EXPLORING RENEWABLE ENERGY OPPORTUNITIES IN SELECT SOUTHEAST ASIAN COUNTRIES

A Geospatial Analysis of the Levelized Cost of Energy of Utility-Scale Wind and Solar Photovoltaics

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NOTICE

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Errata

This report, originally published in June 2019, was revised in June 2020 to reflect updated technical potential data for wind resources (annual generation and nameplate capacity) in Southeast Asian countries. In the original publication, the wind technical potential data in Table B-2 of Appendix B ("Wind levelized cost of energy (LCOE) and technical potential for land-use constraint scenarios") was out of date, and consequently inaccurate, for the 'Relaxed' and 'Restricted' scenarios considered in the report.

These outdated data were limited to the information contained in Table B-2. The results presented for solar photovoltaics, other wind and solar scenarios, and all figures in the report were not impacted. The majority of the report focuses on the results of the 'Moderate' scenario, which were unaffected.

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Executive Summary

The costs of renewable energy-based electricity generation have fallen precipitously in recent years to levels that are increasingly competitive with traditional generation such as fossil fuel-based generation. As these costs become increasingly competitive, private developers, policymakers, and energy system planners are searching for opportunities to harness high-quality renewable energy resources. Developing economies are setting ambitious targets and exploring how cost-effective, grid-connected renewable energy options can help power economic growth and meet growing electricity demands. This includes the member states of the Association of Southeast Asian Nations (ASEAN) that are determined to reach a target of 23% of renewable energy in the region's total primary energy supply by 2025.[1] A critical gap to identifying opportunities and scaling up renewable energy is the lack of quality data and analyses to support decisions on the investment and deployment of renewables—including wind and solar photovoltaics (PV) (ACE and IRENA 2016).

This work supports decision making by providing high-quality data and spatial analysis of the cost of utility-scale wind and solar PV generation in select countries of Southeast Asia—specifically, the ASEAN member states. Generation costs are expressed as the levelized cost of energy (LCOE)—a commonly used metric that represents the net present value of the unit cost of electricity during the lifetime of a particular electricity generation technology. This is the first spatial estimate of LCOE for these technologies within the ASEAN member states—providing insights into the roles that renewable energy resource quality and other factors may play in generation costs.

This analysis is a product of the U.S. Agency for International Development and U.S. Department of Energy's National Renewable Energy Laboratory Partnership (USAID-NREL Partnership) in collaboration with the USAID Clean Power Asia program and the ASEAN Centre for Energy (ACE). The analysis is intended to help policymakers, planners, private developers, and other actors in the ASEAN member states assess the cost of renewable-energy-based, utility-scale, land-based wind and solar PV opportunities and to:

1. Improve access to data and tools for energy decision making through the web-based Cost of Energy Mapping Tool functionality of the Renewable Energy Data Explorer (RE Data Explorer) platform[2]

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[1] The ASEAN member states are Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (PDR), Malaysia, Burma (Myanmar), Philippines, Singapore, Thailand, and Vietnam.
[2] RE Data Explorer is a user-friendly, no-cost, online geospatial analysis tool for analyzing renewable energy potential and informing decisions. Developed by NREL and supported by USAID, RE Data Explorer performs visualization and analysis of renewable energy potential for user-defined scenarios that can be customized for specific locations. Find additional information in Box 1 and at re-explorer.org.

2. Demonstrate the capabilities and constraints of the Cost of Energy Mapping Tool and increase awareness and use of the tool to estimate the LCOE of wind and solar PV generation
3. Estimate the costs of renewable energy-based generation across ASEAN member states to support early-stage target setting, power sector planning, policymaking, and investment.

The results of this analysis show there is abundant potential for utility-scale, land-based wind and solar PV development in the ASEAN member states at a range of generation costs. Potential solar PV capacity exceeds 41 TW (or 59,386 TWh annually), with an LCOE from $64 to $246 U.S. dollars per megawatt hour (USD/MWh) across the region (in the Moderate Technical Potential Scenario). [3] The map in Figure ES-1 presents the estimated LCOEs for solar PV across the region. Potential wind capacity exceeds 1.8 TW (or 3,159 TWh annually) with an LCOE from $42 to $221 USD/MWh. The map in Figure ES-2 depicts the estimated LCOEs for wind across the region (in the Moderate Technical Potential Scenario). The white sections in Figures ES-1 and ES-2 are filtered out areas that were not included in this analysis due to technical potential exclusions (such as protected areas, waterbodies, and agricultural areas among others) and/or resource quality filters (capacity factors less than 10% for solar PV and 15% for wind).[4]

[3] Wind and solar PV results reported in this paragraph are for the moderate technical potential scenario considered in this work (see Section 1.3 for a description and Box 2 for details about technical potential).
[4] See Section 1.3 and Box 2 for details about technical potential. Resource-quality filters were applied as locations with lower-quality resources have a higher cost per unit of energy produced and are less likely to be developed.

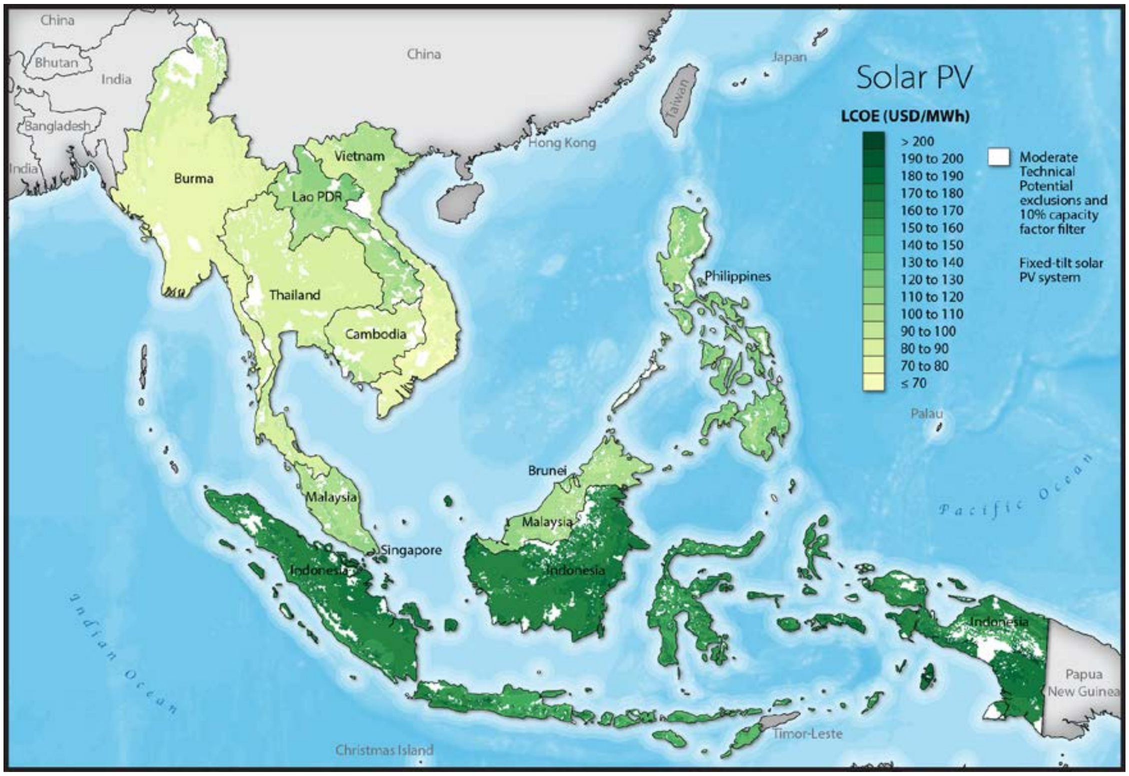


Figure ES-1. Solar photovoltaic levelized cost of energy across ASEAN member states

Using a spatial approach, near-term opportunities for renewables can be assessed in the region to support national and regional renewable energy targets. As an example, this work estimated that total solar PV potential within 20 km of the transmission system in Cambodia may exceed 2 TW (or 3,107 TWh annually) and the LCOE ranges from approximately $69 to $105 USD/MWh.

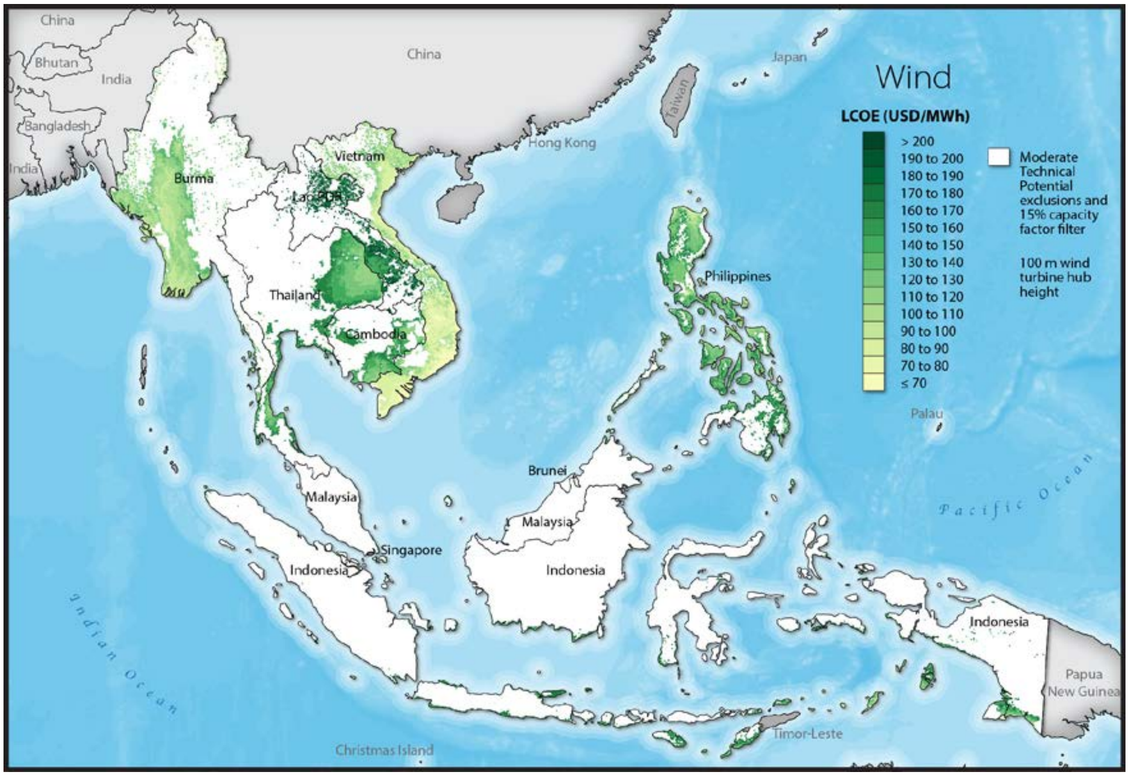


Figure ES-2. Wind levelized cost of energy across ASEAN member states

Generation costs are sensitive to a number of different factors. This work explored sensitivities to the installed cost, fixed operations and maintenance (O&M) cost, debt fraction, depreciation schedule, and discount rate. LCOEs showed the largest sensitivities to installed costs and discount rates for all countries; in addition, assumed debt fraction could also significantly impact the LCOE.

High-quality renewable resources are not evenly distributed across the region. Significant areas are excluded in this study due to lower-quality wind resources (capacity factors less than 15% for wind) that would not be appealing for commercial development because a lower lifetime production or output results in a lower return on investment. This significantly limits the potential wind capacity available at lower generation costs in countries like Indonesia, Malaysia, and Brunei (Figure ES-2). The estimated capacity available may change with new wind turbine generation technology assumptions (such as greater hub heights) and resource quality data.

Potential opportunities and barriers for wind and solar PV development in ASEAN member states can be identified from this analysis of the cost of generation. These are summarized in Table ES-1.

Policymakers, planners, developers, and other actors in the region are invited to further explore solar PV and wind generation costs for countries in the region with the Cost of Energy Mapping Tool on RE Data Explorer. The Cost of Energy Mapping Tool allows users to construct additional scenarios to estimate the cost of generation in the ASEAN member states.

Table ES-1. Opportunities and Barriers for Renewable Energy Development across ASEAN Member States			
Country	**Potential Opportunities[1]** LCOE of Less Than $150 USD/MWh		**Potential Barriers[2]**
	Solar PV Capacity (GW) (suitable land area [km²])	**Wind Capacity (GW)** [suitable land area [km²])	
Brunei	**16 GW** (431 km²)	**0.02 GW** (6 km²)	• Lower-quality wind resources given currently available technologies (and data) • Potentially high installed solar PV and wind costs[3] • Limited suitable land area for wind and solar development
Burma	**7,717 GW** (214,347 km²)	**482 GW** (160,564 km²)	• Potentially high installed wind costs[3]
Cambodia	**3,198 GW** (88,830 km²)	**69 GW** (23,082 km²)	• Potentially high installed wind costs[3]
Indonesia	**1,052 GW** (29,228 km²)	**50 GW** (16,551 km²)	• Lower-quality wind resources given currently available technologies (and data) • High installed solar PV and wind costs
Lao PDR	**1,278 GW** (35,496 km²)	**13 GW** (4,344 km²)	• Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Malaysia	**1,965 GW** (54,575 km²)	**2 GW** (526 km²)	• Lower-quality wind resources given currently available technologies (and data) • Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Philippines	**1,910 GW** (53,062 km²)	**217 GW** (72,337 km²)	• High installed solar PV and wind costs
Singapore	**2 GW** (60 km²)	**0.02 GW** (7 km²)	• Lower-quality wind resources given currently available technologies (and data) • Limited suitable land area for wind and solar development • Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Thailand	**10,538 GW** (292,713 km²)	**239 GW** (79,718 km²)	• High installed wind costs
Vietnam	**2,847 GW** (79,069 km²)	**311 GW** (103,591 km²)	• High operation and maintenance (O&M) cost for wind and solar PV

1. Values from estimated moderate technical potential scenario. The estimated LCOE for solar PV generation ranged from S99 to $200 USD/MWh, and the LCOE for wind generation was approximately $150 USD/MWh in 2018 in ASEAN member states (ACE 2019).
2. Barriers based on the wind and solar PV resource data and techno-economic assumptions used in this analysis.
3. Country data on wind generation costs were not available for this analysis. Regional averages for installed and O&M costs were assumed in the absence of country data. The installed and O&M costs assumed for each country are shown in Appendix A-1.3.1.
4. Installed and O&M costs assumed for each country are shown in Appendix A-1.3.1.

