98	2.03	1.42	1.95	1.99	1.37	2.06	2.06	1.44	2.05	2.06	1.45	1.91	1.91	1.39
Baseline	1.93	1.97	1.38	1.89	1.90	1.33	1.99	2.00	1.33	2.00	2.01	1.41	1.85	1.84	1.37
5%	1.87	1.91	1.34	1.84	1.84	1.29	1.95	1.95	1.38	1.94	1.94	1.34	1.88	1.87	1.35
10%	1.82	1.86	1.31	1.79	1.79	1.26	1.89	1.89	1.31	1.77	1.75	1.29	1.72	1.71	1.24
20%	1.72	1.76	1.24	1.69	1.70	1.19	0.78	0.78	0.58	0.79	0.79	0.62	0.77	0.77	0.55

Table A8. Detailed sensitivity analysis of NPV (in billion USD) by region and sector under varying PV system costs, electricity prices, and discount rates.

	Central			Eastern			Northeastern			Northern			Southern		
	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res
PV System Cost (%)															
−20%	2.38	5.55	2.11	0.41	3.06	0.66	1.27	1.16	2.51	0.92	0.91	1.14	1.77	0.52	0.49
−10%	2.15	5.03	1.72	0.37	2.76	0.53	1.15	1.05	2.06	0.83	1.04	1.45	0.47	0.44	0.61
−5%	2.03	4.76	1.53	0.35	2.60	0.46	1.09	1.00	1.84	0.79	0.99	1.28	0.44	0.41	0.53
Baseline	1.91	4.50	1.33	0.33	2.45	0.39	1.03	0.95	1.62	0.74	0.93	1.12	0.41	0.39	0.45
+5%	1.80	4.24	1.14	0.31	2.29	0.35	0.98	0.89	1.39	0.69	0.88	1.04	0.39	0.36	0.41
+10%	1.68	3.98	0.94	0.29	2.14	0.26	0.92	0.84	1.17	0.66	0.83	0.80	0.36	0.34	0.28
+20%	1.45	3.46	0.55	0.25	1.83	0.13	0.80	0.74	0.72	0.58	0.72	0.47	0.31	0.28	0.12
Electricity Price (USD/kWh)															
−20%	1.07	2.56	0.28	0.18	1.34	0.05	0.60	0.55	0.40	0.43	0.54	0.25	0.22	0.21	0.03
−10%	1.49	3.53	0.81	0.26	1.90	0.22	0.82	0.75	1.01	0.59	0.74	0.68	0.32	0.30	0.24
−5%	1.70	4.02	1.07	0.29	2.17	0.31	0.92	0.85	1.31	0.66	0.83	0.90	0.37	0.34	0.34
Baseline	1.91	4.50	1.33	0.33	2.45	0.39	1.03	0.95	1.62	0.74	0.93	1.12	0.41	0.39	0.45
+5%	2.13	4.99	1.59	0.37	2.72	0.48	1.14	1.05	1.92	0.82	1.03	1.34	0.46	0.43	0.55

Table A8. Cont.

	Central			Eastern			Northeastern			Northern			Southern		
	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res
+10%	2.34	5.48	1.86	0.40	3.00	0.57	1.25	1.15	2.23	0.90	1.13	1.56	0.51	0.47	0.65
+20%	2.76	6.45	2.38	0.48	3.55	0.74	1.47	1.35	2.83	1.06	1.33	1.99	0.60	0.56	0.86
Discount Rate (%)															
-20%	2.42	5.66	1.94	0.42	3.10	0.59	1.30	1.19	2.32	0.93	1.17	1.63	0.53	0.49	0.69
-10%	2.15	5.05	1.62	0.37	2.76	0.49	1.16	1.06	1.95	0.83	1.05	1.36	0.47	0.44	0.56
-5%	2.03	4.77	1.47	0.35	2.60	0.44	1.10	1.00	1.78	0.79	0.99	1.24	0.44	0.41	0.50
Baseline	1.91	4.50	1.33	0.33	2.45	0.39	1.03	0.95	1.62	0.74	0.93	1.12	0.41	0.39	0.45
+5%	1.80	4.25	1.20	0.31	2.30	0.35	0.98	0.89	1.46	0.70	0.88	1.01	0.39	0.36	0.43
+10%	1.69	4.00	1.07	0.29	2.16	0.31	0.92	0.84	1.31	0.66	0.84	0.90	0.37	0.34	0.34
+20%	1.49	3.54	0.82	0.26	1.90	0.23	0.82	0.75	1.03	0.59	0.74	0.70	0.32	0.30	0.43

Table A9. Detailed sensitivity analysis of NPV (percentage change from baseline) by region and sector under varying PV system costs, electricity prices, and discount rates.

