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Article

Heatmaps to Guide Siting of Solar and Wind Farms

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Abstract: Decarbonization of the electricity system coupled with electrification of transport, heat and industry represents a practical and cost-effective approach to deep decarbonization. A key question is: where to build new solar and wind farms? This study presents a cost-based approach to evaluate land parcels for solar and wind farm suitability using colour-coded heatmaps that visually depict favourable locations. An indicative cost of electricity is calculated for each pixel by focusing on key factors including resource availability, proximity to transmission infrastructure or load centres, and exclusion of sensitive areas. The proposed approach mitigates the subjectivity associated with traditional multi-criteria decision-making methods, in which both the selection of siting factors and the assignment of their associated weightings rely highly on the subjective judgments of experts. The methodology is applied to Australia, South Korea, and Indonesia, and the results are made publicly available to provide both qualitative and quantitative information that allows comparisons between regions and within a region. The study aims to empower policymakers, developers, communities and individual landholders to make informed decisions, and ultimately, facilitate strategic renewable energy deployment and contribute to global decarbonization.

Keywords: solar photovoltaics; wind energy; GIS analysis; heatmap; resource assessment

1. Introduction

1.1. Background and Motivation

Approximately three-quarters of global greenhouse gas emissions arise from fossil fuels [1]. A highly credible and economical pathway to achieve rapid and deep emission reductions involves the decarbonization of electricity through the deployment of solar and wind energy, coupled with the electrification of land transport using electric vehicles and heating through electric heat pumps and furnaces [2]. Emissions from fossil fuels used in the chemical industry (metals, chemicals, materials, synthetic aviation and shipping fuels) can also be addressed by solar and wind through electrolysis to produce clean hydrogen.

In 2023, new installations of solar photovoltaics (PV) and wind accounted for 80% of the global net additions in electricity generation capacity, continuing their dominance of new capacity additions since 2020 [3–5]. Therefore, the aforementioned decarbonisation pathway is based on commercial technologies that are currently being deployed on a large scale, with ongoing technical developments expected to further decrease costs. It avoids the need for extravagant and impractical growth rates of emerging technologies to reach significance by mid-century in terms of providing clean energy to reduce emissions.

While substantial solar will be installed on rooftops, a large proportion of solar and wind systems will need to be located in regional areas. The identification of optimal sites for these installations is a critical question. Solar and wind farm developers generally have extensive information at their disposal, and deep knowledge and expertise in locating prospective sites for new solar and wind farms. There is substantial asymmetry in knowledge when developers enter

negotiations with landholders, communities, and governments. The primary objective of this paper is to narrow this gap and develop a publicly available tool that can provide both qualitative and quantitative information about prospective places for solar and wind farms in selected countries.

1.2. A Review of Siting Criteria for Solar and Wind Farms

Many aspects influence decisions around the siting of solar and wind farms, including solar and wind resources; access to transmission, roads, skilled workforce, and suitably priced land; aspect and steepness of land; geology; hydrology; local electrical loads; government incentives or disincentives; and social, cultural, and environmental constraints. These factors are widely examined in the existing literature that attempts to identify and evaluate possible locations for solar and wind farms. Rekik and El Alimi [6] provided a comprehensive summary of the commonly used siting criteria for solar and wind farms in the literature.

Most of the existing literature combines geographic information systems (GIS) with multi-criteria decision-making (MCDM) to calculate a "suitability index" for candidate locations. The suitability index is usually a quantitative metric that integrates multiple siting factors with different weightings, which are usually determined through the analytical hierarchy process (AHP). For example, in the 2017 study by Baseer et al. [7], a GIS-based site suitability analysis was used for wind farm development in Saudi Arabia, employing a MCDM-AHP approach. This study integrated various climatic, economic, and environmental factors, such as wind resource, proximity to roads and grid, and optimum/safe distance from settlements and airports, to identify optimal locations for wind farms. This approach demonstrated the potential for GIS in renewable energy planning by considering spatial data on wind resources, land use, and infrastructural logistics.

In a 2019 study by Ali et al. [8], suitable locations for utility-scale wind and solar farms in Songkhla, Thailand, were identified using GIS and AHP. The study integrated a variety of physiographic, environmental, and economic criteria to assess site suitability. The criteria considered included wind resource availability, access to roads, proximity to the electrical grid, environmental considerations, distance from urban centres and airports, and land use compatibility. In a 2021 study by Saraswat et al. [9], a GIS and MCDM-based approach was utilized to identify suitable locations for solar and wind farm installations across India, considering a range of technical, economic, and socio-environmental factors, such as solar radiation, wind speed, proximity to roads, and land use. Rajasthan emerged as the state with the most suitable land for both types of energy sources, emphasizing its potential role in India's renewable energy expansion.

Other studies used alternative models for decision making. For example, Pambudi and Nananukul [10] introduced a hierarchical fuzzy Data Envelopment Analysis (DEA) methodology integrated with Principal Component Analysis (PCA) to evaluate wind turbine site suitability across Indonesia's provincial and district levels. This method combines hesitant fuzzy linguistic term sets to process expert opinions into a model that assesses both optimistic and pessimistic scenarios, ensuring a robust and context-sensitive analysis for renewable energy site selection. Additionally, PCA was applied to refine the model by identifying and prioritizing the most impactful criteria, thus enhancing the decision-making process by focusing on the most relevant factors. Wang et al. [11] presented a comprehensive MCDM framework by incorporating DEA, Fuzzy Analytical Hierarchy Process (FAHP), and Fuzzy Weighted Aggregated Sum-Product Assessment (FWASPAS) to optimize wind plant location selection in Vietnam. The DEA phase initially screens potential locations using quantitative criteria, and the FAHP component subsequently weights qualitative criteria, which include social, technical, economic, and environmental aspects, using fuzzy numbers to handle uncertainty. FWASPAS then ranks these locations by combining the benefits of additive and multiplicative decision-making models, providing a robust rank order under uncertainty.

Although the existing literature provides valuable insights into promising locations for solar and wind farms in various regions, a key limitation is that the results depend highly on the siting factors selected and the associated weightings assigned, both of which rely significantly on the subjective judgments of experts. This subjectivity introduces variability and potential bias in the final outcomes,

as different experts and project developers may have different views. This variability can greatly affect the robustness and replicability of the site selection results [12–14]. While methods like fuzzy AHP attempt to address uncertainties in expert judgments by using fuzzy logic, traditional AHP and many MCDM applications do not adequately account for uncertainty in data and criteria weighting. This can lead to suboptimal decision-making, especially when trying to incorporate an excessive number of factors into the model. Additionally, most studies focus on a single region or country. A broader comparative framework that could evaluate and compare potential sites across different geographic and regulatory environments is lacking. Such a framework would be particularly useful for international investors and policymakers.

Ultimately, it is the judgment of the project developer and their funding partners that determines the location of concrete proposals for solar and wind farms.

To address the aforementioned gaps in the existing literature, we propose a cost-based approach to evaluate land parcels for solar and wind suitability. To avoid unnecessary uncertainties associated with trivial siting criteria, we focus on only the most important factors: the presence of good solar and wind resources, access to transmission infrastructure or load centres, and the exclusion of sensitive areas such as national parks, urban areas, native forests, and areas with large slope (for solar only). Depending upon local context, further sensitive areas can be excluded.

The output of a wind turbine scales with the cube of wind speed and the output of a solar farm scales linearly with average solar insolation. Windfarm location within a particular region is therefore strongly driven by access to the best wind resources. In contrast, solar insolation usually varies slowly across a landscape, and so exact location of a solar farm within a particular region is usually determined by factors other than the solar resource. Additionally, the annual energy output of a solar farm is typically much higher per square kilometre than from a windfarm. Thus, siting options for solar farms within a particular region are usually far more numerous than for wind farms with similar annual generation.

Large-scale transmission is required to bring new solar and wind power to the cities. Access to transmission is often the bottleneck for the deployment of new solar and wind farms. Typical power lines span across dozens to hundreds of properties and are highly visible. In contrast, solar and wind farms tend to be more compact and typically can be accommodated on one or a few properties. Negotiating access agreements with fewer landowners is usually much easier than engaging with a broader ownership base. There is often social pushback against new transmission lines. Therefore, locations in close vicinity to existing or planned high-power transmission or close to load centres are highly desirable. If a remote solar or wind farm, located away from the cities, is not near an existing transmission line or substation, then substantial additional connection cost for a dedicated transmission line might be necessary.

Land tenure is an important criterion. Local factors often determine whether there is environmental or social opposition to new energy infrastructure. Forest, protected land and urban land that are listed on a recognised database can be readily excluded from consideration in a GIS analysis to focus on regional areas for large-scale systems while minimizing environmental and social impacts.

Road access is generally available everywhere that transmission is available, and in many other areas besides. Within a region, the cost of road access will generally vary only slowly from place to place. Construction of access roads has far lower cost and difficulty than construction of new transmission. Thus, road access will rarely be a significant factor in site choice for solar and wind farms with scale above 10 megawatts (MW). However, it's worth noting that beyond the cost, new road access and transmission may extend timelines and create more complicated planning approval processes. For roads in particular, new road access to a solar/wind farm site would need to be completed prior to development of the solar/wind farm, whereas the transmission could be built in parallel once development approval is received).