This work shows broad trends in LCOE for the region. It does not attempt to calculate the actual cost of generation at any location. The results are not definitive and should not be used for specific project siting or be adopted into policies without further detailed analyses. To further refine LCOE estimates and support decision making, economic and techno-economic assumptions (such as installed and O&M costs) should be updated when data become available. Further studies, long-term data measurement, and validation activities are essential to confirm resource availability or project performance for policy, planning, or project development.

Table of Contents

1 Introduction

The costs of renewable energy-based electricity generation have fallen precipitously in recent years to levels that are increasingly competitive with traditional generation such as fossil fuel-based generation. As these costs fall, private developers, policymakers, and energy system planners are searching for opportunities to harness high-quality renewable energy resources. Developing economies are setting ambitious targets and exploring how cost-effective, grid-connected renewable energy options can help power economic growth and meet growing electricity demands. This includes the Association of Southeast Asian Nations (ASEAN), which is determined to reach a target of 23% of renewable energy in the region's total primary energy supply by 2025.[5] A critical gap in the process of identifying opportunities and scaling up renewable energy is the lack of quality data and analyses to support decisions on the investment and deployment of renewable-based generation, including wind and solar photovoltaics (PV) (ACE and IRENA 2016).

This work supports decision making by providing high-quality data and spatial analysis of the cost of utility-scale wind and solar PV generation in select countries of Southeast Asia—specifically the ASEAN member states. Presented here is the 1 km by 1 km spatially-estimated cost of wind and solar generation under various techno-economic assumptions for the ASEAN member states, an initial step in the assessment of economic potential (Brown et al. 2016). Generation costs are expressed as the levelized cost of energy (LCOE), a commonly used metric that represents the net present value of the unit cost of electricity during the lifetime of a particular electricity generation technology. LCOE values for select ASEAN member states and technologies have been estimated at the national level in previous work (ACE and IRENA 2016). Although these aggregated, national level LCOE estimates support higher-level planning activities, they do not account for the spatial diversification in renewable energy resources within countries and across the region (such as wind and solar) necessary for planning, target setting, and high-level feasibility studies. This is the first spatial analysis of LCOE for these technologies within the countries of interest, and it provides insight into differences in renewable energy resource quality as well as other factors that can impact generation costs.

This spatial analysis of the cost of renewable-based generation across the ASEAN member states is a product of the U.S. Agency for International Development and the U.S. Department of Energy's National Renewable Energy Laboratory Partnership (USAID-NREL Partnership) in collaboration with the USAID Clean Power Asia program and the ASEAN Centre for Energy (ACE).

[5] The ASEAN member states are Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (PDR), Malaysia, Burma (Myanmar), Philippines, Singapore, Thailand, and Vietnam.

1.1 What is the purpose of this work?

This work estimates the spatially-resolved LCOE of utility-scale, wind- and solar PV-based electricity generation across the ASEAN member states and provides necessary data and analytical tools for clean energy decision making in the region. These data are useful for a high-level screening of the economic viability of generation technologies and can aid project developers in the initial identification of favorable locations for further on-the-ground resource measurement and validation. It supports policymakers and planners in considering the impact of key factors, such as the installed costs or discount rates, on the cost of renewable energy resources in the region. The purpose of this work is to:

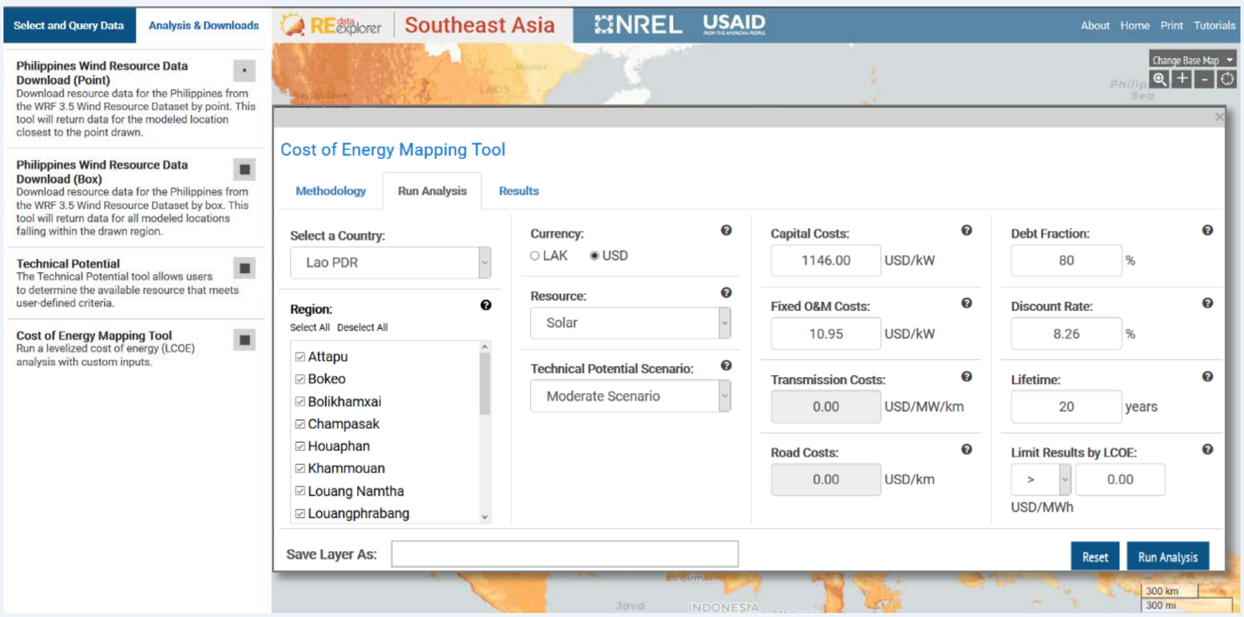
1. Improve access to data and tools for energy decision making through the web-based Cost of Energy Mapping Tool functionality of the Renewable Energy Data Explorer (RE Data Explorer) platform (Box 1)
2. Demonstrate the capabilities and constraints of the Cost of Energy Mapping Tool and increase awareness and use of the tool to estimate the LCOE of wind and solar PV generation
3. Estimate the costs of renewable energy-based generation across the ASEAN member states to support early-stage renewable energy target setting, power sector planning, policymaking, and investment in the region.

Box 1. Renewable Energy Data Explorer

Reliable, robust, and validated data are critical for informed, data-driven planning, policy development, and investment in the clean energy sector. Renewable Energy Data Explorer (RE Data Explorer) is a user-friendly, no-cost, flagship online geospatial analysis tool for analyzing renewable energy potential and informing decisions. Developed by the National Renewable Energy Laboratory (NREL) and supported by the U.S. Agency for International Development (USAID). RE Data Explorer performs visualization and analysis of renewable energy potential for customizable, user-defined scenarios.

RE Data Explorer was developed to support data-driven renewable energy analyses and decisions that enable ambitious, cost-effective, and achievable outcomes for renewable energy deployment. RE Data Explorer can support prospecting, integrated planning, policymaking, and other decision-making activities to accelerate renewable energy deployment. In addition to renewable energy resource data, other complementary, modeled, or measured geospatial data layers play an important role in decision making. These data layers include land use, weather data, population density, and the location of existing transmission lines, among others.

RE Data Explorer users can visually explore spatial renewable energy resource and complementary spatial data sets, complete technical potential analyses (Technical Potential Tool), and levelized cost of energy estimates for wind and solar PV technologies with the Cost of Energy Mapping Tool. Users can replicate the scenarios presented in this work and develop new scenarios for specific countries to visually explore (or download) the results for additional analyses. Find additional information at re-explorer.org.



Cost of Energy Mapping Tool in the RE Data Explorer

Utilizing the Cost of Energy Mapping Tool from RE Data Explorer (Box 1), users can estimate and visually explore how the cost of utility-scale wind- and solar PV-based electricity generation spatially varies within and across the ASEAN member states. This user-friendly tool provides private developers, policymakers, and energy system planners the data and analysis functionalities needed to assess opportunities for economic renewable energy deployment in the region.

1.2 Who is the intended audience of this work and the Cost of Energy Mapping Tool?

This analysis is intended to provide useful results and demonstrate the spatially-resolved LCOE methodology for a variety of audiences:

1. **Policymakers and planners of ASEAN member states**

— Support policymaking, planning, and target setting at the national and regional level by providing an estimate of the available cost-effective energy resources given regionally-specific assumptions and inputs.

— Aid in the identification of favorable sites for on-the-ground resource measurement and validation for renewable energy auctions and/or early-stage proactive transmission planning approaches (such as the renewable energy zone transmission planning process).[6]

— Identify potential barriers to energy investment in ASEAN members states—including land-use or development constraints, generation technology installed costs, and discount rates, among other factors.

— Provide a methodology and tool to conduct future LCOE analyses with updated technology costs and other assumptions.

2. **Developers, utilities, and investors of ASEAN member states**

— Help to identify areas that may have attractive wind and/or solar PV generation costs that could warrant more detailed project feasibility studies.

— Identify potential barriers to investment and possible levers that developers may be able to address to make renewable energy projects more appealing for investment

3. **Other actors including donor agencies, development banks, and development partners**

— Demonstrate the capabilities of the Cost of Energy Mapping Tool and the spatial methodology to estimate LCOE to increase awareness and use of the tool to support energy policymaking and planning activities.

1.3 How is the cost of generation estimated?

The cost of generation is estimated through a calculation of the LCOE—a commonly used metric that represents the net present value of the unit cost of electricity (U.S. dollars per MWh [USD/MWh]) during the lifetime of a particular electricity generation technology and a first step in estimating economic potential. Simply, LCOE represents a first-cut estimate of the "breakeven" price of power that would cover a generator's lifetime costs. The metric embeds engineering assumptions (such as the expected annual generation based on technology specifications) and economic assumptions (such as the inflation rate, real cost of capital, and tax

[6] The renewable energy zone transmission planning process is an approach to connect areas with concentrated renewable energy resources (renewable energy zones) to the power grid. This process helps to plan, approve, and build transmission infrastructure to access areas with high-quality resources, suitable topography and land-use designations, and demonstrated developer interest—supporting reliable and economic integration of renewable energy. For more information see the Renewable Energy Zone Toolkit at https://greeningthegrid.org/Renewable-Energy-Zones-Toolkit.

rates). Importantly, the LCOE estimates presented in this analysis do not reflect all of the considerations that will impact a particular project's economics. For example, they do not reflect the seasonal and intraday variability in generation from solar and wind resources and thus do not reflect either the economic benefits when a generator produces electricity during peak demand hours nor losses in revenue due to curtailment during periods of overproduction. Appendix A further details the methodology used to estimate technical potential, the approach to calculating LCOE, the economic and techno-economic inputs, the technical potential scenarios, and the assumptions made in this work.

This analysis combines geospatial analysis tools and the LCOE calculation methodology established in NREL's Annual Technology Database to estimate LCOE (NREL 2018). The Annual Technology Database methodology is applied in a site-based approach to calculate LCOE for utility-scale systems. The resulting site-based LCOE represents the cost of electricity at the point of interconnection and does not include additional transmission interconnection or access road costs. LCOE is calculated on a 1 km by 1 km grid using capacity factors from a set of technical potential scenarios for both wind and solar PV. Results are limited to locations with net capacity factors greater than 15% for wind and 10% for solar PV, as locations with lower-quality resources have a higher cost per unit of energy produced and are less likely to be developed.

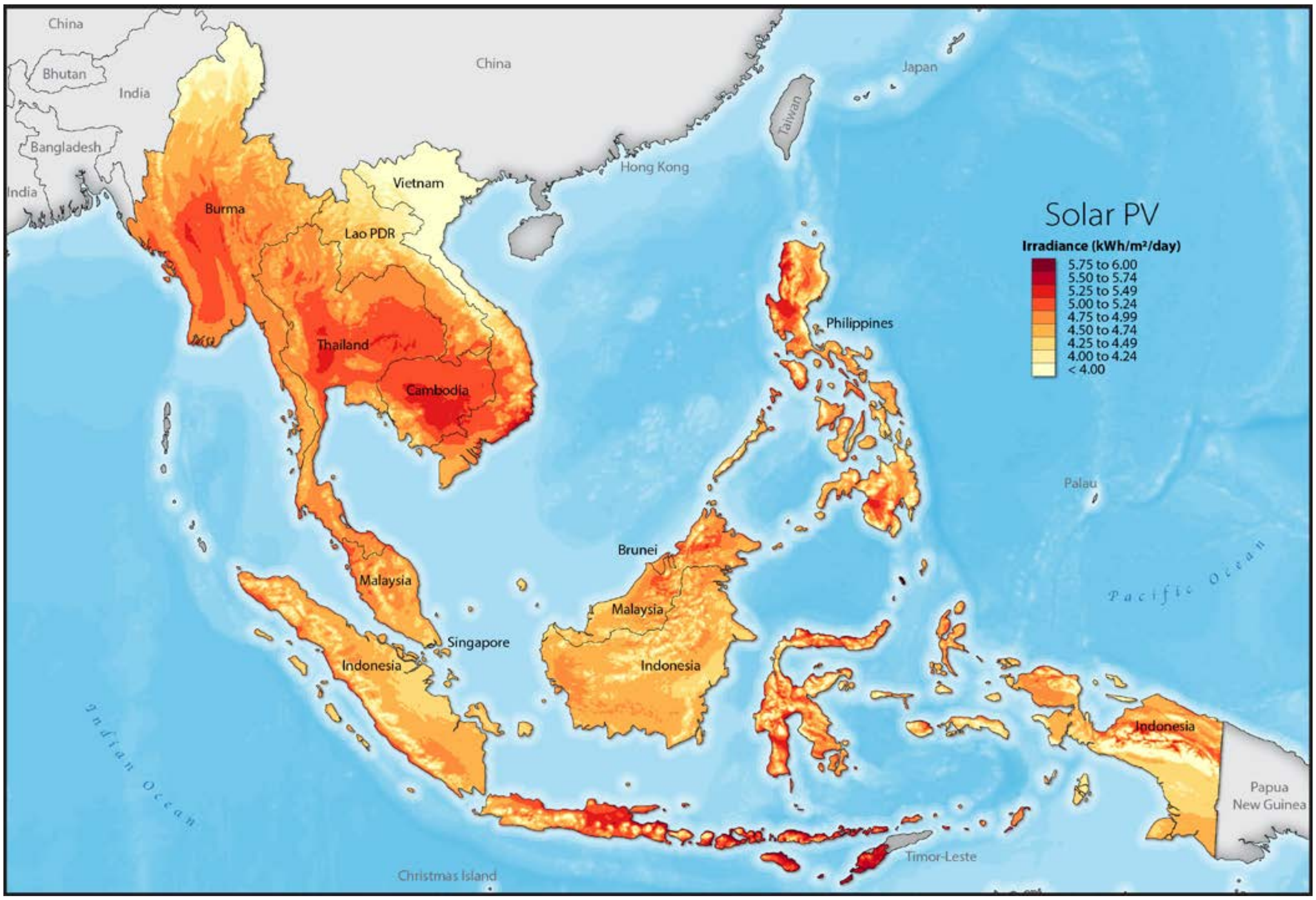
The economic and techno-economic data and assumptions for calculating LCOE, such as installed costs and interest rates, were collected and estimated together by NREL and the ASEAN Centre for Energy (ACE) with the support of the USAID Clean Power Asia Program. These data and assumptions are based on country-specific project data where available. Publicly available values from in-country and international sources were used when no country-specific project data were available (see Appendix A for details on the data used in this work). To account for recent trends in the cost of renewables, techno-economic data (such as installed costs for solar PV and wind) were limited to values from the time period between 2015 and 2018. Older project data were filtered out to minimize the impacts of inflation, exchange rates, and declines in the costs of renewables on estimated LCOE results. Project-specific data were aggregated by country to ensure that any proprietary data remained anonymous.