	Central			Eastern			Northeastern			Northern			Southern		
	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res
PV System Cost (%)															
-20%	1.24	1.23	1.59	1.25	1.25	1.68	1.22	1.22	1.55	1.23	1.23	1.58	1.26	1.26	1.73
-10%	1.12	1.12	1.29	1.13	1.13	1.34	1.11	1.11	1.28	1.11	1.11	1.29	1.13	1.13	1.36
-5%	1.06	1.06	1.15	1.06	1.06	1.17	1.06	1.06	1.14	1.06	1.06	1.14	1.14	1.06	1.07
Baseline	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
+5%	0.94	0.94	0.85	0.94	0.94	0.90	0.94	0.94	0.90	0.94	0.94	0.94	0.86	0.85	0.80
+10%	0.88	0.88	0.71	0.87	0.87	0.66	0.89	0.89	0.72	0.89	0.89	0.71	0.87	0.87	0.64
+20%	0.76	0.77	0.41	0.75	0.75	0.32	0.78	0.78	0.45	0.77	0.77	0.42	0.74	0.74	0.27
Electricity Price (USD/kWh)															
-20%	0.56	0.57	0.21	0.55	0.55	0.12	0.58	0.58	0.25	0.57	0.57	0.22	0.54	0.54	0.07
-10%	0.78	0.78	0.61	0.77	0.77	0.56	0.79	0.79	0.62	0.79	0.79	0.62	0.77	0.77	0.61
-5%	0.89	0.89	0.80	0.80	0.89	0.78	0.89	0.89	0.81	0.89	0.89	0.81	0.89	0.88	0.78
Baseline	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
+5%	1.11	1.11	1.20	1.11	1.11	1.22	1.11	1.11	1.19	1.11	1.11	1.19	1.11	1.12	1.23
+10%	1.22	1.22	1.39	1.23	1.23	1.44	1.21	1.21	1.38	1.21	1.21	1.38	1.23	1.23	1.46
+20%	1.44	1.43	1.79	1.45	1.45	1.88	1.42	1.42	1.75	1.43	1.43	1.78	1.46	1.46	1.93
Discount Rate (%)															
-20%	1.26	1.26	1.46	1.27	1.27	1.51	1.25	1.25	1.44	1.25	1.25	1.45	1.27	1.27	1.53
-10%	1.13	1.12	1.22	1.13	1.13	1.24	1.12	1.12	1.21	1.12	1.12	1.22	1.13	1.13	1.21
-5%	1.06	1.06	1.11	1.06	1.06	1.12	1.06	1.06	1.10	1.06	1.06	1.11	1.06	1.06	1.10
Baseline	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
+5%	0.94	0.94	0.90	0.89	0.90	0.94	0.94	0.94	0.90	0.94	0.94	0.90	1.00	1.00	1.00
+10%	0.89	0.89	0.80	0.78	0.88	0.78	0.89	0.89	0.81	0.89	0.89	0.81	0.88	0.89	0.88
+20%	0.78	0.79	0.62	0.78	0.78	0.58	0.79	0.79	0.64	0.79	0.79	0.62	0.77	0.77	0.55

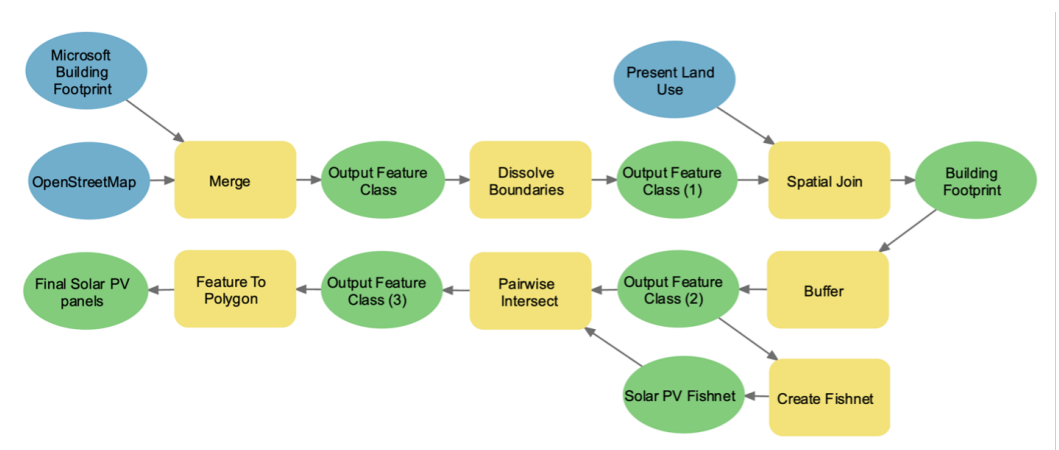


Figure A1. ArcGIS ModelBuilder for rooftop solar PV potential assessment.

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