In many jurisdictions, the cost of access to a skilled workforce will vary only slowly across a region, and hence is a weak influence on site choice for solar and wind farms. The difference in travel

times from places of residence is small on a scale of tens of kilometres since vehicle speeds are typical 60-100 km per hour. However, access to skilled labour in a remote region may be problematical and require dedicated work camps and the payment of loadings on wages. Globally, the availability and cost of skilled labour can vary significantly. The difference in labour costs can be accounted for by using local cost assumptions for each country or region. In most countries where there is a lack of skilled and affordable labour, the commitment to decarbonization means that solar and wind will be deployed at large scale in the coming decades, gradually narrowing the gap through the development of a more experienced workforce and driving costs closer to global norms.

1.3. Objectives and Novelties of this Study

In this study, we develop heatmaps that visually display preferred locations for new solar and wind infrastructure. Heatmaps are visual representations of a regional landscape in which warmer colours (redder) denote better prospective areas and cooler colours (bluer) denote less prospective areas.

The key novelty of this study is that, in contrast to the existing studies that produce heatmaps based on a “suitability index”, we calculate an indicative cost of electricity for each pixel by incorporating only the most important siting factors as discussed above. The indicative cost of electricity comprises the cost of energy from a solar/wind farm and the associated powerline connecting the solar/wind farm to the existing and planned high voltage transmission network. This mitigates the subjectivity and uncertainties associated with trivial siting factors and their weightings. The methodology also allows comparisons across several countries.

We apply the proposed methodology to three countries with different geographical conditions: Australia, South Korea, and Indonesia. The heatmaps are mounted on an online platform that allows users to zoom and pan with ease and to obtain both qualitative and quantitative comparisons between regions and within a region.¹ We also calculate key statistics for administrative regions within each country, and the summary is publicly available.

By making all results publicly available, this study aims to:

- Develop public methodologies to reduce knowledge asymmetry between developers and landholders.
- Empower groups of landholders, perhaps with the support of local governments, to negotiate as a bloc. This can also assist the solar and wind farm developers by reducing the complexity and time required to gain legal access and community acceptance.
- Empower local governments to identify promising potential sites and attract solar and wind farm developers to their district to benefit from the associated economic activity.
- Assist state and regional governments and transmission companies to identify promising Renewable Energy Zones (REZ). This allows focus on a few regions for solar and wind farms, including the provision of new or upgraded transmission.

In this paper, the US dollar is used unless otherwise stated.

2. Methodology

2.1. GIS Analysis

Geospatial analysis can readily identify solar and wind resources. In this study, we produce heatmaps for both solar PV and wind using geospatial analysis. The pixels in the heatmaps cover an area of 1 km² (1 km × 1 km) for solar heatmaps and 62,500 m² (250 m × 250 m) for wind heatmaps. This recognizes that annual solar insolation usually varies much more slowly spatially than annual wind energy. To derive the indicative cost of solar or wind generation within each pixel, we assume

¹ RE100 Map: <https://re100.anu.edu.au/>

that a 1 MW solar or wind farm is built within each pixel and that a high-voltage alternating current (HVAC) line connects the solar or wind farm to the nearest load centre or high-voltage transmission network.

The process to derive the heatmaps and the key statistics for administrative areas consists of two major steps: raster calculation and zonal statistics analysis. The entire process is implemented in ArcGIS Pro's Model Builder, as shown in Figure 1.

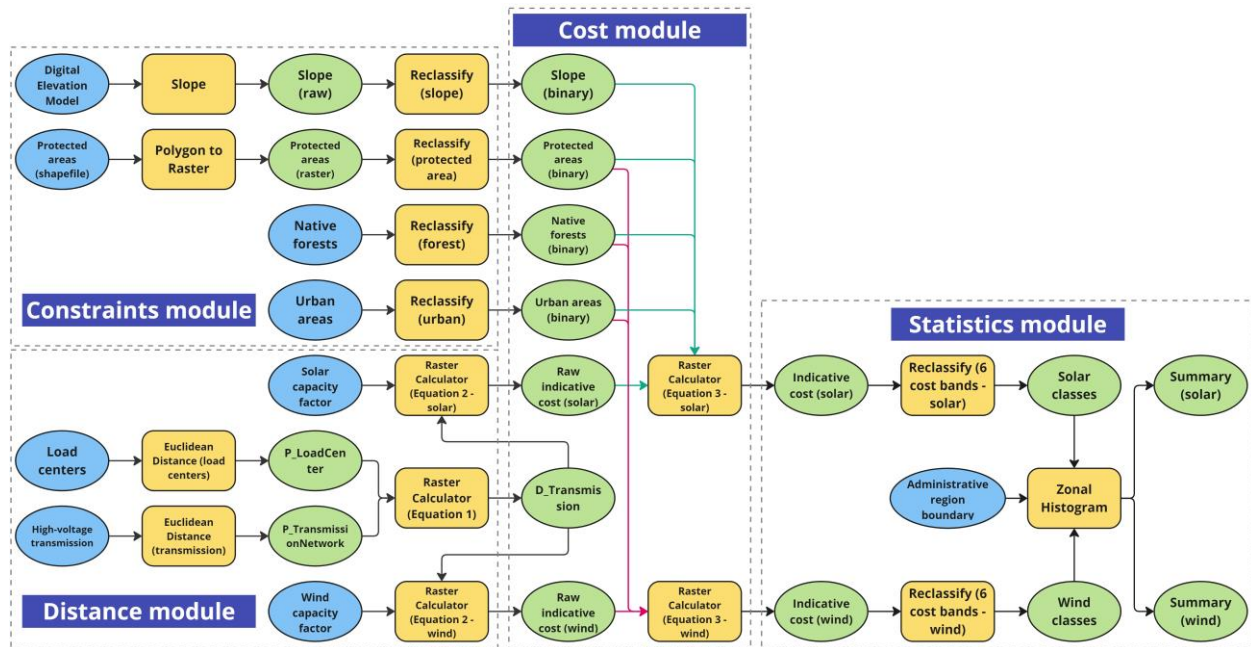


Figure 1. GIS analysis process. The original flowchart in ArcGIS Model Builder is reproduced for better readability.

First, for each pixel, we calculate the proximity to load centers (cities with populations larger than 250,000), denoted as $P_{\text{load centre}}$, and the proximity to the existing and planned high-voltage transmission network, denoted as $P_{\text{transmission network}}$. The smaller of the two values is used to represent the length of the HVAC powerline connecting the hypothetical solar or wind farm to the grid or load centers, as shown in Equation 1.

Equation 1

$$D_{\text{transmission}} = \min (P_{\text{load centre}}, P_{\text{transmission network}})$$

Next, we calculate the capacity factor for solar based on the PVOUT data from the Global Solar Atlas [15] and derive the capacity factor map from Global Wind Atlas [16]. The raw indicative cost (in \$/MWh) is then calculated for each pixel using Equation 2.

Equation 2

Raw indicative cost

$$= \frac{\frac{\text{Transmission CAPEX} \times D_{\text{transmission}}}{\text{PVF}} + \frac{\text{RE CAPEX}}{\text{PVF}} + \text{RE OPEX} + \text{Transmission OPEX} \times D_{\text{transmission}}}{1\text{MW} \times 8760 \text{ hours} \times \text{CF}_{\text{RE}} \times (1 - \text{Transmission loss})^{D_{\text{transmission}}/100}}$$

Here:

- Transmission CAPEX: Capital expenditure of the transmission line connecting the solar or wind farm to the load centers or the high-voltage transmission network, in \$/MW-km.
- Transmission OPEX: Operating expenses of the transmission line, in \$/MW-km per annum.
- RE CAPEX: Capital expenditure of the solar or wind farm, in \$/MW.
- RE OPEX: Operating expenses of the solar or wind farm, in \$/MW per annum.
- $D_{\text{transmission}}$: Length of the HVAC powerline connecting the hypothetical solar or wind farm to the load centers or the high-voltage transmission network, in kilometers.
- CF_{RE} : Annual capacity factor of the solar or wind farm, expressed as a decimal (e.g., 0.2 for 20%).
- Transmission loss: Transmission loss of the transmission line per 100 km, expressed as a decimal. The default value is 0.03 [17,18].
- PVF (Present Value Factor): Present value factor calculated using the given discount rate and lifetime of the solar/wind farm and transmission line.

Binary raster maps are created via reclassification for sensitive areas such as protected areas, urban areas and native forests, with a value of 0 representing these incompatible areas and a value of 1 representing the remaining areas that are compatible for solar and wind farms. Global datasets are available for protected areas [19] and urban areas [20], which can be applied to any country, while country-specific datasets are used for native forests. Note that the protected area data is originally presented as shapefiles, so it is first rasterized before reclassification.

We have also created a binary slope with a 10-degree cutoff from Digital Elevation Model (DEM) data [21] to represent hilly regions that are likely to incur additional costs for solar PV. The binary slope map is applied only to solar PV, as the deployment of wind farms in steep, hilly regions is common.

The raw indicative cost is then multiplied by the binary maps so that if a pixel is within any of the protected areas, urban areas, native forests, or large slope areas (for solar only), the indicative cost becomes zero (unsuitable); otherwise, the indicative cost remains the same, as shown in Equation 3.