To explore the cost of utility-scale generation across the region, this work assessed the LCOE within a set of technical potential scenarios.[7] These scenarios define the sites on which development of a particular technology is technically feasible. Feasibility refers to constraints to developing renewable energy generation in particular areas. For example, it is technically infeasible to develop land-based, utility-scale wind power plants within water bodies, in urban

[7] Technical potential is a subset of resource potential and represents the resources that are feasible for development after considering topographical and land-use constraints, as well as generation system performance. Economic potential is a further subset of technical potential and, in this work, refers to the cost of electricity generation of a particular technology (see Appendix A-1.1 for additional description of renewable energy potentials).

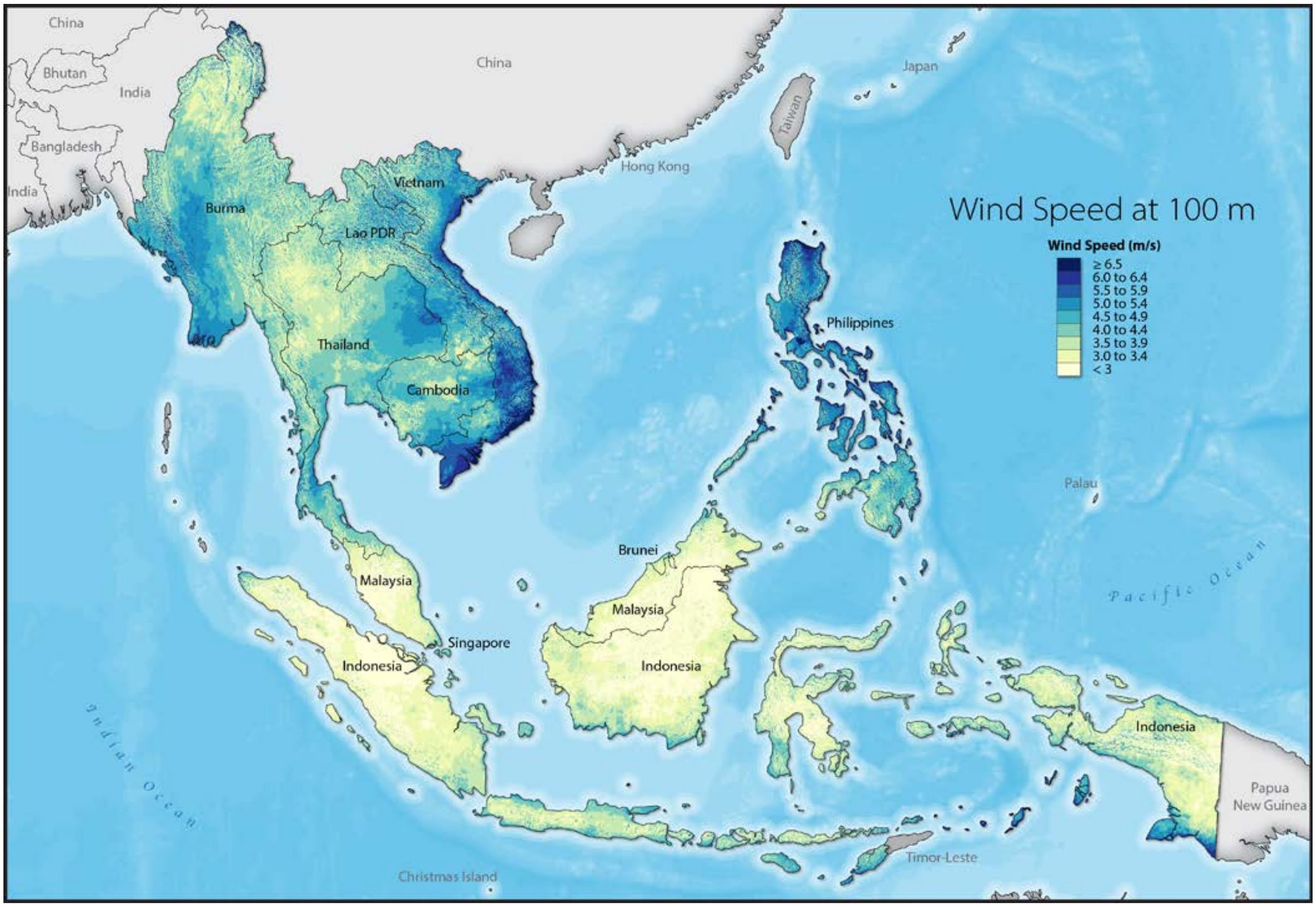
areas, and on extremely steep terrain. Therefore, these areas were excluded from utility-scale wind estimates. These high-level technical exclusions do not capture the various local siting considerations for specific projects (such as the interest or opposition to development from local organizations), which are outside the scope of this work.

Countries across the ASEAN member states have abundant renewable energy resources (ACE and IRENA 2016). Figures 1 and 2 show the solar and wind energy resources, respectively, that exist throughout the region. Although abundant resources exist, the actual technical and economic potential of these resources depends on multiple factors. This work builds on the region's renewable energy resource potential to estimate the LCOE of utility-scale, land-based wind and solar PV generation.



Source: NREL with solar resource data from World Bank (2017)

Figure 1. Solar resource potentials across ASEAN member states



Source: NREL with wind resource data from the Danish Technical University (2017)

Figure 2. Wind resource potentials across ASEAN member states

1.4 How can the results be applied?

This work can help policymakers, planners, and private developers assess the cost of utility-scale, land-based wind and solar PV opportunities with:

- An estimate of the approximate cost of utility-scale wind- and solar PV-based electricity generation in ASEAN member states, considering regionally-specific assumptions and inputs
- An estimate of the total generation potential of wind and solar PV that fall within specific LCOE thresholds in the region and specific countries (and corresponding suitable land areas)
- A preliminary identification of areas that may have attractive costs for wind and solar PV development and that could warrant more detailed feasibility studies
- An initial prioritization, within certain geographic areas, of the generation technologies that may be considered in future planning analyses
- An initial insight into the impact of technology costs, potential land development policies, and other sensitives (detailed below) that may affect investment in the region.

This work supports the exploration of opportunities for renewables in the ASEAN member states; however, it also has several limitations:

- The results are not intended to be definitive, to be used for specific project siting, or to be adopted into policies. Appropriate long-term data measurement and validation activities are essential to confirm actual resource availability or project performance for any policy or project development.
- The costs of generation presented in this work are estimates. The actual LCOE at any location may vary significantly due to myriad factors related to the developer and each specific project (such as their capital costs, rates of return on equity, interest rates, discount rates, debt fractions, and appropriate taxes, among many other factors).
- The results of this analysis are not meant to predict where or when technologies should be, or will be, deployed.
- Estimates of LCOE are highly sensitive to input data and assumptions, and the results of this analysis may differ from those in other work with different input values and assumptions. The estimates provided here were based on the best available data and information collected by NREL, ACE, and Renewable Energy Sub Sectoral Network (RE SSN) Focal Points in ASEAN at the time of publication. The cost of generation for wind and solar technologies changes constantly. Newer data and assumptions would change the resulting estimates of LCOE.
- The methodology used (and associated results) does not attempt to capture any potential economies of scale (such as plant installed capacity or multiple projects) that could impact costs and LCOE results. Nor does this work necessarily capture many of the recent falling costs resulting from the adoption of competitive procurement approaches (such as auctions) in the region.
- The LCOE results do not capture any externalities of the generation systems (such as economic, environmental, or energy security impacts).
- A single value for installed costs and a single value for operation and maintenance (O&M) costs for each technology in each country were assumed, even though installation costs will vary from developer to developer and region to region. All existing wind and solar PV projects in the ASEAN member states are not represented in these data sets. Also, this work does not use any cost multipliers that would estimate cost differences for different locations within a country (such as installation or O&M costs).
- Actual installed and O&M costs for utility-scale wind projects were not available for all countries in the region. In the absence of project data, an average regional representative value was assumed for the country (see Appendix A-1.3.1).
- LCOE is estimated with a "site-based" approach that considers the electricity generated at the site of the generator and does not include any transmission interconnection or access road costs (or transmission system transfer capacities).
- The technical potential for any given area assumes that the area would be almost completely covered with solar or wind generation plants; however, it is likely that only a portion of the area (and generation) will ultimately be developed.
- Actual depreciation schedules or wind and solar PV incentives, such as tax breaks or discounts for the ASEAN member states were not collected or included in this analysis.

2 Solar Photovoltaic and Wind Generation Costs across the ASEAN Member States

This section presents the results of the spatial analysis of LCOE for utility-scale wind and solar PV in ASEAN. The section is framed around potential questions of interest from the intended audience (see Section 1) to highlight the capabilities of the Cost of Energy Mapping Tool and to support decision making. Policymakers, planners, developers, and other actors in the region can develop additional scenarios for specific countries with this tool on RE Data Explorer (see Box 1).

This work assessed the LCOE within a set of technical potential scenarios that define the sites on which development of a particular technology is technically feasible. Feasibility refers to constraints to developing renewable energy generation in particular areas. Box 2 details the technical potential scenarios considered in this work for Southeast Asia (see Appendix A-1.2 for additional details).

Box 2. Technical Potential Scenarios for the ASEAN Member States

Technical potential represents the capacity (MW), generation (GWh), and suitable land area (km^2) that are feasible for development after considering topographical and land-use constraints, as well as generation system performance. A technical potential scenario is a pre-defined set of assumptions that establish the constraints for development for each generation technology. Technical potential results (and subsequent LCOE and economic potential analyses) are highly sensitive to the exclusions (or constraints to development) assumed. Scenario analyses allow for an assessment of the technical potential that could result from different plausible land-use designation and related policies for renewable energy development. These high-level exclusions do not capture the various local siting considerations for specific projects (such as the interest or opposition to development from local organizations), which are outside the scope of this work.

The technical potential scenarios considered in this work for solar PV and wind in the ASEAN member states are presented in Tables 1 and 2, respectively. These scenarios were developed in coordination with ACE and ACE's Renewable Energy Sub Sectoral Network (RE SSN) Focal Points. As an example for solar PV (Table 1), in the first, "Relaxed" technical potential scenario all protected areas, waterbodies, and urban areas are excluded from consideration, while forested areas, agricultural areas, and areas with any slope are considered (or included). The third, "Restricted" scenario adds exclusions for forested areas, agricultural areas, and areas with a slope greater than 5%.

Table 1. Solar Photovoltaic Technical Potential Scenarios

Scenario	Protected Areas	Water-bodies	Forested Areas	Urban Areas	Agricultural Areas	Slope Exclusion
Relaxed	*Exclude*	*Exclude*	*Include*	*Exclude*	*Include*	*None*
Moderate	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Include*	> 5% Slope
Restricted	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Exclude*	> 5% Slope
Urban Emphasis	*Exclude*	*Exclude*	*Exclude*	*Include*	*Exclude*	> 3% Slope

Table 2. Wind Technical Potential Scenarios						
Scenario	**Protected Areas**	**Water-bodies**	**Forested Areas**	**Urban Areas**	**Agricultural Areas**	**Slope Exclusion**
Relaxed	*Exclude*	*Exclude*	*Include*	*Exclude*	*Include*	*None*
Moderate	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Include*	**> 20% Slope**
Restricted	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Exclude*	**> 20% Slope**

Refer to Appendix A-1.2 for additional details on these scenarios and associated technology assumptions.

2.1 What is the cost of utility-scale solar photovoltaic and wind generation across the ASEAN Member States?

This section explores the cost of utility-scale solar and wind generation across the ASEAN member states. The cost of generation for utility-scale renewables across the ASEAN member states depends on multiple factors that are often specific to each country, such as resource availability and quality, installed costs, O&M costs, and financial considerations (see Appendix A-1.3 for a complete list of inputs).

2.1.1 Solar photovoltaics

Variations in the LCOE for solar PV across the region result from changes in energy resource quality as well as the economic and techno-economic assumptions for each country. Figure 3 presents the variations in LCOE across the region and within each country for solar PV within the Moderate Technical Potential Scenario and with a capacity factor of more than 10% (detailed in Box 2). The LCOE for solar PV in this scenario ranges from $64 USD/MWh in Vietnam to more than $200 USD/MWh in Indonesia. The lowest LCOE values across the region are seen in Vietnam, Burma, Thailand, and Cambodia, with minimum LCOEs of approximately $64, $70, $80, and $82 USD/MWh, respectively. The lower LCOE results are from areas with high solar energy resource qualities along with the assumed economic (such as inflation and tax rates) and techno-economic (such as installation and O&M costs) assumptions for each country. In these estimates, higher LCOEs in Indonesia result mostly from the assumed installed costs for solar PV in the country. Distinct changes in LCOE along country borders in the region are also evident (such as between Thailand and Lao PDR). LCOE variations along country borders result from the country-specific economic and techno-economic assumptions, not from distinct changes in resource quality, which is relatively continuous along the borders.