Equation 3

Indicative cost

$$= \text{Raw indicative cost} \times \text{Protected area binary} \times \text{Urban area binary} \\ \times \text{Native forest binary} \times \text{Slope binary (solar only)}$$

The indicative costs are later categorized into six bands: Unsuitable, and Classes A to E. Each pixel is color-coded, with Classes A to E ranging from below \$30/MWh to above \$60/MWh, respectively, with Bands B, C, and D incrementing by \$10/MWh. The solar and wind potential of a local administrative area can be compared with other areas by assigning each category a unique value. Zonal histograms [22] are produced for each administrative area to calculate the frequency distribution of the cost classes represented by these unique values within each area.

Indicative costs include expenses for wind or solar generation and the powerline connection to the load centers or the existing and planned high-voltage transmission network. However, they exclude costs associated with environmental/geotechnical approvals, road upgrades, substations, landholder compensation, and risk. These costs vary greatly based on the project scale. To account for these costs, users can select high, medium, or low-range costs in the heatmaps, as discussed later.

The indicative costs presented above are intended to compare relative costs by location rather than to calculate absolute costs. The ranking of one pixel compared with another is less impacted by uncertainty in cost and other factors than the absolute indicative cost, since most factors are common across locations. Importantly, the cost factors that are not included (mentioned above) are often

similar for similar projects in neighboring areas. Thus, inclusion or exclusion of these cost factors may not change the ranking of one site over another – only the indicative cost.

2.2. Cost Estimation

The cost assumptions used in this study are primarily based on Australian industry standards. Australia leads the global renewable energy market with one of the highest levels of per capita solar and wind generation in the world [23,24]. It is a low-mid latitude country, typical of where most of the global population lives; it is affluent with relatively high labour costs; it has an unsubsidized and open market for electricity, allowing price discovery; international companies are heavily involved in Australian solar and wind developments; and the data used are mostly real-world values produced by consensus among industry practitioners. Prices in immature markets are likely to converge to global norms such as those in Australia as scale, affluence, and market maturity grow.

Acknowledging that the local costs of solar PV, wind, and transmission may differ in other countries, we developed high, medium, and low-cost scenarios. In general, continued deployment of solar, wind, and transmission worldwide means that the costs in most countries are likely to eventually reach global norms. Moreover, the ranking of potential sites is not greatly altered by adopting different cost scenarios.

Transmission cost data were derived from the 2023 updated Australian Energy Market Operator (AEMO) Transmission Cost Database [25]. Each solar and wind farm is connected to load centers or the high-voltage transmission network via an overhead or underground 220 kV single-circuit AC line. The reason for this choice is that the cost of constructing dedicated 330–500 kV transmission lines is beyond the reach of most solar and wind farms in the size range of 10–1000 MW. However, it is straightforward to construct an alternative dataset that allows for the construction of new 330–500 kV transmission.

Three cost scenarios were developed by adjusting project attributes. For example, the high-cost scenario results from a combination of project attributes that significantly increase overall project costs, while the low-cost scenario is based on a combination of optimistic attributes. The detailed methodology to convert a wide range of project attributes to quantitative information about transmission costs is introduced by GHD [26]. In summary, a baseline cost estimate is first provided for each network element selected by the user (e.g. a specific type of an overhead HVAC line with certain length), followed by further adjustments based on user specified network element attribute factors (e.g. land use, location etc.). Then, known and unknown risk allowances are added based on user specified risk profile (e.g. geotechnical findings, market activities etc.), and indirect costs (e.g. project development, stakeholder and community engagement etc.) are incorporated to derive the total expected project cost. For example, compared to no environmental sensitive areas, there would be a 0.25% increase in the “Contractor Project Management & Overheads” cost if the “proportion of environmentally sensitive areas” is set to 50% to account for the additional work required and the associated costs to manage environmental issues in sensitive areas. Similarly, the “management and administration costs to liaise and engage with various project stakeholders and impacted communities” would increase by 25% if the community is in general sensitive with transmission projects. This approach aligns with the objective to allow stakeholders comprehensively estimate the cost of candidate transmission projects and assess the project viability at early stage. In particular, the incorporation of environmental and social factors in the cost estimate means that environmental assessment and community engagement can be integrated into planning to ensure that those real-world impacts are not overlooked.

The selected project attributes and detailed transmission costs are summarized in Table 1.

Table 1. Project attributes and costs for high, medium and low transmission cost scenarios.

Project attributes	High-cost	Medium-cost	Low-cost
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Overhead line	1 × Mango SCST 306 MVA, 220kV	2 × Lychee SCST 491 MVA, 220kV	2 x Phosphorus SCST 796 MVA
Contract delivery model	EPC contract	EPC contract	EPC contract
Delivery timetable	Long	Optimum	Optimum
Greenfield or brownfield	Brownfield	Partially brownfield	Greenfield
Jurisdiction	NSW	NSW	NSW
Land Use	Developed area	Grazing	Desert
Location wind loading zones	Cyclone region	Non-cyclone region	Non-cyclone region
Proportion of environmentally sensitive areas	100 percent	50 percent	None
Terrain	Mountainous	Hilly/Undulating	Flat/Farmland
Location (regional/distance factors)	Remote	Regional	Urban
Project network element size	50 km	50 km	50 km
Risks	BAU & Class 5b ²	BAU & Class 5b	BAU & Class 5b
Stakeholder and community sensitive region	Highly sensitive	Sensitive	Commensurate with land use
Total cost (USD)	104 million	84 million	58 million
Unit cost (CAPEX in USD)	\$6,800/MW-km	\$3,400/MW-km	\$1,450/MW-km
Transmission OPEX (USD)	1% of CAPEX p.a.		
Transmission lifetime	30 years		

It’s worth noting that the project attributes listed above are used to derive the cost assumptions for transmission only and are not investigated further in this study. Transmission project attributes do not directly affect the siting of solar and wind farms.

In one set of maps, transmission to load centres and the high-voltage transmission network is by overhead 220 kV transmission, while in another set, underground 220 kV transmission is assumed. Underground transmission is assumed to cost 10 times more than overhead transmission and is employed if visual impact is an overriding criterion. The factor of ten differential allows users to interpolate the effect of transmission costs per kilometre over a wide range. As stated above, the prime purpose of the heatmaps is ranking of sites between and within regions rather than absolute cost determination.

Solar and wind costs are sourced from GenCost 2022–23 [26], an annual report published by AEMO and CSIRO (Commonwealth Scientific and Industrial Research Organisation). The GenCost report provides comprehensive estimates of the levelized cost of electricity (LCOE) for various generation technologies in Australia and is regularly updated to reflect changes in technology costs, policy developments, and market conditions. The GenCost consensus process involves releasing a consultation draft for stakeholder feedback, including input from individuals and energy sector

² Early-stage cost estimates using concept level scoping with no site-specific review. See AACE’s Cost Estimate Classification System (<https://aacei-pittsburgh.org/wp-content/uploads/2021/11/cost-estimating-classification-system.pdf>) for details.

organizations. Feedback is reviewed and incorporated into the final report, with major changes implemented where possible. This process ensures the report reflects diverse perspectives and remains a credible source for energy cost projections in the Australian context.

In this study, we use the 2022 “Low,” 2030 “High,” and 2030 “Low” cost assumptions from GenCost for the high, medium, and low-cost scenarios, respectively, as shown in Table 2.

Table 2. Cost assumptions for solar PV and wind.

Cost components	High-cost	Medium-cost	Low-cost
Solar CAPEX	\$1,100/kW	\$732/kW	\$662/kW
Solar OPEX	\$12/kW p.a.		
Solar lifetime	30 years		
Wind CAPEX	\$1,849/kW	\$1,397/kW	\$1,229/kW
Wind OPEX	\$18/kW p.a.		
Wind lifetime	25 years		
Discount rate	5.99%		

2.3. Land Requirements of Solar and Wind Farms

The amount of land alienated by a wind farm is minimal — limited to the area around the towers and access tracks. However, the area of land spanned by a wind farm is much larger. Wind turbines are typically spaced 5–10 rotor diameters apart [27,28], which corresponds to 2–8 MW per km², assuming a 3.5 MW IEC Class 2 turbine (100 m hub height, 125 m rotor diameter). Sufficient land must be available to achieve economies of scale for a wind farm. In this study, we assume 7.2 MW/km² based on the Vestas V162-6.8 MW turbine [29] with 6 × 6 spacing.

The amount of land spanned by a solar farm depends on the spacing between panels. A dense non-tracking array yields 150 MW per km² [30], while a tracking array with 20% efficient panels occupying 30% of the land yields 60 MW per km². Bolinger and Bolinger’s (2022) analysis on the 2019 US data suggested that the power density of solar farms varies by latitude for both fixed-tilted and tracking systems [31], with most fixed-tilted systems in the US ranging 75 – 105 MW per km² and tracking systems ranging 55 – 67 MW per km². In this study we assume 100 MW per km² for solar PV systems.

An important point is that the area spanned by a wind farm is one to two orders of magnitude larger than that of a solar farm with the same power rating. Thus, it is usually much easier to find space for a solar farm close to transmission infrastructure than for a wind farm. Additionally, the solar resource varies slowly with location, which generally provides greater siting flexibility.

Solar and wind farms are often co-located to share the cost of substations and transmission. The primary siting decision for a hybrid solar/wind farm usually relates to the wind farm because it is typically easier to find sufficient suitable land for the physically smaller and less obtrusive solar farm.

2.4. Visualization

GeoServer is an open-source server that allows users to share and edit geospatial data [32]. The ANU RE100 Map [33], developed by the Australian National University RE100 Group, is a fork of TerriaMap [34] which serves vector data and rasters as Web Map Service (WMS) through GeoServer. Solar and wind heatmaps developed in this study are mounted on the ANU RE100 Map for visualization. Users can zoom and pan and click on specific areas of the map to access detailed information regarding the indicative costs.