Intra-country variations in solar PV LCOE are smoother and result from variations in the solar energy resource quality (capacity factor), because economic and techno-economic assumptions are constant across each country (a single value for installed cost is assumed for each country). As an example, the LCOE values in southern Vietnam are predominantly less than the values in northern Vietnam—mirroring the higher quality of solar resources in the south, as seen in Figure 1.

Supply curves help to quantify the cumulative capacity of solar PV or wind that can be developed for a maximum cost, or minimum capacity factor, in a region. On its vertical axis, a supply curve shows the levelized cost of each unit of energy produced by potential generators sited in each area. On its horizontal axis, a supply curve shows the total potential cumulative installed capacity (MW) equal to or less than a given LCOE. The supply curve in Figure 4 shows that the total potential cumulative installed capacity from solar PV available across all ASEAN member states for an LCOE equal to or less than $246 USD/MWh—corresponding to a minimum capacity factor of 10% in the region—is approximately 42 TW (Moderate Technical Potential Scenario). The minimum LCOE in the region is $64 USD/MWh, and the median LCOE for the region is $111 USD/MWh. The ranges in Figure 4 correspond to the colors mapped across the ASEAN member states in Figure 3. Table B-1 (Appendix B) presents the technical potential results (i.e., suitable land area, capacity, and generation) within the available LCOE ranges for each of the technical potential scenarios considered for solar PV.

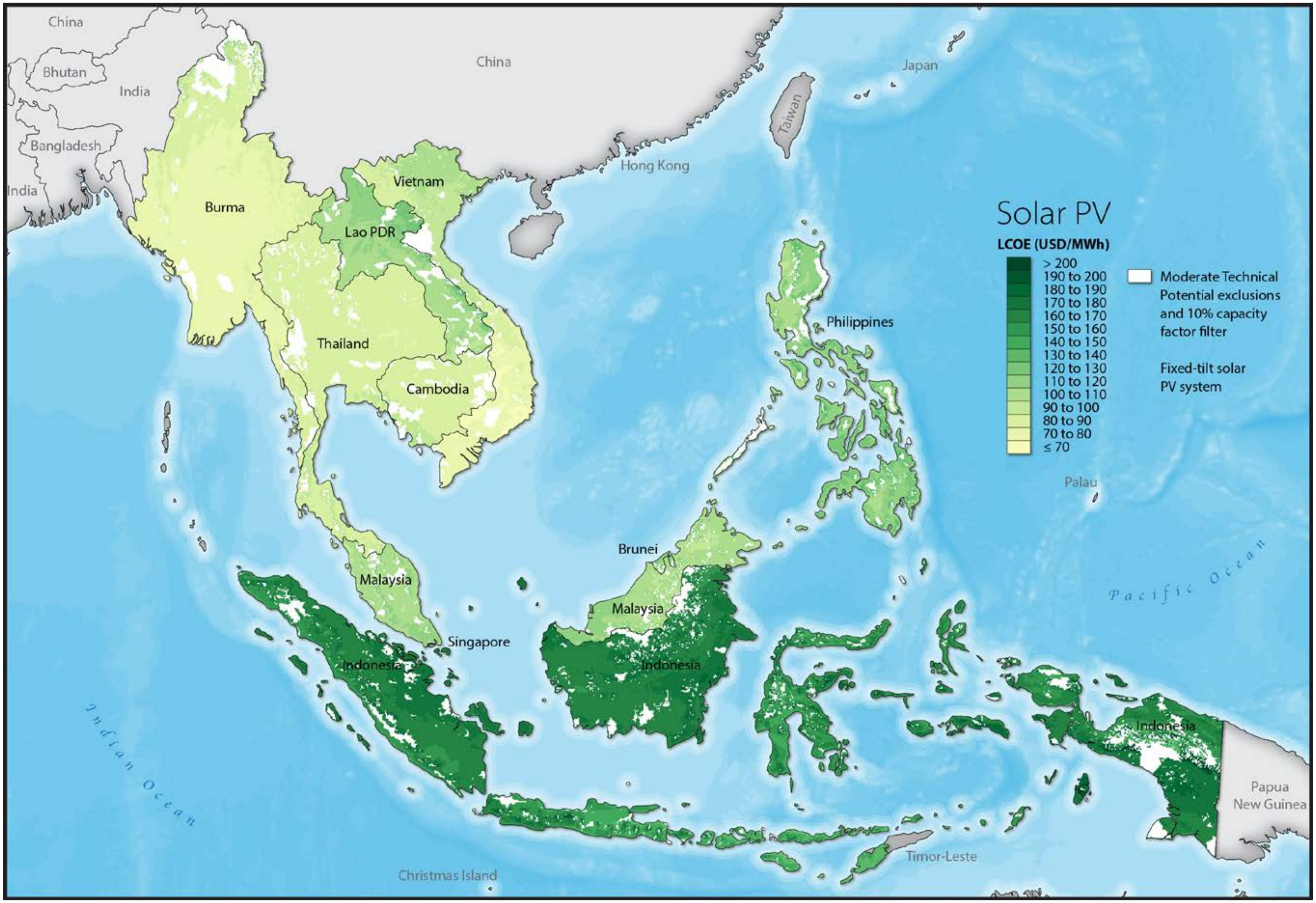


Figure 3. Solar photovoltaic levelized cost of energy across ASEAN member states for the Moderate Technical Potential Scenario

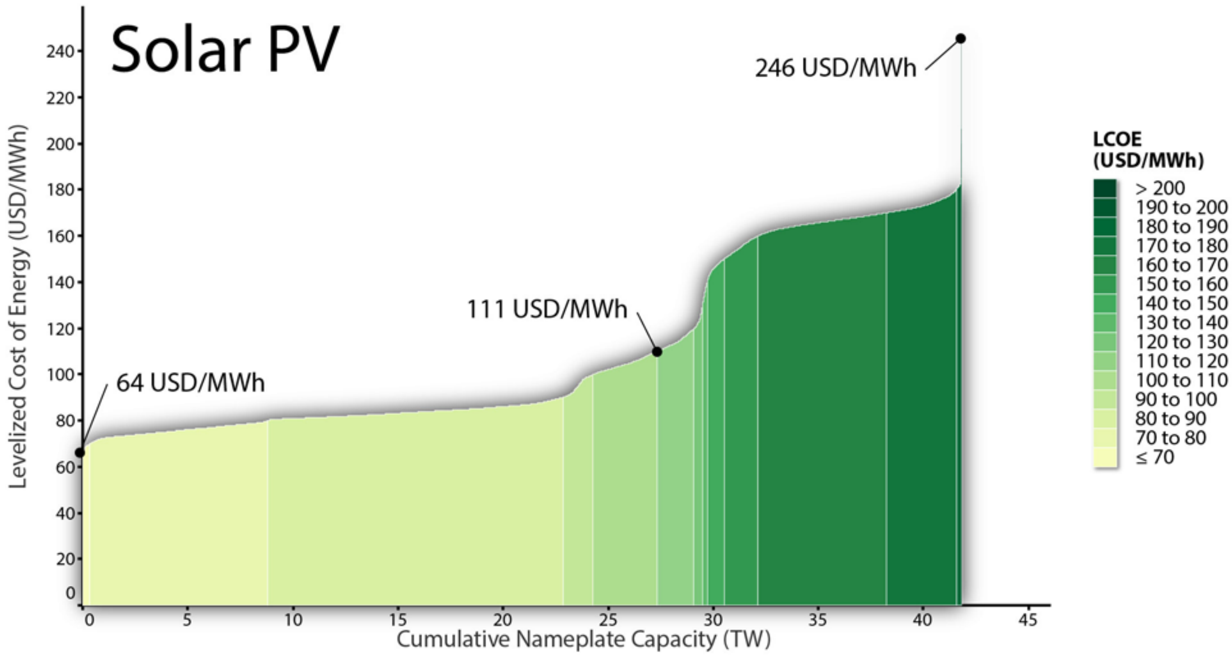


Figure 4. Solar photovoltaic supply curve for ASEAN—Moderate Technical Potential Scenario (capacity factors of more than 10%)

Note: The horizontal axis of the supply curve illustrates the potential **cumulative** installed capacity that could produce electricity at an LCOE less than or equal to the LCOE given on the vertical axis. For example, the graphic above indicates that across the entire area of the ASEAN member states, the potential exists for approximately 28 TW of solar PV capacity that could produce electricity at an LCOE less than or equal to $111 USD/MWh, 42 TW that could produce electricity at an LCOE less than or equal to $246 USD/MWh, or 9 TW that could produce electricity at an LCOE less than or equal to $80 USD/MWh, and so forth.

2.1.2 Wind

The variations in the LCOE for wind-based generation across the region result from changes in energy resource quality as well as the economic and techno-economic assumptions for each country. Figure 5 shows the estimated LCOE across the region and within the ASEAN member states for wind within the Moderate Technical Potential Scenario (described in Box 2). Estimated LCOEs for wind across the region range from approximately $42 USD/MWh in Vietnam to more than $200 USD/MWh in Lao PDR. Figure 5 shows that a significant amount of area in the region is excluded (colored white) as a result of the wind resource quality filter, which excludes areas with capacity factors of 15% or less.[8]

The supply curve in Figure 6 shows that the estimated cumulative potential for installed wind capacity across the region at or below $221 USD/MWh is approximately 2 TW for the Moderate Technical Potential Scenario. The minimum LCOE for wind in the region is $42 USD/MWh and

[8] This work focuses on areas in the region with the highest-quality wind resources, assuming that developers would concentrate on these areas. Less cost-effective areas with lower capacity factors would not typically be developed. With new wind technology assumptions (such as turbine hub height) and additional data or analyses, capacity factors may change.

the median LCOE is $124 USD/MWh. The colors depicted in this supply curve correspond to the color ranges mapped across the ASEAN member states in Figure 5. Table B-2 (Appendix B) presents the technical potential results (i.e., suitable land area, capacity, and generation) within the available LCOE ranges for each of the technical potential scenarios considered for solar PV.

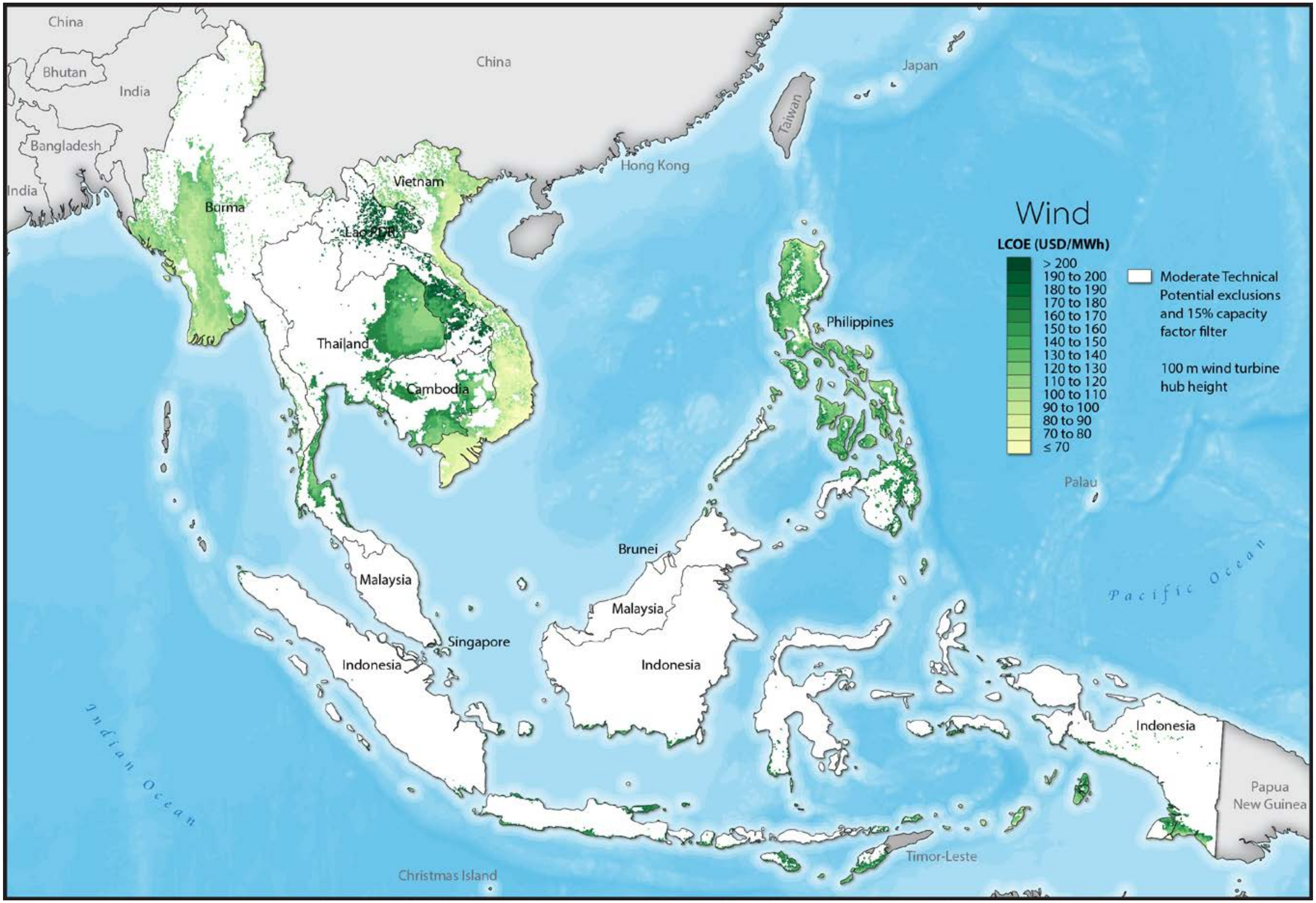


Figure 5. Wind levelized cost of energy across ASEAN member states—Moderate Technical Potential Scenario