Subject to data availability, additional information can be added to the heatmaps by creating multi-band rasters, with each band representing a unique dataset. The bands are spatially coincident

and represent pixel values for the same geographical area. This will not change the appearance of the heatmaps but will provide additional pop-up information when clicking on a pixel. As shown in Section 3, land use and land tenure information are added to the heatmaps of Australia.

3. Case Studies

3.1. Australia

Australia, with a population of 27 million, presents an ideal case study for the application of heatmaps in identifying optimal locations for solar and wind farms. The country's vast and diverse landscapes—ranging from arid deserts to coastal areas—offer extensive opportunities for renewable energy development. Australia has excellent solar and wind resources, especially in its southern and western regions, while the majority of the population is concentrated along the eastern coastal areas.

Australia is committed to decarbonization and requires significant solar and wind generation to meet the increasing demand due to electrification. The National Electricity Market currently produces 33% of its electricity from solar and wind [35], and is expected to reach 77% - 80% by 2030 [36]. The findings for Australia could similarly benefit other large, diverse countries such as the United States, Canada, and nations in Central Asia and Africa, where renewable resource availability and infrastructure needs vary widely across vast territories.

GIS data representing existing transmission lines in Australia are available from Geoscience Australia [37]. Future transmission lines, including committed, actionable, anticipated and future projects, are summarized in AEMO's Transmission Expansion Options report [38]. Only existing, committed, actionable and anticipated transmission lines with a voltage higher than 275 kV are included in this analysis. Lower-voltage transmission lines are likely to be saturated already and incapable of bringing large-scale additional generation to the load centres. Future transmission lines involve only conceptual designs and are not guaranteed for implementation. Approximate routes were created in ArcGIS Pro for actionable and anticipated transmission projects based on the proposed schematics and descriptions provided, as the exact routes are not finalized yet.

A total of 12 scenarios are modelled for Australia (6 each for solar and wind), including high, medium and low-cost assumptions and overhead or underground transmission configurations, as shown in Table 3.

Table 3. Modelled scenarios for Australia.

Overhead transmission				Underground transmission		
<i>High-cost Medium-cost Low-cost</i>				<i>High-cost</i>	<i>Medium-cost</i>	<i>Low-cost</i>
Solar (1000m)	Solar	Solar	Solar	Solar	Solar	Solar
	overhead	overhead	overhead	underground	underground	underground
	high-cost	medium-cost	low-cost	high-cost	medium-cost	low-cost
Wind (250m)	Wind	Wind	Wind	Wind	Wind	Wind
	overhead	overhead	overhead	underground	underground	underground
	high-cost	medium-cost	low-cost	high-cost	medium-cost	low-cost

The wind overhead low-cost and solar overhead low-cost heatmaps are shown in Figure 2. Comparative heatmaps without transmission cost and transmission loss—representing the spatial distribution of solar and wind resources—are also presented to demonstrate the large effect of including transmission costs in the analysis. All other heatmaps are available on the ANU RE100 mapping platform [33]. Existing solar and wind farms locations from Open Street Map [39] are labelled in the heatmaps.

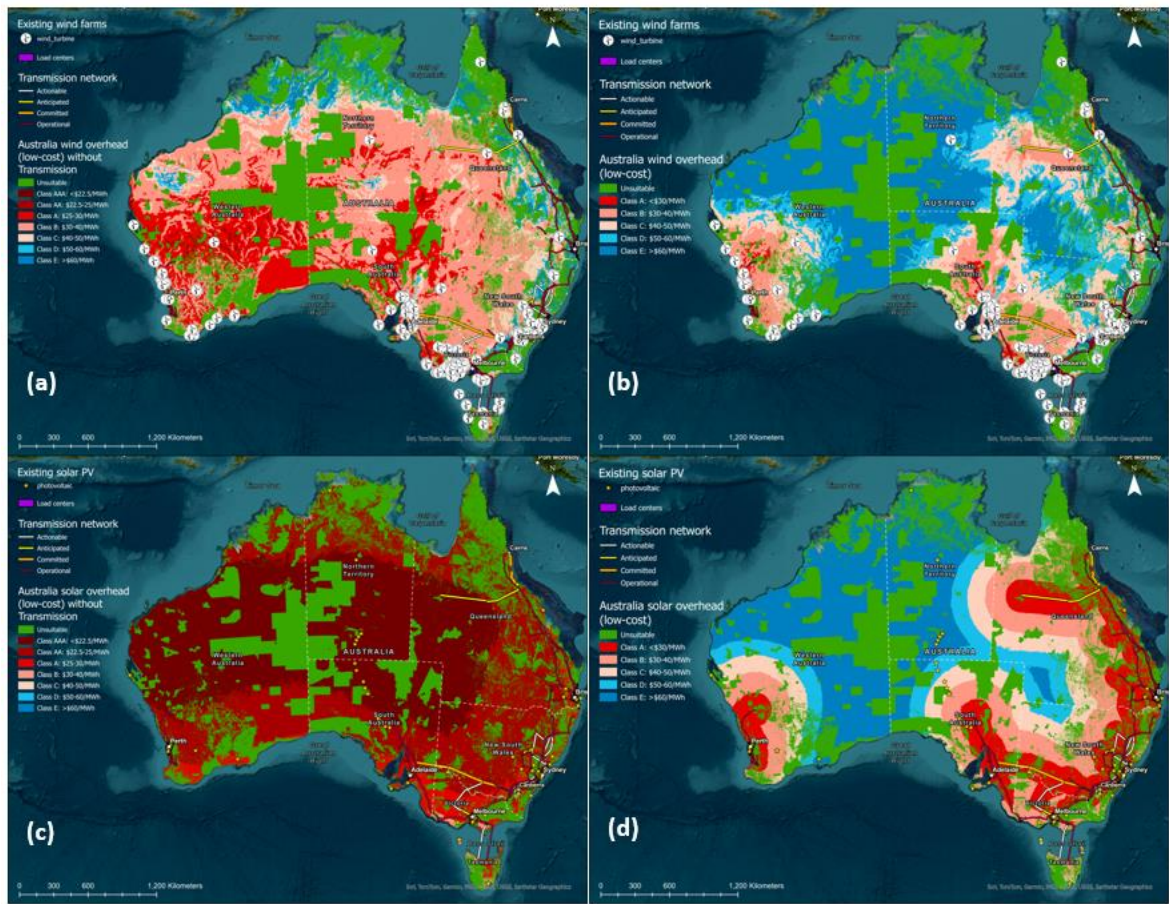


Figure 2. Australia wind overhead low-cost (b) and solar overhead low-cost (d) heatmaps. Comparative heatmaps without the effect of transmission are shown as (a) for wind and (c) for solar.

As shown in Figure 2, the connection cost has a major influence on determining the optimal siting of solar and wind farms in Australia. Most of the low-cost solar and wind potential (Classes A to C, <\$50/MWh) is located within 500 km of load centers and the high-voltage transmission network. Solar resources are distributed more uniformly across the landscape, with central regions generally having better solar resources compared to coastal areas, although they are farther from either the existing network or the load centers. When connection costs are taken into account, the preferable sites for solar depend largely on proximity to the load centers and the main grid.

Wind resources, however, show more variation. Areas around Perth, Adelaide, Melbourne, and along the CopperString route in the northeast benefit from good wind resources, while there are fewer options available for low-cost wind sites around major load centers like Sydney and Brisbane. For these two cities, the majority of the wind potential comes from regions like Upper Lachlan, Oberon, and Toowoomba, which, as shown in Figure 3, already have several wind farms deployed. In general, the distribution of existing solar and wind farms (marked with stars and wind turbine icons) largely coincides with Class A and B zones, indicating that current installations are well-optimized in terms of connection cost and resource availability. This spatial correlation validates the practical application of the heatmaps in guiding future investments. This also suggests that future expansion in these areas is viable and can leverage existing infrastructure and community acceptance.

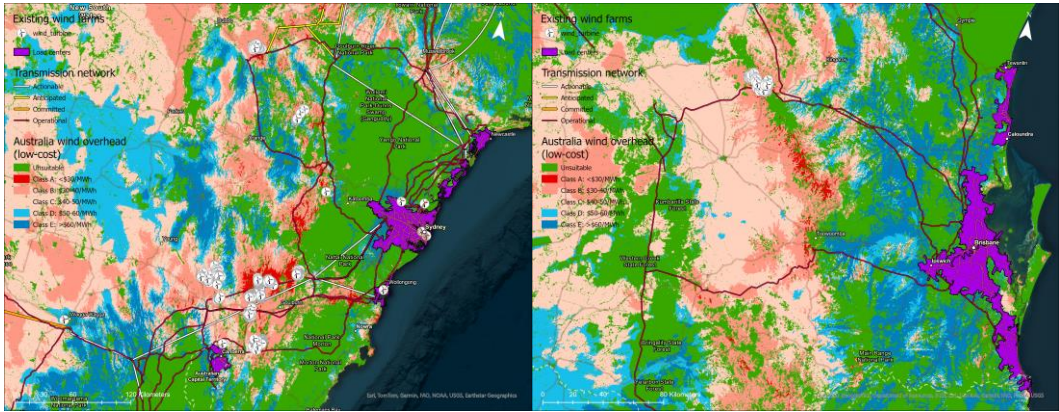


Figure 3. Promising locations identified and existing wind farms near Sydney (left) and Brisbane (right).