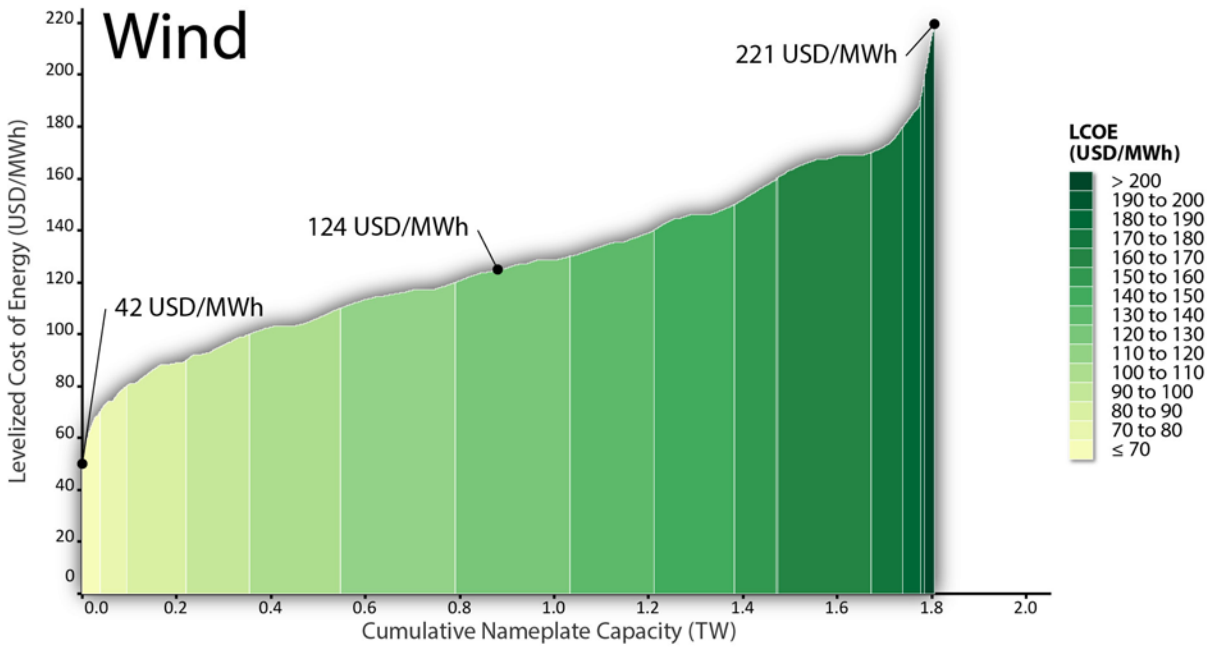


Figure 6. Wind supply curve for ASEAN—Moderate Technical Potential Scenario

Note: Supply curves illustrate on the horizontal axis the potential **cumulative** installed capacity that could produce electricity at and LCOE less than or equal to the LCOE given on the vertical axis. For example, the graphic above indicates that across the entire area of the ASEAN member states, the potential exists for approximately 0.09 TW of wind capacity that could produce electricity at an LCOE less than or equal to $124 USD/MWh, 1.8 TW that could produce electricity at an LCOE less than or equal to $221 USD/MWh, or 0.09 TW that could produce electricity at an LCOE less than or equal to $80 USD/MWh, and so forth.

Key Takeaways

The LCOE for wind and solar PV varies significantly across the ASEAN member states. The existence of high-quality wind and solar energy resources plays a significant role in the estimated cost per unit of generation. Solar PV and wind LCOEs range from $64 to $246 USD/MWh and from $42 to $221 USD/MWh, respectively, across the region. The estimated cumulative potential capacity from solar PV available across the ASEAN member states less than or equal to $246 USD/MWh is approximately 42 TW. The estimated cumulative wind potential capacity across the region less than or equal to $221 USD/MWh is approximately 1.8 TW (Moderate Technical Potential Scenario). Wind resources, in particular, are not equitably distributed across the region (given current wind resource data and technology assumptions), and significant areas are excluded in this study because of lower-quality resources (capacity factors less than 15%), which would not typically be appealing for commercial development.

The capacity factor is the ratio of actual annual output to output at rated capacity for an entire year for a wind or solar PV system. Capacity factors depend on both the energy resource quality and technology assumptions.[9] The capacity factor at a specific site can significantly influence the estimated LCOE as poor resource qualities will result in higher LCOEs. As noted above,

[9] Capacity factors are estimated for this work on a site-specific basis using geospatial resource data and generation technology assumptions (see Appendix A-1.3 for more details).

significant areas were excluded from this study as they had capacity factors for wind and solar PV of less than 15% and 10% respectively, which resulted in significantly higher LCOEs. With updated wind and solar resource data and technology assumptions, the capacity factors assumed in this work may be revised.

Figure 7 shows the cumulative solar PV and wind opportunities (capacity in GW) potentially available in each ASEAN country with an LCOE of less than $150 USD/MWh.[10]

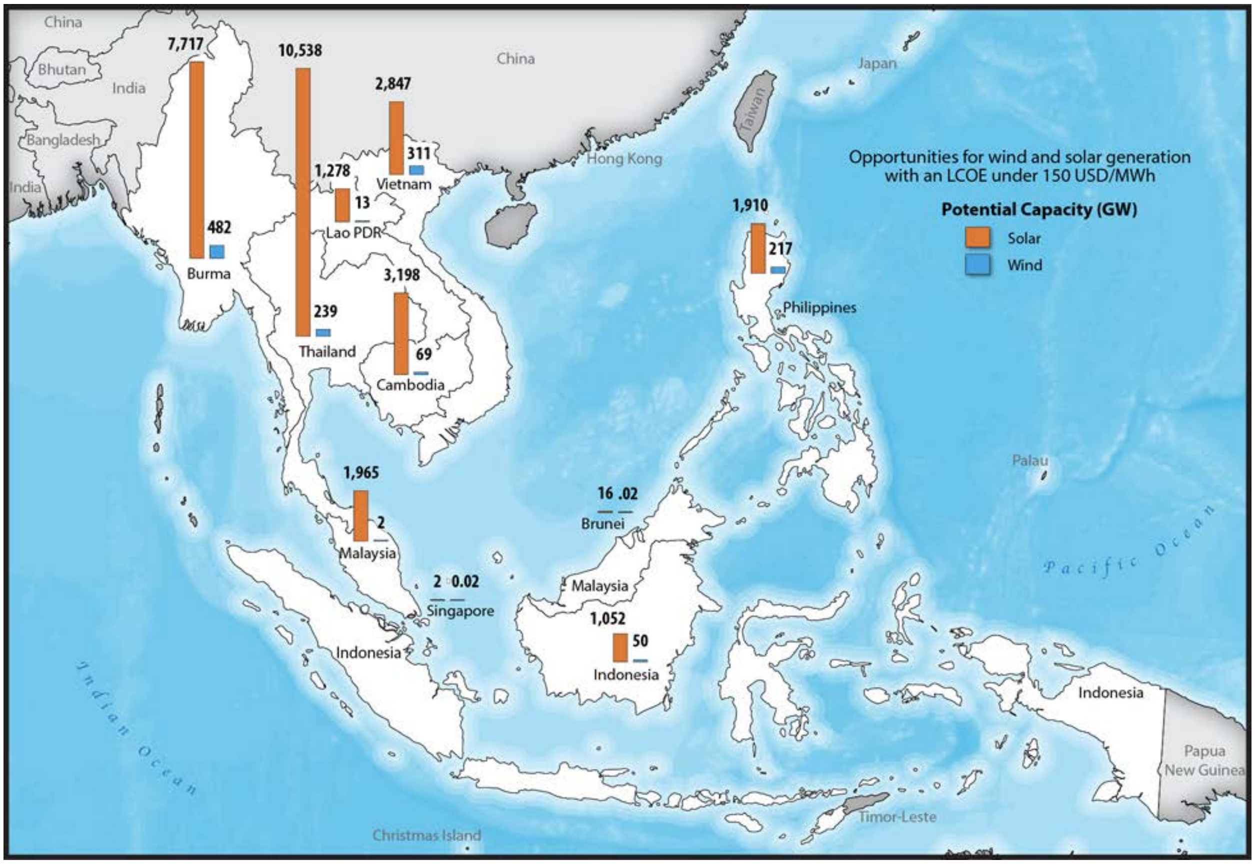


Figure 7. Cumulative solar photovoltaic and wind opportunities (capacity in GW) potentially available at a levelized cost of energy of less than $150 USD/MWh in each ASEAN member state

The Cost of Energy Mapping Tool allows users to visually explore (or download) estimated costs for utility-scale solar PV and wind generation in countries across the ASEAN member states. Users can also develop additional scenarios by modifying techno-economic input assumptions.

2.2 How do land-use constraints affect the cost of generation?

With economic development, population growth, and increased demand for resources, competing demand for land use will likely rise. Land-use designation policies that establish the areas where

[10] ACE (2019) estimated that LCOEs for solar PV generation ranged from $99 to $200 USD/MWh and that LCOEs for wind generation were approximately $150 USD/MWh in 2018 in the ASEAN member states.

renewables can be developed often impact the feasible areas considered by developers and the resulting generation costs. Decision makers must frequently consider trade-offs between land-use designations that may support energy system expansion and land uses that support other development objectives (such as agricultural land or forests). This section explores how different land-use constraints for wind and solar development may affect LCOE in the region by considering additional technical potential constraint scenarios (see Box 2 for details on the technical potential scenarios).[11] These constraints do not attempt to capture more local generation siting considerations (such as local organizations' acceptance or opposition to siting in a specific location), which are outside the scope of this work.

2.2.1 Solar photovoltaics

The solar PV technical potential scenarios represent progressively restrictive exclusions for potential wind and solar PV development, detailed in Box 2. Generally, the suitable land area (km^2), potential capacity (MW), and generation (GWh) available decrease as more constraints (i.e., exclusions) are added to development. Figure 8 and Figure 9 show the estimated solar PV LCOE for the Relaxed and Restricted Technical Potential Scenarios, respectively. The Relaxed Technical Potential Scenario (Figure 8) results in the most suitable area (km^2) for solar PV development (fewer constraints to development) and potential capacity (MW) across the region. The cumulative potential capacity across the region in the Relaxed Technical Potential Scenario is approximately 134 TW. The cumulative potential capacity in the Moderate Scenario is approximately 42 TW (Figure 4). Finally, the Restricted Scenario has a regional cumulative capacity of approximately 6 TW.

At the country level, different technical potential scenarios limit the suitable land area available. With less available land area there is also less potential installed capacity. Lao PDR and the Philippines, for example, see total potential capacity with LCOEs of less than $100 USD/MWh reduced from 139 to 49 GW and 42 to 5 GW in the relaxed and restricted scenarios, respectively. With a reduction of potential capacity, and especially in regions with high capacity factors, the estimated generation (GWh) also falls across the region. Table B-1 (see Appendix B) presents the technical potential results (i.e., suitable land area, capacity, and generation) within the available LCOE ranges for each of the technical potential scenarios considered for solar PV.

The average LCOE for solar PV in each country does not vary significantly among the three technical potential scenarios (Table 3). The consistent average LCOE suggests that land area (and resources) are excluded equitably among regions of different LCOE levels. Within the Moderate Scenario, Indonesia has the highest average LCOE in the region at approximately $165 USD/MWh, and Burma has the lowest average LCOE at $79 USD/MWh.

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[11] Technical potential is the achievable electricity generation capacity (MW), generation (GWh), and suitable land area (km^2) given system performance, certain geographic constraints, and technology-specific limitations (such as the need for minimum spacing between solar PV panels or wind turbines) (refer to Box 2 and Appendix A for additional descriptions of technical potential).

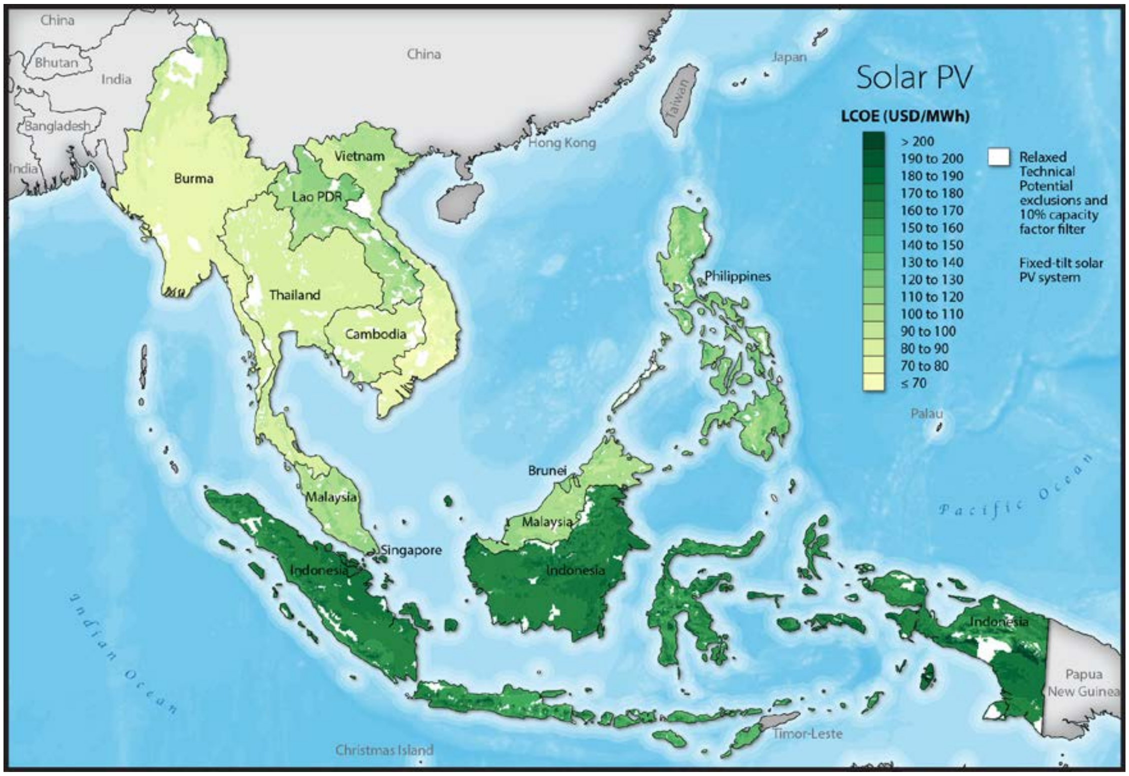


Figure 8. Solar photovoltaic levelized cost of energy across ASEAN member states—Relaxed Technical Potential Scenario

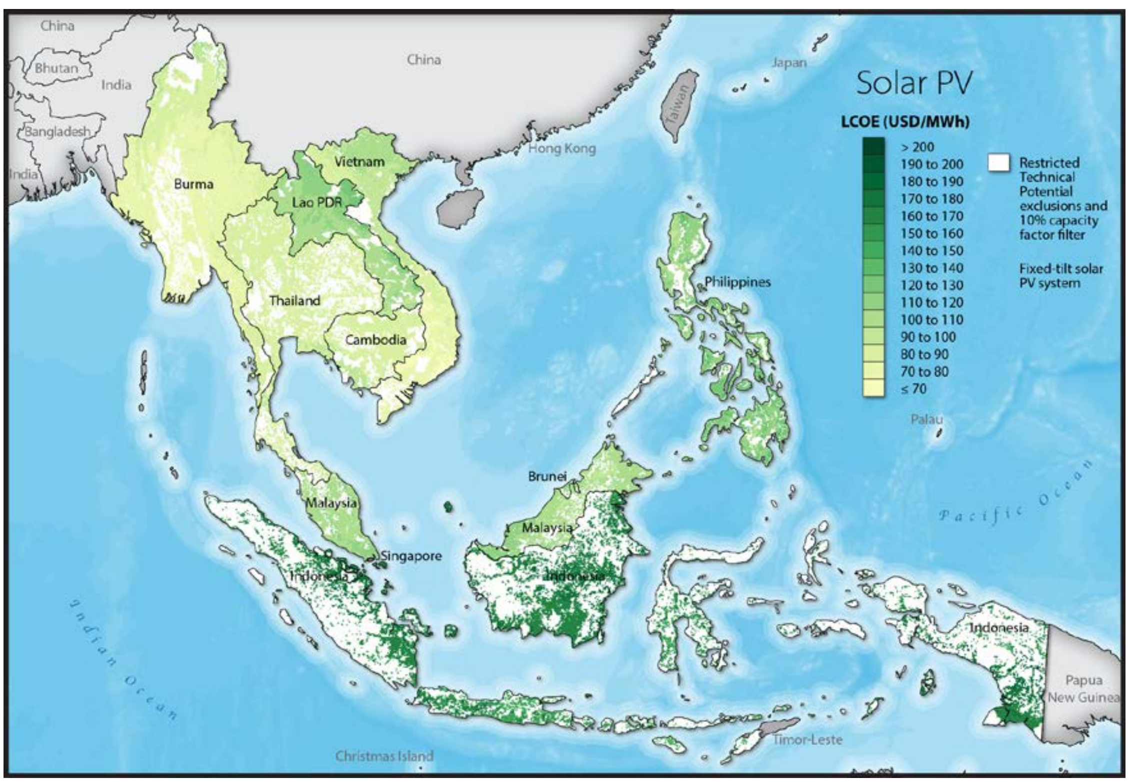


Figure 9. Solar photovoltaic levelized cost of energy across ASEAN member states—Restricted Technical Potential Scenario

Table 3. Average Solar Photovoltaic Levelized Cost of Energy for Technical Potential Scenarios*				
Country	Average LCOE (USD/MWh)			
	Relaxed Scenario	Moderate Scenario	Restricted Scenario	Urban Scenario
Brunei	118.2	117.9	117.6	116.1
Burma	80.3	79.1	79.8	77.8
Cambodia	87.5	87.4	87.7	87.2
Indonesia	166.5	164.8	165.3	157.3
Lao PDR	111.1	110.5	110.7	107.1
Malaysia	108.0	107.5	107.5	106.1
Philippines	118.5	116.8	117.6	113.6
Singapore	123.0	123.1	122.7	123.2
Thailand	85.1	84.9	85.3	84.6
Vietnam	87.1	86.6	87.5	85.1

*Refer to Box 2 for additional descriptions of technical potential scenarios. The Urban Scenario and results are detailed further in Section 2.2.3.

2.2.2 Wind

The wind technical potential scenarios also represent progressively restrictive exclusions for potential wind development and are detailed in Box 2. Figure 10 and Figure 11 present the resulting wind LCOEs across the region within the Relaxed and Restricted Technical Potential Scenarios. In these figures it is evident that the suitable land area (km^2) is further restricted from the Moderate Scenario with the addition of development constraints. The cumulative potential capacity across the region in the Relaxed Technical Potential Scenario is approximately 30 TW. The cumulative potential capacity in the Moderate Scenario is approximately 19 TW (Figure 6). Finally, the Restricted Scenario has a regional cumulative capacity of approximately 4 TW.

As with solar PV development, with less available land area for wind development the potential installed capacity is reduced. Thailand and Indonesia, for example, see total potential capacity with LCOEs of less than $150 USD/MWh reduced from 2,667 GW to 104 GW and 974 to 64 GW in the relaxed and restricted scenarios, respectively. With a reduction of potential capacity, and especially in regions with high capacity factors, the estimated generation (GWh) also falls across the region. Table B-2 (see Appendix B) presents the technical potential results (i.e., suitable land area, capacity, and generation) within the available LCOE ranges for each of the technical potential scenarios considered for wind.

The average LCOE for wind in each country does not vary significantly among the three technical potential scenarios (Table 4). The consistent average LCOE suggests a fairly consistent resource quality within each country as areas are progressively excluded from development within the scenarios considered. The Lao PDR has the highest average LCOE for wind in the region at $186 USD/MWh, and Vietnam has the lowest average LCOE for wind at approximately $92 USD/MWh (Moderate Scenario).

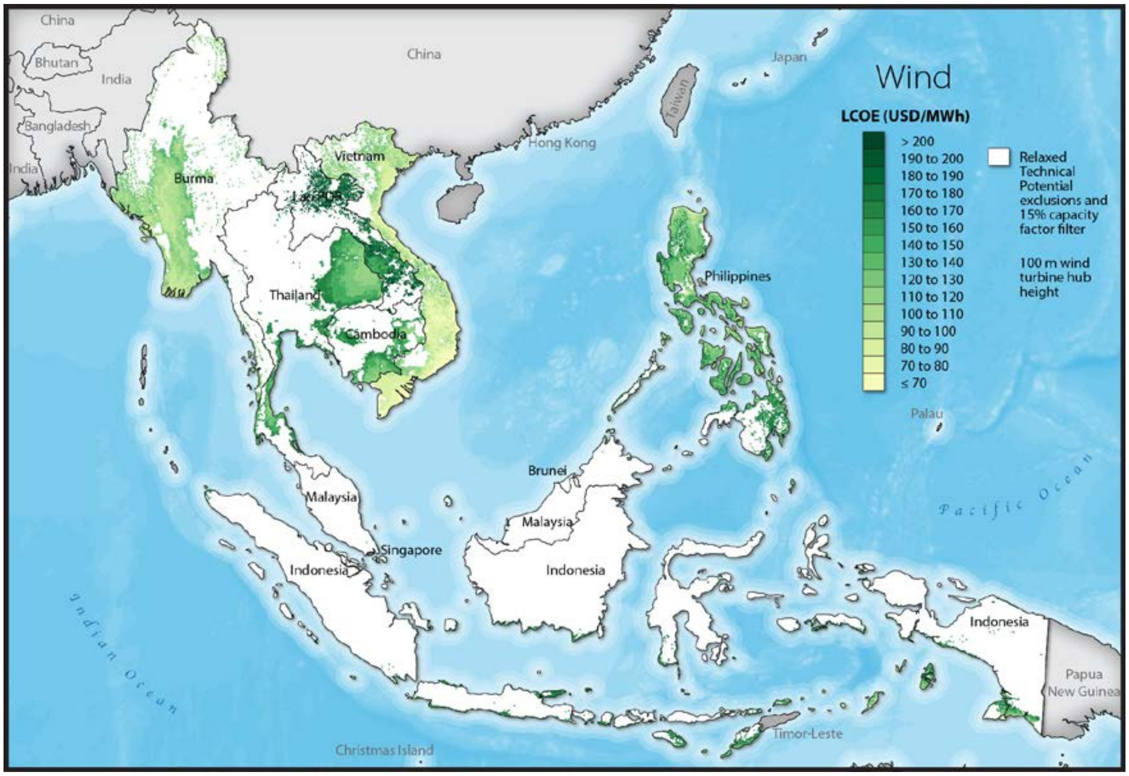


Figure 10. Wind levelized cost of energy across ASEAN member states—Relaxed Technical Potential Scenario

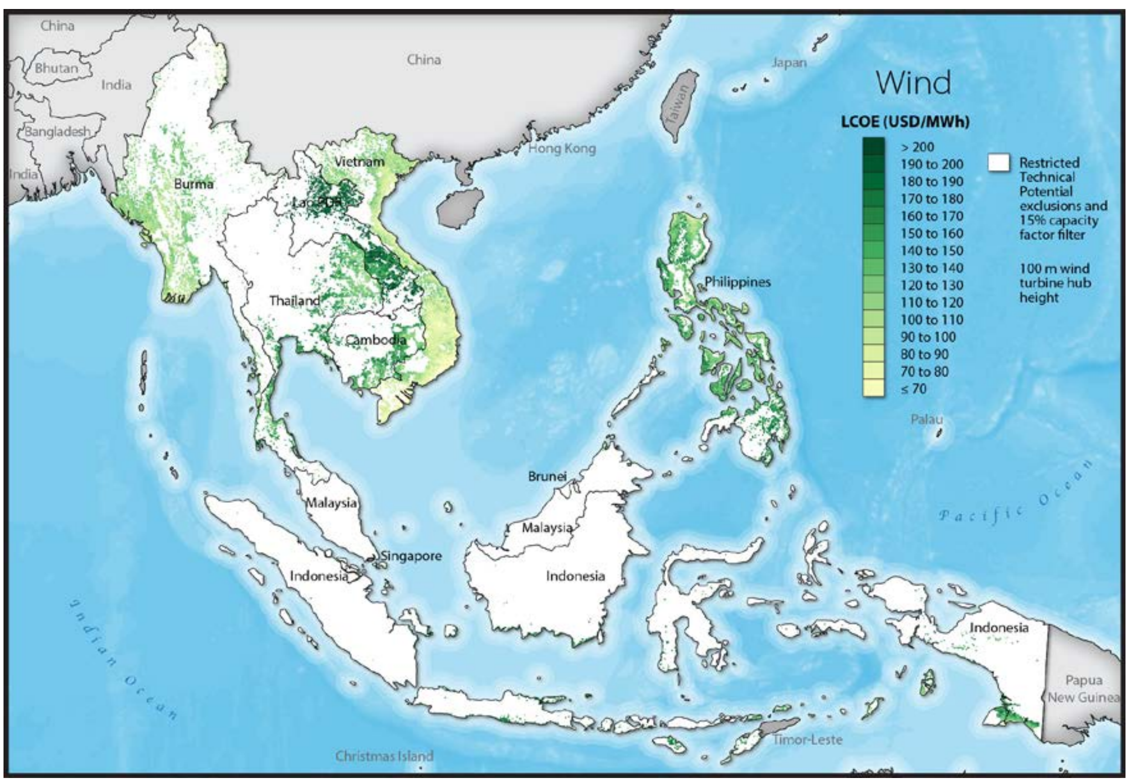


Figure 11. Wind levelized cost of energy across ASEAN member states—Restricted Technical Potential Scenario

Table 4. Average Wind Levelized Cost of Energy for Technical Potential Scenarios

Country	Average LCOE (USD/MWh)		
	Relaxed Scenario	Moderate Scenario	Restricted Scenario
Brunei	140.4	140.1	129.9
Burma	111.6	111.4	112.0
Cambodia	146.5	146.6	145.4
Indonesia	146.1	145.9	148.6
Lao PDR	186.3	186.0	187.0
Malaysia	134.3	135.0	136.1
Philippines	126.3	127.6	127.1
Singapore	150.0	153.6	151.3
Thailand	145.0	145.1	144.7
Vietnam	91.8	91.6	93.0

2.2.3 Solar photovoltaics in urban areas

Technical potential scenarios typically exclude urban areas that are too densely developed for the siting of utility-scale generation. The technical potential scenarios in the preceding sections all exclude urban areas; however, to highlight potential use cases of the Cost of Energy Mapping Tool (see Box 1), this work also includes an urban scenario for solar PV (see Box 2). This scenario assesses the LCOE of solar PV only within urban areas in the region (it excludes all rural areas). The focus is not on comparisons with the other scenarios (Relaxed, Moderate, and Restricted), but rather on an exploration of the potential LCOE around population centers—regions where significant energy demand likely exists. Generation in these dense urban regions would not likely be utility-scale development, but an estimate of LCOE in urban areas could inform distributed solar PV and rooftop solar PV development. This analysis does not, however, include available rooftop area or other considerations that would limit development. The Urban Scenario also does not consider regional cost multipliers that could account for potential increased land-acquisition costs in dense, urban areas. The average country LCOEs for the Urban Technical Potential Scenario are shown in Table 3. The Urban Scenario solar PV technical potential is summarized by country in Table B-1 of Appendix B.

Figure 12 shows the spatial LCOE results for the Hanoi Metropolitan Area in Vietnam, as an example of the LCOE results for urban areas in the region.[12] The LCOE range for a significant share of the Hanoi metropolitan area is from $95 to $99 USD/MWh. Higher LCOEs, which result purely from lower solar resource quality, from approximately $95 to $105 USD/MWh, are

[12] Results for Hanoi are shown here as an example of the functionality of the Cost of Energy Mapping Tool. Readers can use the tool to explore the capitals of other ASEAN member states and urban areas with similar urban-focused scenarios.

seen around the Hanoi city center. LCOEs in the range of $105 to $110 USD/MWh are seen around the periphery of the Hanoi.