The basic land unit employed in the heatmaps for Australia is the Local Government Area (LGA), of which there are 544. For each LGA, the total land area represented by each cost class is calculated using zonal histogram analysis, as discussed in Section 2.1, and later converted to the estimated solar and wind potential in gigawatts (GW) based on the land use factors introduced in Section 2.3.

As an example, the distribution of each cost class within Oberon, New South Wales, under the “wind low-cost overhead” scenario is shown in Figure 4. Around 45% of the land within this LGA is classified as "unsuitable" due to the presence of national parks and is marked green in the heatmap. However, there are approximately 5,000 and 16,000 pixels that fall into Class A and Class B, representing around 310 km² and 1,025 km² of land area and 2 GW and 7 GW of wind potential, respectively. Combined, the Class A and B wind potential could produce around 34 terawatt-hours (TWh) of electricity annually, assuming a 40% capacity factor.

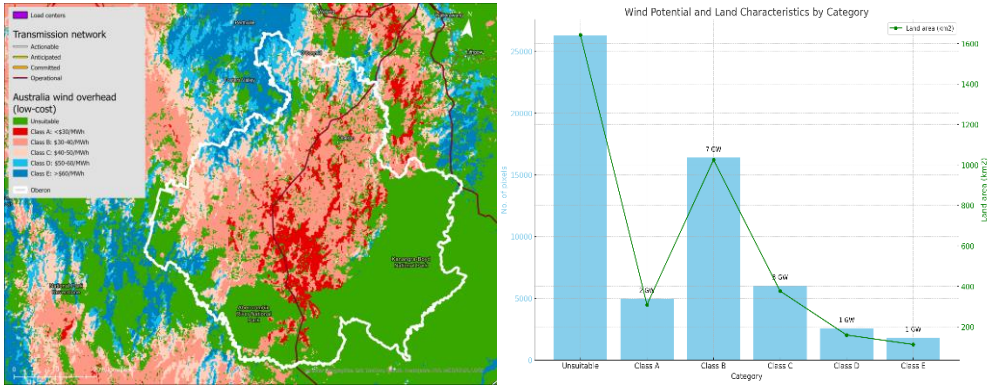


Figure 4. Wind low-cost overhead heatmap zoomed to Oberon (left) and cost class distribution within Oberon (right).

A comprehensive summary for all LGAs under all scenarios is publicly available on the ANU RE100 website [40]. A snapshot of the spreadsheet for a single LGA (Oberon) is shown in Figure 5.

LGA_CODE	16100
LGA_NAME	Oberon
STE_NAME	New South Wales
AREASQKM	3625

Scenarios	Class A (GW)	Class B (GW)	Class C (GW)	Class D (GW)	Class E (GW)
Solar Overhead Low	196	0	0	0	0
Solar Overhead Medium	150	47	0	0	0
Solar Overhead High	22	174	0	0	0
Solar Underground Low	84	111	2	0	0
Solar Underground Medium	19	84	68	23	2
Solar Underground High	3	47	41	103	3
Wind Overhead Low	2	7	3	1	1
Wind Overhead Medium	0	7	4	2	1
Wind Overhead High	0	1	6	3	4
Wind Underground Low	0	5	3	2	4
Wind Underground Medium	0	4	4	2	4
Wind Underground High	0	0	3	3	9

Figure 5. Snapshot of the summary of solar and wind potential by cost classes for Oberon.

Figure 6 shows the indicative cost of an average solar farm (20% capacity factor) and an average wind farm (40% capacity factor) as a function of the length of the connecting powerline. It can be seen that the overhead powerline connecting the solar and wind farms to the main grid adds little to the cost of a solar or wind farm out to a distance of 100 km, while underground transmission costs are substantial.

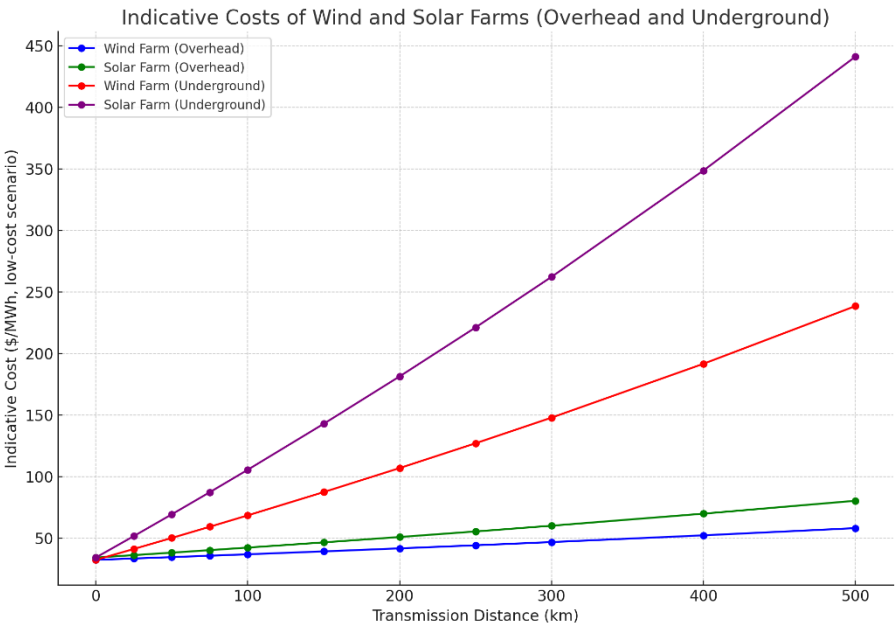


Figure 6. Indicative cost as a function of transmission line distance for sample solar and wind farms under the low-cost scenario.

High-quality land tenure [41] and land use [42] data are available for Australia. The land tenure data has a resolution of 250 m, while the land use data has a resolution of 50 m. To avoid losing information contained in the input datasets, we created three-band solar and wind heatmaps with 50 m resolution. The first band represents the indicative cost and is used for color-coding, while the second and third bands represent land tenure and land use, respectively.

These detailed heatmaps are also mounted on the ANU RE100 map server [33] and provide additional information to users. By clicking on specific areas of the map, users can access detailed

information regarding the indicative costs, land tenure, and land use, enabling more informed decision-making.

3.2. Indonesia

Indonesia is an equatorial archipelago comprising over 17,000 islands and has a population of approximately 280 million people. Most of the population resides on the islands of Java (55%), Sumatra (18%), Sulawesi (7%), and Kalimantan (6%). Indonesia currently relies heavily on fossil fuel-based electricity generation, predominantly from coal and gas. The nation's increasing population, improving affluence, and the shift toward utilizing electricity for transportation, heating, and industrial processes are expected to lead to a substantial increase in electricity demand. The current annual per capita electricity demand of 1 MWh is low by world standards and may rise in the coming years to align with levels seen in developed countries, currently in the range of 6 to 12 MWh per capita [43]. Without a transition to renewable energy sources, carbon emissions will escalate.

Indonesia has relatively poor wind resources due to its equatorial location [44]. Therefore, wind energy is not considered further in this section. However, Indonesia's equatorial location provides abundant solar energy potential that is non-seasonal [45]. Solar panels in Indonesia can be located on rooftops, in defunct coal mines, and in conjunction with agriculture. Additionally, there is vast potential for offshore floating solar in the calm equatorial seas of the Indonesian archipelago [46]. An analysis of the land availability in Indonesia [45] suggested that most ground-mounted solar will be in combination with agriculture [47], with support from solar farms located in defunct coal mines.

Large-scale future deployment of renewable energy is expected in Indonesia, primarily solar PV. In accordance with the current Nationally Determined Contribution (which is due to be updated in 2025), the Government of Indonesia is committed to reducing carbon emissions from the power sector, as outlined in the National Electricity Masterplan (*Rencana Umum Ketenagalistrikan Nasional*) [48]. Indonesia has announced a policy of stopping new coal plant projects with the exception for those that are currently under construction or have secured financial closure [49]. Recently, Indonesia constructed a 145 MW floating solar PV plant, the largest in the Southeast Asia region, co-located with a hydropower plant reservoir in Cirata, West Java [50]. Global Energy Monitor reported that there are 16.5 GW of prospective (construction, pre-construction, announced) solar farms in Indonesia [51]. The Government of Indonesia has announced its goal of integrating 30 GW each of solar and wind power into its electricity planning by 2030 and plans to integrate a combined capacity of 500 GW of solar and wind power to achieve net-zero emissions by 2060 [52].

Indonesia comprises seven major regions with different levels of transmission infrastructure and population. Sumatra, Java and Kalimantan have 80% of the national population [53] and have numerous high voltage transmission lines (above 275 kV) and cities with populations exceeding 250,000. Sulawesi, located in the east, is the 4th largest island in Indonesia with around 7% of the total population. Bali, Nusa Tenggara, and Maluku consist of smaller islands that lack high-voltage transmission networks. The Papua region is mostly made up of small villages with historically small electricity demand and currently lacks major transmission or urban infrastructure, with no cities having a population larger than 250,000. Due to the need for expensive submarine cables to share electricity between islands, and the need for current transmission network data, this study focuses on the islands in Western Indonesia—Sumatra, Java, and Kalimantan—which represent the largest needs for the future deployment of grid-connected solar farms due to the dense population, and additionally have well-developed transmission networks.

The solar heatmap with low-cost assumptions and overhead transmission is shown in Figure 7. Comparative heatmaps without the effect of transmission are again presented. High voltage transmission data for Indonesia were obtained from the PLN's Electricity Roadmap [54]. Prospective and existing solar farm locations were from Global Energy Monitor [51] and Open Street Map [39], respectively.

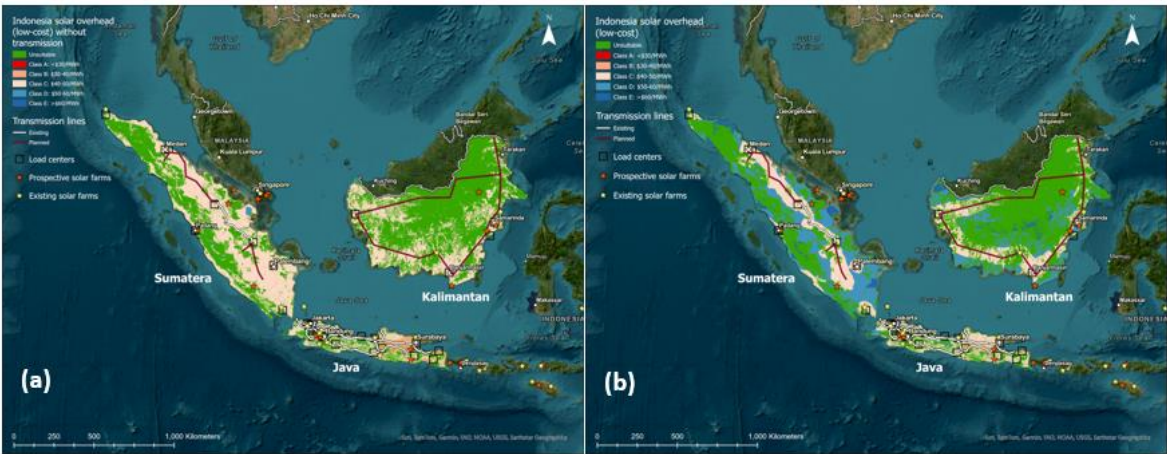


Figure 7. Indonesia solar overhead low-cost (b) heatmap and comparative heatmap without the effect of transmission (a). Only the three major islands in Western Indonesia are modelled in this study.

As shown in Figure 7, there is no Class A (<\$30/MWh) solar potential identified in Indonesia, due to the lack of exceptional solar resources. For comparison, average daily global horizontal irradiation (GHI) ranges between 3.5 – 5.7 kWh/m² in Indonesia, while it ranges between 3.8 – 6.4 kWh/m² in Australia [15]. However, there are many Class B and C sites identified on the three islands, with central Java standing out compared to other regions.

Similar to the case in Australia, the distance from load centres and high-voltage transmission networks means additional expenses for building transmission infrastructure. Factoring in these transmission costs significantly alters the generation cost-heatmap (Figure 7a), strongly favouring locations near transmission networks or cities (Figure 7b). For Eastern Indonesia, which is not included in this study due to lower population and less developed transmission networks, the expense of long transmission lines needed to transfer energy to main islands or cities makes decentralized solar energy generation more cost-effective.

Figure 7 also labels the locations of existing and prospective solar farms. Most of the existing solar farms are concentrated in Java, close to major load centres where infrastructure and energy demand are strongest. In contrast, the prospective solar farms are distributed across multiple cost classes in the heat maps, including one utilizing an old mining site in East Kalimantan [55]. Future deployment of solar PV in Indonesia may require more detailed coordination and planning as the demand for new generation capacities escalates. The heatmaps can play a useful role in guiding future cost-effective and environmentally friendly site identification in this context.

Table 4 summarizes the identified solar PV potential under each cost class for the three islands. A total of 53,362 GW of solar potential was identified, among which 1,145 GW (2%) and 26,254 GW (49%) are Class B and Class C potential, respectively. All identified Class B sites are located in Java, which also has the highest population. The total Class B and Class C identified potential corresponds to 119 kW per capita of solar PV capacity or 208 MWh per capita of annual generation, which far exceeds the current per capita electricity demand of developed countries (around 10 MWh per year) and the expected future energy demand in a fully decarbonised Indonesian energy system.

Table 4. Summary of solar PV potential in Sumatra, Java and Kalimantan under low-cost, overhead transmission scenario.

Cost Classes	Sumatra	Java	Kalimantan
Class A: <\$30/MWh	-	-	-
Class B: \$30-40/MWh	-	1,145 GW	-
Class C: \$40-50/MWh	10,363 GW	6,698 GW	9,193 GW
Class D: \$50-60/MWh	13,708 GW	471 GW	7,253 GW

Class E: >\$60/MWh	3,488 GW	1 GW	1,041 GW
Total	27,559 GW	8,316 GW	17,487 GW
Population (millions)	61	152	17

Several geospatial studies have evaluated Indonesia's solar PV potential [56–58], with identified solar PV potential ranging between around 3,000 GW to 20,000 GW. The higher potential identified in this study (53,362 GW) is due to the inclusion of larger areas deemed suitable based on the cost-based methodology, different assumptions regarding land availability, and the exclusion of certain constraints considered in other studies. This study provides additional information that allows potential sites for large-scale solar farms to be quantitatively evaluated based on indicative costs.

3.3. South Korea

South Korea has a population of 52 million people and an area of 100,000 km², resulting in a high population density by global standards. Its latitude ranges from 34 to 38 degrees North. Annual electricity production is about 600 TWh, or 12 MWh per person, which is also high by global standards. Production of this amount of electricity using high-density, non-tilted arrays of 25% efficient solar panels would require a panel area of about 1,700 km² [15]. Some of this could be accommodated on rooftops, but most would need to be integrated with agriculture. South Korea also has significant onshore wind resources and vast offshore wind resources in generally shallow seas with excellent windspeeds [16]. Despite its high population density, South Korea can readily become self-sufficient in energy with a combination of solar, onshore wind and offshore wind.

South Korea's geographic and economic landscape makes it an interesting case for the application of heatmaps. With limited land available and high population density, particularly in urban areas, finding suitable locations for solar and onshore wind farms requires efficient planning. The heatmaps generated in this study can provide useful insights into the identification of potential sites that offer both economic viability and minimal environmental and social impacts. The findings from South Korea can be applied to other densely populated, technologically advanced regions such as Japan, the northeastern United States, and northern Europe, where land constraints similarly prioritize the need for strategic siting of renewable energy installations. It should be noted that Japan, northeast United States, northern Europe and Korea all have vast offshore wind potential.

High-voltage transmission and forest data for South Korea were obtained from NextGIS [59]. Load centres were identified based on data from GADM [60] and Michael Bauer Research GmbH [61]. The same cost-based methodology and other global datasets described in Section 2 were applied to generate the heatmaps for South Korea.

The wind overhead low-cost and solar overhead low-cost heatmaps for South Korea are shown in Figure 8. Again, heatmaps without the effect of transmission are shown for comparison.

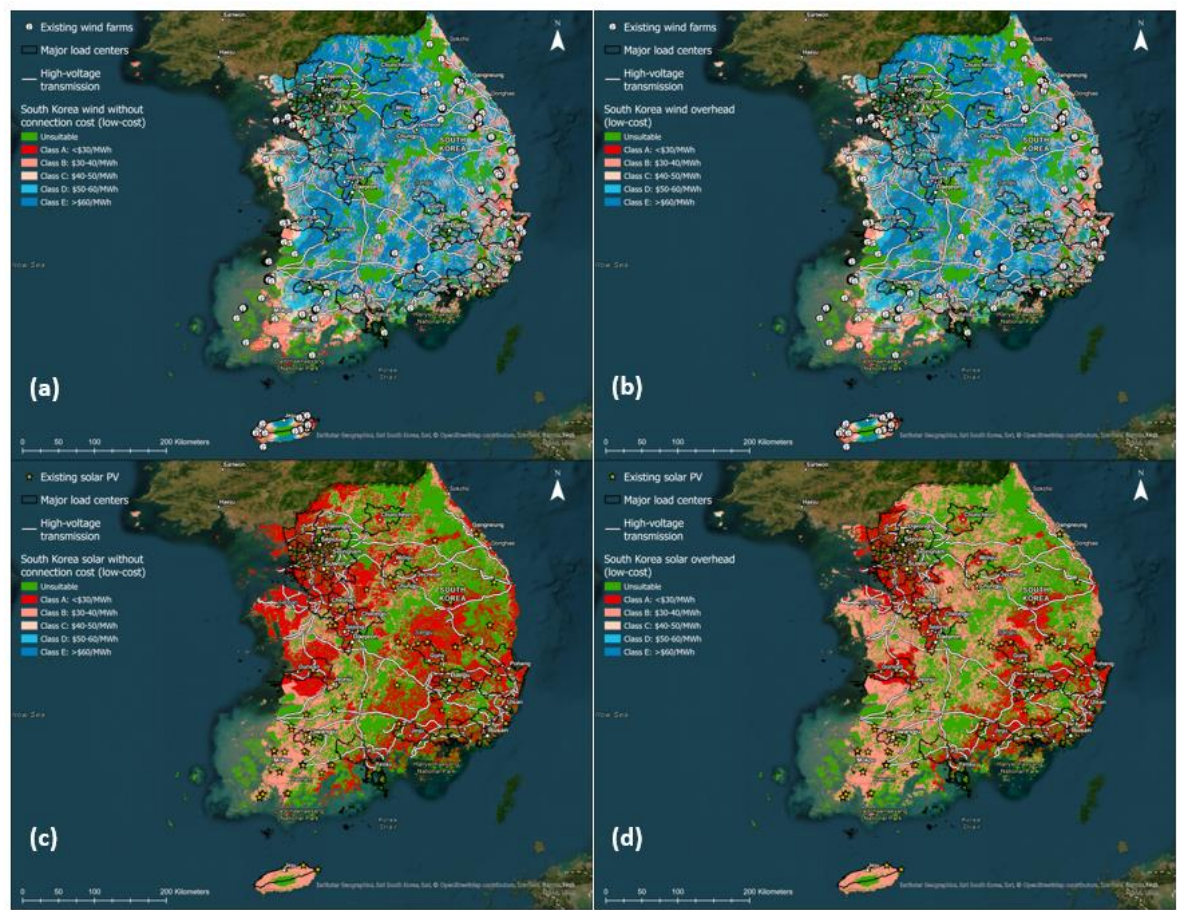


Figure 8. South Korea wind overhead low-cost (b) and solar overhead low-cost (d) heatmaps. Comparative heatmaps without the effect of transmission are shown as (a) for wind and (c) for solar.