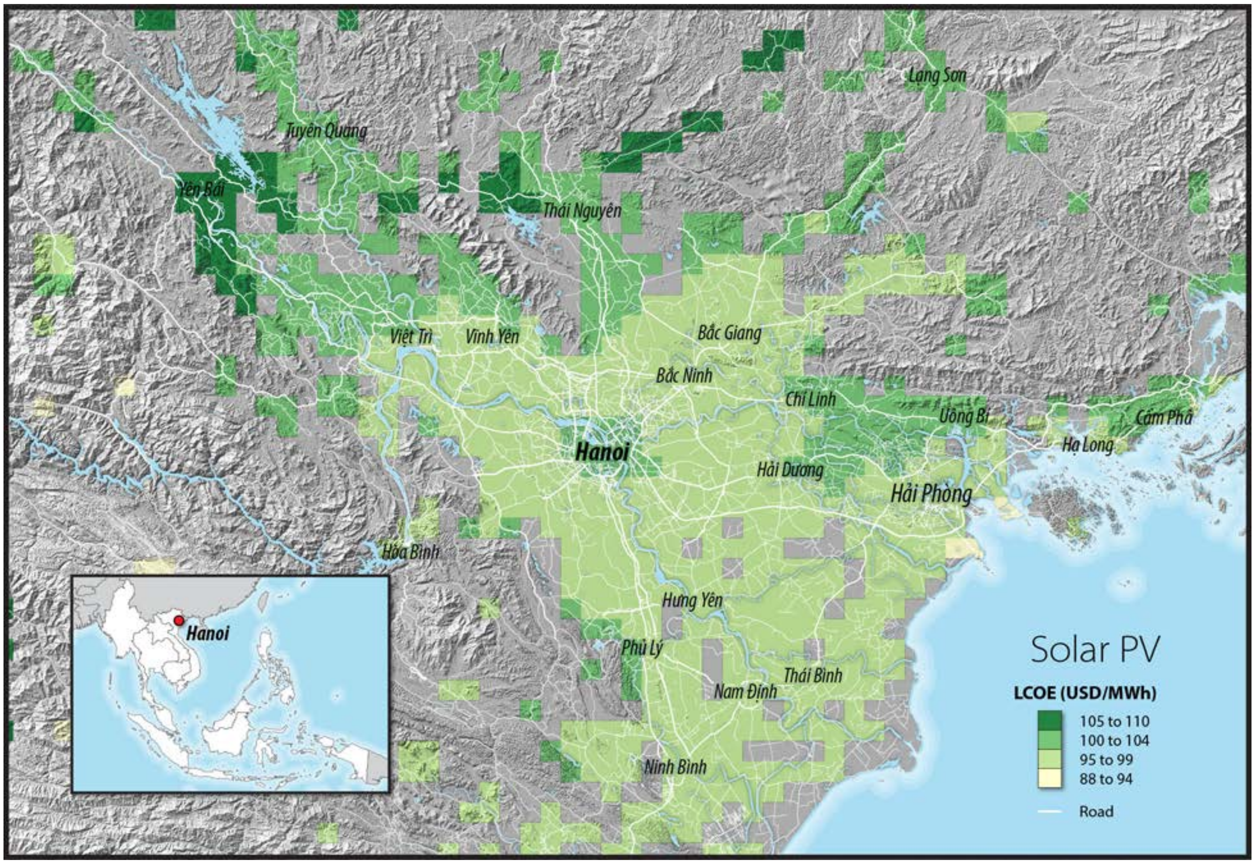


Figure 12. Solar photovoltaic levelized cost of energy for Hanoi Metropolitan Area, Vietnam, for Urban Technical Potential Scenario

Key Takeaways

Land-use constraints play a significant role in available land area for the development of both solar PV and wind generation and, thus, technical potential across the region. However, average LCOE remains relatively consistent in each country, and is fairly independent of the land-use constraints assumed in this work. Other factors, such as wind and solar energy resource quality and the installation costs, play a larger role in determining the estimated LCOE of projects in the ASEAN member states, which should help guide developers and policymakers to identify opportunities for the deployment of renewables.

The Cost of Energy Mapping Tool can help developers and policymakers explore the LCOE of wind and solar PV within different technical potential scenarios by representing potential land-use constraints (including urban scenarios).

2.3 What are the near-term opportunities for solar photovoltaic development?

This section explores near-term development opportunities for solar PV in Cambodia, as an example application of the spatial LCOE data and complementary data sets. In this example, near-term opportunities for wind and solar development are based on proximity to the existing transmission system. Proximity of resources to existing transmission lines is often attractive because transmission expansion (often costly and time-consuming) can be avoided through interconnection with the existing grid. This work does not consider transmission interconnection costs or potential remaining transfer capacities (MW) in the existing transmission system. An examination of the resources in the region surrounding transmission lines provides insight into the location and estimated generation of potential short-term, cost-effective projects.

To assess near-term opportunities in Cambodia (as an example), transmission system data for the country was overlaid on the LCOE results for solar PV (for the Moderate Technical Potential Scenario) to filter out any available solar resources further than 20 km from the existing grid.[13, 14] Figure 13 depicts the resulting generation of costs of potential near-term solar PV opportunities in Cambodia within 20 km of the existing transmission system following this scenario. Near-term LCOE results range from approximately $75 USD/MWh in regions close to the capital, Phnom Penh, to approximately $105 USD/MWh along the western coast. The average cost of generation within 20 km for solar PV in this scenario is $86.7 USD/MWh.

[13] Results for Cambodia are shown as an example of the functionality of the Cost of Energy Mapping Tool. Readers estimate LCOE and download results to explore near-term opportunities in other ASEAN member states. High-resolution, validated spatial transmission system data sets for all ASEAN member states were not available at the time of this analysis.

[14] The most recent spatial transmission system data for Cambodia on RE Data Explorer was used to identify near term-term opportunities (Open Development Cambodia 2014). These include lines that were in operation, under construction, or under study. Similar analyses could be completed that control for proximity to updated transmission system data from local sources.

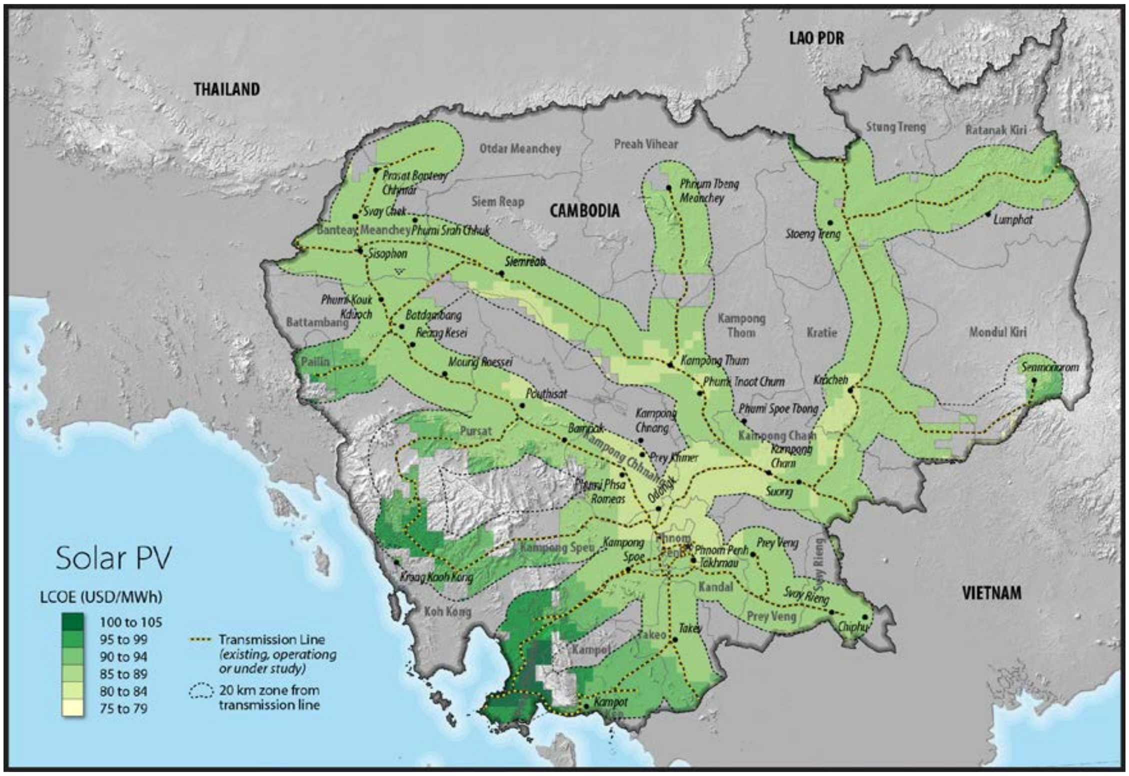


Figure 13. Generation costs of near-term solar photovoltaic opportunities in Cambodia (≤20 km of transmission and Moderate Technical Potential Scenario Exclusions)

Table 5 summarizes the potential suitable land area, capacity, and generation within the LCOE bands from $80 to $110 USD/MWh. Within 20 km of the existing grid, there is an estimated total technical potential capacity of 2,081 MW. Of this total technical potential capacity, 1,901 GW has an estimated LCOE of less than $90 USD/MWh. Additional potential capacity may also be available at higher costs.

Table 5. Solar Photovoltaic Technical Potential within 20 km of Transmission by Levelized Cost of Energy in Cambodia

Country	LCOE (USD/MWh)	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
Cambodia	Up to 90	2,231.0	1,900.8	2,857.8
	90 to 100	408.0	169.1	235.6
	100 to 105	35.0	11.0	14.0
	Total	**2,674.0**	**2,080.9**	**3,107.4**

Key Takeaways

Near-term opportunities for solar PV (or wind) development may exist in proximity to existing power system infrastructure across the region. For example, in Cambodia, approximately 1,901 GW of potential capacity may be available at an LCOE of less than $90 USD/MWh within 20 km of transmission infrastructure.

Using the data and visualization functionalities of the Cost of Energy Mapping Tool, developers, planners, and policymakers can identify potential near-term development opportunities for renewables when constraints such as transmission distance (or other constraints such as proximity to population centers) are used as a scenario input.

2.4 How do installation, operation, and maintenance costs affect generation costs?

This section explores how declining installed and fixed O&M costs may affect LCOE in the region. With further technology improvements and new drivers that include utility business models, competitive procurement, and implementation of best practices in project development, generation costs for renewables—including wind and solar PV—may continue to fall in the ASEAN member states (ACE 2019; IRENA 2018; ACE and IRENA 2016). These advances may lead to further decreases in both the installed costs and fixed O&M costs for renewables.[15]

Three scenarios are considered to explore reduced installed and fixed O&M costs. The first scenario reflects reduced installed costs (Low Installed Cost Scenario). The second scenario considers both reduced installed and fixed O&M costs (Low Installed Cost and Fixed O&M Scenario). The LCOE results from these two low-cost scenarios are compared to a third Base-Case Scenario (Moderate Technical Potential Scenario).

Representative regional wind and solar PV installed and fixed O&M costs for the year 2025 from a recent regional ASEAN renewable energy road map analysis are used for the two low-cost scenarios (ACE and IRENA 2016).[16] These regional values were assumed for all countries as a basis to explore how LCOE may be affected by declines in installed and fixed O&M costs. It is acknowledged that the actual technology costs in each country and for every system will vary. The Low Installed Cost Scenario assumes solar PV and wind installed costs at $1,000 USD/kW and $1,500 USD/kW, respectively. The Low Installed Cost and Fixed O&M Scenario assumes solar PV and wind fixed O&M are $10 USD/kW/year and $60 USD/kW/year, respectively.

2.4.1 Solar photovoltaics

Reduced installed and fixed O&M costs for solar PV (and wind) result in lower estimated LCOEs throughout the region. Figure 14 shows the results of the two low-cost scenarios compared to the base scenario for both wind and solar PV for all countries. In Figure 14, the boxes for each scenario show the 1st quartile, median, and the 3rd quartile for the LCOE values, and the vertical lines extend to the minimum and maximum values. The Low Installed Cost

[15] Installed cost here refers to the total cost for the generation system investment including plant and machinery, civil work, erection and commissioning, and financing costs during construction. Fixed O&M costs are the annual expenditures to operate and maintain generation systems, which are not incurred on a per-unit-energy basis, for electricity generation (see Appendix A for additional descriptions).

[16] These costs represent future low-cost renewables from an analysis exploring pathways to achieve the ASEAN member states' aspirational renewable energy targets for 2025 (see Section 1).

Scenario for solar PV results in lower minimum, maximum, and mean LCOE values than the Base Scenario in all countries. Also considering lower solar PV Fixed O&M costs (Low Installed Cost and Fixed O&M Scenario) results in further reducing the LCOEs in the majority of the countries from the Base Scenario. Declines in LCOE from the Base Scenario depend significantly on the cost assumed in the Base Scenario for each country (see Appendix A for assumed technology costs). More significant reductions in LCOE are seen in countries with higher Base Scenario installed costs (such as Brunei, Indonesia, Malaysia, and the Philippines).

Table 6 shows the mean LCOE for each country under the scenarios considered and the percentage (%) change from the Base Scenario. Significant declines in the mean LCOE for solar PV are seen in most countries. Brunei, Indonesia, and the Philippines see a 40% or greater drop in the mean LCOEs from the Base Scenario to the Low Installed Cost Scenario. For example, the mean LCOE in Indonesia falls from approximately $165 to $96 USD/MWh, respectively. In the Low Installed Cost and Fixed O&M Scenario, the mean LCOE in Indonesia sees a further decrease in mean LCOEs from $96 to approximately $90 USD/MWh. The change in mean LCOE is less dramatic for countries with lower assumed Base Scenario costs. The LCOE in Lao PDR drops from approximately $110 to $97 USD/MWh in the Low Installed Cost and Fixed O&M Scenario (a 12% change from the Base Scenario).