In South Korea, the distribution of wind and solar resources shows distinct regional characteristics. The country's onshore wind resources are primarily concentrated in mountainous regions and along coastal areas where wind speeds are generally higher. The mountainous regions are often less populated and have higher elevation, both ideal factors for wind farm installations. However, many of these ridges are protected areas that are incompatible with renewable energy projects, as shown in Figure 8. The rugged terrain can also increase the costs of construction and maintenance and hinder the transportation of large turbine components. As a result, the most viable locations for onshore wind energy development are primarily along the southern and eastern coastlines.

Incorporating the cost of overhead transmission has less impact on the distribution of wind sites in South Korea compared to Australia and Indonesia, due to the country's dense population and extensive transmission network connecting much of the country. However, when underground transmission is assumed, as shown in Figure 9, many potential sites in the southern coastline become less attractive due to the higher costs per unit distance. Meanwhile, the best wind sites on the eastern coast are more densely populated compared to the southern coast. Therefore, underground transmission in the east may be viable to earn social licence for that infrastructure, but less necessary in the south as it impacts fewer people.

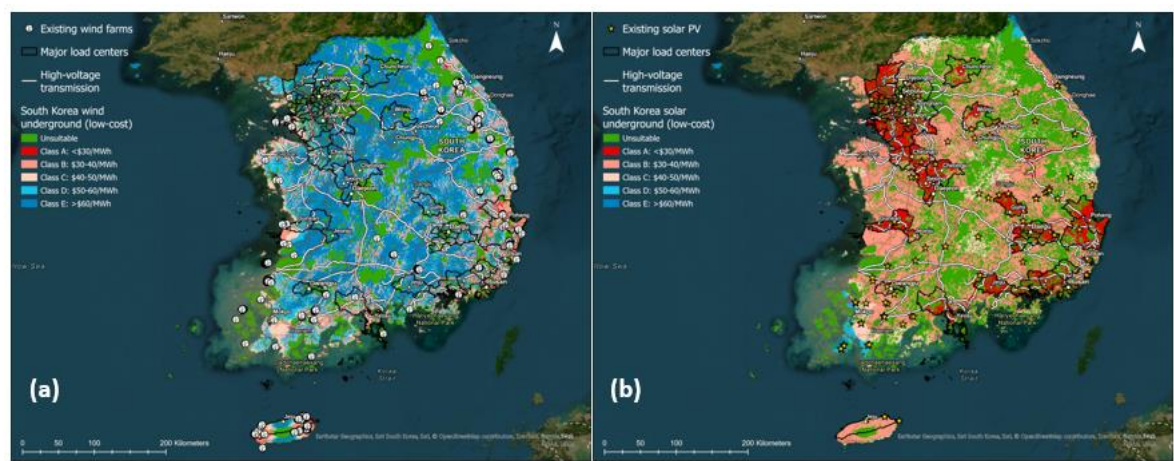


Figure 9. South Korea wind underground low-cost (a) and solar underground low-cost (b) heatmaps.

In contrast, solar resources are notably more favourable in the southeastern regions of South Korea, unlike the less irradiated mountainous zones. The variability in solar resources across the nation is relatively small. This uniformity results in widespread suitability for solar energy projects, particularly in areas proximate to the existing transmission network and load centres.

A detailed view of the vicinity of Cheongju, a load centre, is shown in Figure 10, overlaying the solar overhead low-cost heatmap with satellite imagery. Although the urban area is classified as “unsuitable” as only large-scale solar farms are considered in this study, many of the surrounding barren and farmland areas are ideal for the deployment of solar farms to meet the demand from the city at low cost. Local government policymakers can utilise this information to increase local electricity generation.

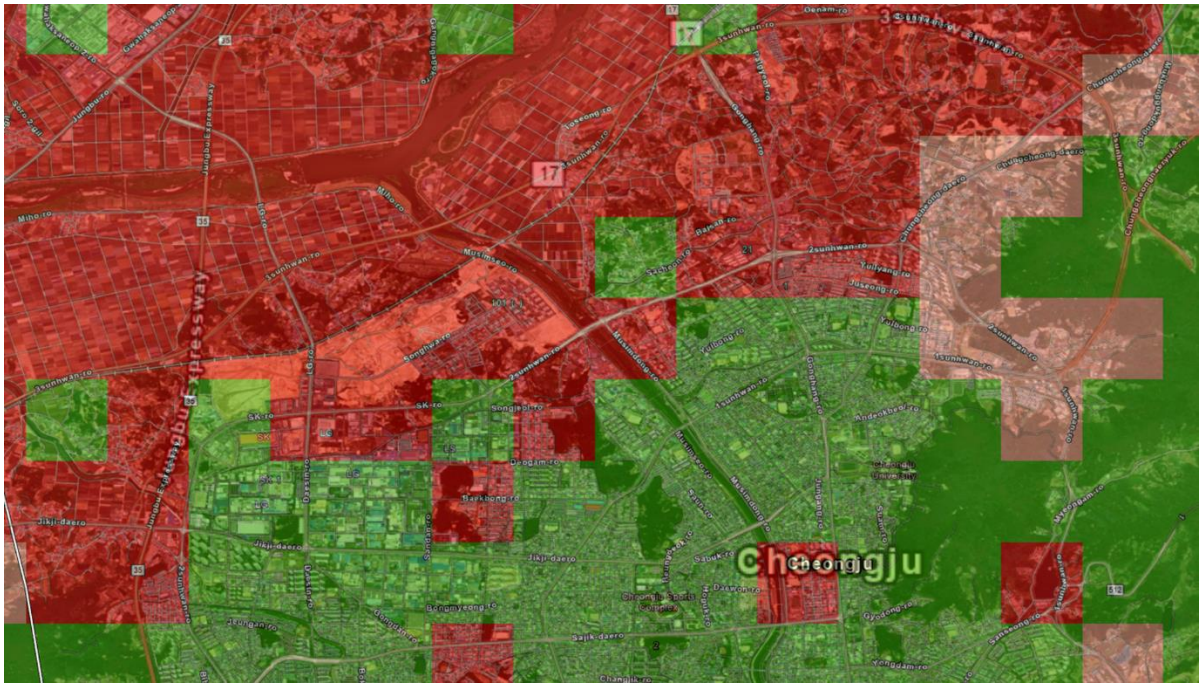


Figure 10. South Korea solar overhead low-cost heatmap overlaid with satellite image around Cheongju.

The total identified solar PV and wind potential by cost class in South Korea under the “low-cost, overhead transmission” scenario are summarized in Table 5. On a regional level, Hongcheon, Uiseong, and Andong lead in solar PV potential with over 120 GW each in combined Class A and B categories. In comparison, Pohang and Haenam present the highest wind potential with close to 5

GW each. Other notable cities like Gyeongju, Jeju, and Seogwipo also show high potential in both solar and wind, making them ideal for hybrid renewable energy deployments that can benefit from the typical anti-correlation between solar and wind availability. Full data for all regions and all scenarios are available on the ANU RE100 website [40].

The total Class A, Class B and Class C identified potential corresponds to 155 kW per capita of solar capacity or 203 MWh of annual solar generation per capita, which matches the level identified in Indonesia. The available onshore wind potential is only 3.6 kW per person or about 10 MWh per person per year. Clearly, the future of wind energy in Korea is offshore.

Table 5. Identified solar PV and wind potential by cost class under the "low-cost, overhead transmission" scenario.

Cost Classes	Solar PV	Wind (onshore)
Class A: <\$30/MWh	3,188 GW	14 GW
Class B: \$30-40/MWh	4,853 GW	75 GW
Class C: \$40-50/MWh	9 GW	100 GW
Class D: \$50-60/MWh	0 GW	101 GW
Class E: >\$60/MWh	0 GW	264 GW
Total	8,050 GW	555 GW

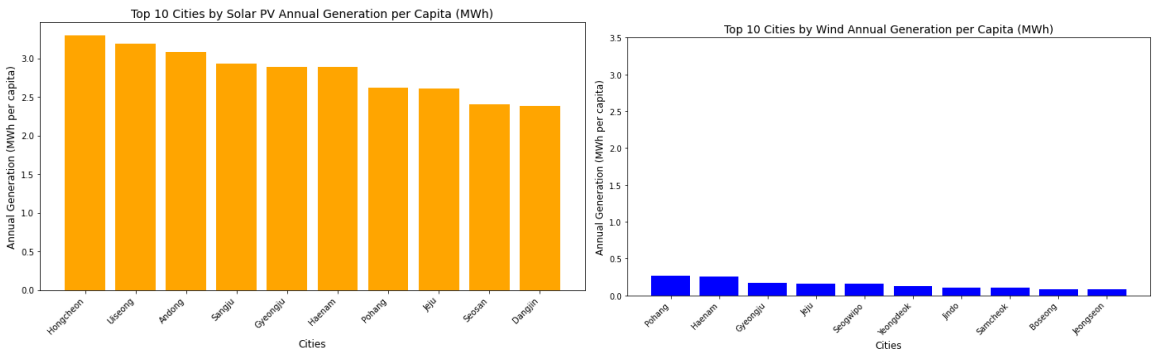


Figure 11. South Korea top 10 cities by Class A & B solar PV and wind potential (low-cost, overhead transmission scenario).

4. Discussion

In this study, we introduced a cost-based approach to evaluate land parcels for their suitability for solar and wind farm deployment, focusing on the most critical factors: resource availability, proximity to high-voltage transmission infrastructure or load centers, and exclusion of sensitive areas. By calculating an indicative cost of electricity for each pixel, we mitigated the subjectivity and uncertainties associated with traditional multi-criteria decision-making methods that often rely on expert judgments and weightings. The proposed methodology was applied to Australia, Indonesia, and South Korea as case studies, yielding heatmaps that visually display promising locations for new solar and wind farms. The heatmaps and detailed statistics for each administrative area are publicly available on the ANU RE100 mapping platform [33], allowing stakeholders to access detailed information and make informed decisions.

4.1. Summary of Key Findings

In Australia, the results show significant opportunities for solar and wind energy deployment, thanks to the country’s vast landscapes and excellent renewable resources. Analysis showed that

overhead transmission adds little to the indicative cost up to 100 km (Figure 6), suggesting that developers and landowners can benefit from the consideration of sites that are not very close but still within a reasonable distance of the existing infrastructure. However, connection costs gradually add up as proximity to load centers and high-voltage transmission networks increases. Figure 2 highlights that transmission costs become a major factor influencing site selection in Australia in a broader picture, with the most promising sites for solar and wind farms located within 500 km of load centers and high-voltage transmission networks. The strong correlation between existing installations and the optimal regions identified indicates that current deployment of solar and wind farms in Australia aligns well with cost-effective practices, which in turn validates the proposed methodology.

In Indonesia, despite large available land area for solar deployment, the lack of exceptional solar insolation and the archipelagic geography pose challenges. The heatmaps (Figure 7) show that in the near future there will likely be a lack of Class A (<\$30/MWh) solar potential, although substantial Class B and C potential that far exceeds the required amount is identified. Similar to Australia, access to load centers and high-voltage transmission networks is a key factor that differentiates promising sites from other regions. However, in many smaller islands that were not included in this study, decentralized solar generation and other types of solar installations like floating solar in calm equatorial seas may be more viable and cost-effective solutions.

In South Korea, high population density and limited land availability require efficient planning. The heatmaps (Figure 8) show significant low-cost solar PV potential, particularly near existing infrastructure. The limited low-cost onshore wind potential due to terrain and land use constraints highlights the need for alternative solutions like offshore wind or hybrid energy systems. A key difference between South Korea and the other two countries is that the connection costs play a less important role in the siting of solar and wind farms due to the relatively small land area and widespread access to existing infrastructure which results in shorter and less expensive powerline requirements.

In this study, we quantified the solar and wind potential by cost class for each administrative area for all three countries. The results demonstrate that the identified solar and wind potentials are much more than required to supply the current and future electricity demand. However, it is worth noting large values of potential capacity (in GW) represent the theoretical maximum values based on land availability. These figures are indicative of the vast solar and wind potential but should be interpreted with caution, as practical deployment will be constrained by various factors such as infrastructure, market demand, investment capacity, and other factors such as demand for land for carbon farming. The heatmaps are most useful for comparative quantitative analysis that allows potential solar and wind sites to be visualized and evaluated, rather than providing information on the real development potential or exact project costs.

4.2. Implications for Key Stakeholders

The study demonstrates that a cost-based, GIS-driven approach can effectively guide the siting of solar and wind farms. It provides a useful tool for policymakers to make informed decisions regarding land use planning, infrastructure development, and regulatory frameworks. For example, Australia has been actively developing Renewable Energy Zones (REZs), where clusters of solar, wind, and storage projects connected by augmented transmission to load centres can be developed efficiently, as part of its strategy to accelerate the energy transition in its National Electricity Market. AEMO plays a central role in identifying such regions with strong renewable energy potential, with state governments also considering REZs as a key part of state initiatives. The heatmaps developed in this study are well-positioned to guide the identification of REZs not only in Australia but also in other countries. Therefore, governments can prioritize these zones for development, adjust zoning regulations, and streamline permitting processes.

Heatmaps are also useful for inexperienced renewable energy developers to identify cost-effective sites, reducing project risk and improving financial viability. The detailed visualization of potential sites allows quick screening of promising areas in a certain region before detailed field visit

and site assessment. In Indonesia, where future deployment requires careful coordination and planning, developers can leverage the heatmaps to target areas with high solar potential and proximity to infrastructure.

By making the results publicly available, the study empowers communities and landholders with knowledge about the renewable energy potential of their regions. This transparency reduces the knowledge asymmetry between developers and landholders, enabling more equitable and efficient negotiations. In South Korea, where land constraints are significant, community engagement becomes crucial for successful project implementation.

4.3. Limitations and future work

This study's accuracy depends on the quality and resolution of the data used. Inconsistencies or inaccuracies in data regarding solar irradiance, wind speeds, transmission infrastructure, and sensitive areas (protected area, urban areas, native forests) can affect the results. While reputable sources were used, variations in data availability across countries may introduce uncertainties. Furthermore, while the methodology excludes sensitive areas like protected lands and urban areas, it does not fully account for all environmental and social impacts. Factors such as biodiversity, cultural significance, and community acceptance are critical for project success but are challenging to quantify in a GIS-based analysis. Further studies integrating environmental impact assessments and community engagement would improve site evaluation information from the heatmaps.

Additionally, this study did not include the remaining capacity of existing high-voltage networks. In regions like Australia, some transmission lines may already be near saturation, limiting the ability to connect new renewable energy projects (heatmaps can be used to identify transmission corridors which ought to be upgraded using the existing easement). Future research incorporating grid capacity constraints would provide a more accurate representation of practical current potential. Another key area for future research is the identification of new high-voltage transmission routes that are required to support the rapid deployment of new solar and wind in response to the increasing demand and soon-to-be saturated existing network.

Continued monitoring of technological developments and cost trends in renewable energy is essential. As costs of solar panels, wind turbines, and transmission components evolve, as well as new transmission projects implemented, updating the models will ensure that the heatmaps remain relevant and useful for the various stakeholders.

Offshore wind is not included in this study but may play an important role in densely populated countries like South Korea and Japan, which also have exceptional offshore wind resources. Identification of promising offshore wind sites requires a different set of considerations in addition to the quality of wind resources, such as proximity to coastline, sea depth, impacts on fishing and ferry routes etc. Additionally, a cost premium would be required for floating offshore wind turbines in deep water, compared to the normal fixed-bottom setup. Offshore wind heat maps will be explored in future work.

5. Conclusion

This study presented a cost-based, GIS-driven approach for evaluating land suitability for solar and wind farm deployment, focusing only on critical factors such as resource availability, proximity to high-voltage transmission infrastructure or load centers, and exclusion of sensitive areas. By calculating an indicative cost of electricity for each pixel, we reduced the subjectivity associated with many methods in the existing literature.

Applying this approach to Australia, Indonesia, and South Korea yielded valuable insights. In Australia, vast landscapes and excellent renewable resources offer significant opportunities, with transmission costs being a major influence on site selection. In Indonesia, despite challenges from archipelagic geography and moderate solar insolation, substantial Class B and C solar potential were identified near load centers and transmission infrastructure. In South Korea, the heatmaps revealed significant low-cost solar PV potential near existing infrastructure, while the limited low-cost onshore

wind potential highlighted the need for alternatives such as offshore wind or hybrid energy systems. The methodology demonstrated that connection costs play a less significant role due to the country's small land area and widespread infrastructure access.

By making the heatmaps publicly available, we aim to empower policymakers, developers, and communities to make informed decisions. Policymakers can prioritize regions for renewable energy development, adjust zoning regulations, and plan infrastructure investments more effectively. Developers can identify cost-effective sites, reducing project risks and enhancing financial viability. Communities gain transparency, enabling equitable negotiations and fostering engagement. Ultimately, this collaborative approach would facilitate strategic renewable energy deployment and contribute to global decarbonization.

Data Availability: The heatmaps developed in this study are publicly available via the following links: Australia: <https://re100.anu.edu.au/#share=g-83b88726498afb1a19117bb834a2e3fd>, Indonesia: <https://re100.anu.edu.au/#share=g-ba669f609aa00730489ba97686e497e3>, South Korea: <https://re100.anu.edu.au/#share=g-3555913cafc68c10100aef981734ea79>

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