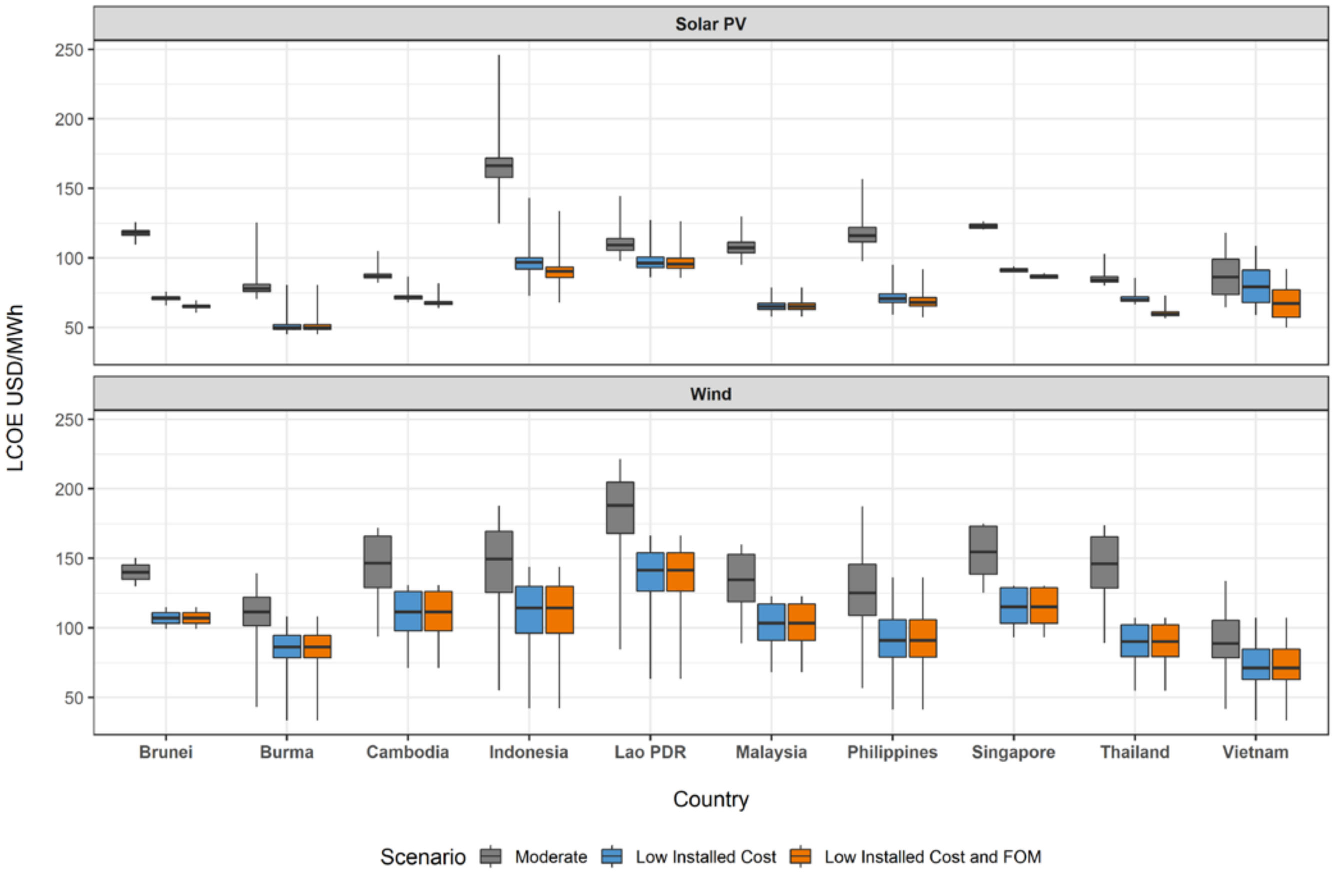


Figure 14. Low installed cost and fixed operation and maintenance scenarios' levelized cost of energy compared to the Moderate Scenario (or Base Scenario)

2.4.2 Wind

The Low Installed Cost scenario for wind (Figure 14) also results in lower minimum, maximum, and mean LCOE values than the Base Scenario in all countries. There is no change between the two low-cost scenarios for wind as the fixed O&M values in the Base Scenario were already at or below the assumed representative low-cost value for 2025 from IRENA and ACE (2016) for all countries.

Table 6 also shows the mean LCOE for wind generation for each country under the scenarios considered and the percentage (%) change from the Base Scenario. In the Low Installed Cost Scenario, the mean LCOE in Thailand falls from approximately $145 to $90 USD/MWh (a 38% change from the Base Scenario).

Table 6. Mean Solar Photovoltaic and Wind Levelized Cost of Energy and Change from Base Scenario for Installed Costs and Fixed Operation and Maintenance Costs Scenarios						
Country	**Technology**	**Base Installed and Fixed O&M Costs**	**Low Installed Costs***	**Low Installed and Fixed O&M Costs**	**Change from Base, Low Installed Costs**	**Change from Base, Low Installed and Fixed O&M Costs**
Brunei	Solar PV	117.9	71.0	65.1	-40%	-45%
	Wind	140.1	107.2	107.2	-24%	-24%
Burma	Solar PV	79.1	50.8	50.8	-36%	-36%
	Wind	111.4	86.3	86.3	-22%	-22%
Cambodia	Solar PV	87.4	72.1	68.0	-18%	-22%
	Wind	146.6	111.4	111.4	-24%	-24%
Indonesia	Solar PV	164.8	96.0	89.6	-42%	-46%
	Wind	145.9	111.7	111.7	-23%	-23%
Lao PDR	Solar PV	110.5	97.5	96.8	-12%	-12%
	Wind	186.0	140.0	140.0	-25%	-25%
Malaysia	Solar PV	107.5	65.2	65.2	-39%	-39%
	Wind	135.0	103.6	103.6	-23%	-23%
Philippines	Solar PV	116.8	71.1	68.5	-39%	-41%
	Wind	127.6	92.7	92.7	-27%	-27%
Singapore	Solar PV	123.1	91.5	86.8	-26%	-29%
	Wind	153.6	114.3	114.3	-26%	-26%
Thailand	Solar PV	84.9	70.7	60.1	-17%	-29%
	Wind	145.1	89.6	89.6	-38%	-38%
Vietnam	Solar PV	86.6	79.7	67.5	-8%	-22%
	Wind	91.6	73.5	73.5	-20%	-20%

* There is no change between the two low-cost scenarios for wind, as the fixed O&M values in the Base Scenario were already at or below the assumed representative low-cost value for 2025 from IRENA and ACE (2016).

Key Takeaways

Countries with higher installed and O&M costs will see the largest decreases in LCOE as these costs potentially fall in the next few years. Specifically, lower installed costs can significantly decrease LCOE from the Base Scenario—up to 40% in some cases (Brunei, for example). In countries with lower installed and O&M costs, significant cost decreases may also result from potential further declines in costs as well as other changes in cost structures such as debt fraction, depreciation schedules, and discount rates as explored in the sections that follow. Policymakers may explore additional ways to support lower installed costs such as import duties and tax exemptions where appropriate.

The Cost of Energy Mapping Tool enables developers, planners, and policymakers to explore how installed and O&M costs affect the cost of generation within their country.

2.5 How does debt fraction impact the cost of generation?

This section explores how the debt fraction impacts the estimated LCOE. The debt fraction (or debt-to-equity ratio) is the share of capital financed with debt for generation system assets. The difference between 100% and the debt fraction (%) is assumed to be financed with equity. For example, a debt fraction of 80% means that this share of the capital for a project was financed with debt and 20% was financed with equity. The debt fraction is important, as developers have limited capital for project investment. Reducing the share of equity required for projects potentially allows developers to invest in an increased number of power system projects (such as solar or wind generation) with their available capital. The debt fraction can also be an indicator of project risk (as well as other factors) as financiers allow for a larger debt fraction when there is less perceived risk in an investment, increasing the debt fraction. This work does not explore approaches to changing the debt fraction (or addressing project risk), which is a complex question outside the scope of this work.[17]

An Increased Debt Fraction Scenario, with a 95% debt fraction, was used to evaluate how this factor affects generation costs. A debt fraction of 95% was assumed to provide an example value higher than that assumed for any of the countries in the Base Case. For example, the base-case debt fraction was 82.5% for Vietnam (see Table A-5 of Appendix A and respective sources). The Increased Debt Fraction Scenario results are compared with the results from a Base-Case Debt Fraction Scenario (the Moderate Technical Potential Scenario).

Figure 15 presents the resulting minimum, maximum, and mean LCOEs for solar PV and wind generation for both the Base Debt Fraction and the Increased Debt Fraction Scenarios. Table 7 reports the mean LCOE for these scenarios and the percentage (%) change from the Base Debt Fraction scenario. For the majority of countries, an increased debt fraction results in reduced mean estimated LCOEs for both wind and solar PV. In two countries, Cambodia and Lao PDR, the Increased Debt Fraction Scenario results in higher LCOEs. The increased LCOEs in these countries are related to the interest rates and the larger portion of debt assumed. Cambodia and Lao PDR had relatively higher assumed interest rates for the region, approximately 9.1% and 11.1%, respectively (see the assumed interest rates for all ASEAN member states in Table A-5 of Appendix A). The mean LCOEs for wind and solar PV in Brunei see a 25% and 23% reduction in the Increased Debt Fraction Scenario, respectively. These significant reductions in LCOE can also be linked to the assumed interest rate for the country, which is approximately 0.5%, the lowest in the region.

[17] However, it is worth noting that global competition and spread of best practices for project development are helping to reduce project risk for renewables internationally (IRENA 2018).

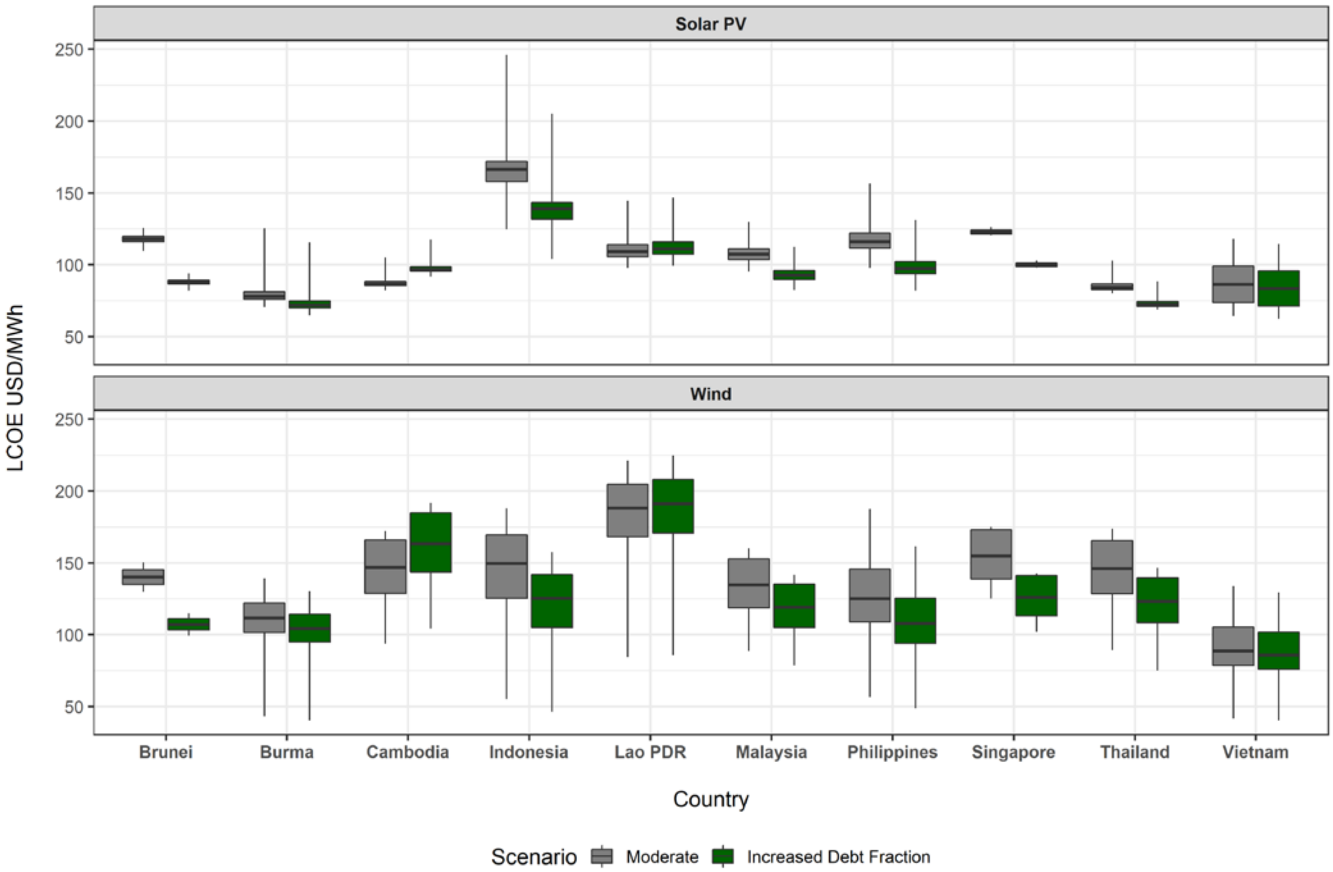


Figure 15. Levelized cost of energy values for Moderate Technical Potential and Debt Fraction Scenarios

Table 7. Mean Solar Photovoltaic and Wind Levelized Cost of Energy and Change from Base Scenario for Debt Fraction Scenario

Country	Technology	Mean LCOE (USD/MWh) Base Debt Fraction Scenario	Mean LCOE (USD/MWh) Increased Debt Fraction Scenario	Percentage Change from Base, Increased Debt Fraction
Brunei	Solar PV	117.9	88.0	-25%
	Wind	140.1	107.2	-23%
Burma	Solar PV	79.1	72.9	-8%
	Wind	111.4	104.2	-6%
Cambodia	Solar PV	87.4	97.8	12%
	Wind	146.6	163.3	11%
Indonesia	Solar PV	164.8	137.5	-17%
	Wind	145.9	122.2	-16%
Lao PDR	Solar PV	110.5	112.4	2%
	Wind	186.0	189.0	2%
Malaysia	Solar PV	107.5	93.0	-14%
	Wind	135.0	119.5	-12%
Philippines	Solar PV	116.8	98.0	-16%
	Wind	127.6	109.9	-14%
Singapore	Solar PV	123.1	100.2	-19%
	Wind	153.6	125.2	-18%
Thailand	Solar PV	84.9	73.0	-14%
	Wind	145.1	122.4	-16%
Vietnam	Solar PV	86.6	83.9	-3%
	Wind	91.6	88.5	-3%

Key Takeaways

For the majority of countries in this analysis, taking on a higher fraction of debt lowers generation costs for both wind and solar projects. However, as shown in the results for Cambodia and Laos, this is not always true because there are other relevant variables such as the tax rate and rate of return on equity for each country. The financial terms (and debt fraction) for each individual project and developer will undoubtedly vary depending on myriad factors outside the scope of this work, but this insight on the debt fraction may support decision makers in identifying opportunities for RE deployment in the region.

The Cost of Energy Mapping Tool allows users to explore debt fraction scenarios to estimate the impact on wind and solar PV generation costs in ASEAN member states.

2.6 How does a shorter depreciation schedule impact the cost of generation?

This section examines how alternative depreciation schedules for power system assets may impact the LCOE. Depreciation is an accounting mechanism for the reduction in value of a tangible capitalized asset over time (such as a solar PV system). Depreciation schedules break down this depreciation into a number of years and are generally associated with capital cost recovery for high-value property (such as power system assets) for accounting and tax purposes. Applicable depreciation schedules for generation system assets can vary widely between countries. Investors typically want to write off assets (or recover costs) as soon as possible in order to reduce their tax liability and thus increase the profitability of these assets. Governments often offer different depreciation schedules that allow for this. Accelerated depreciation schedules are often attractive as they allow investors to reduce their tax liability sooner rather than later, while straight-line depreciation schedules often break depreciation out evenly over an assumed time period with slower, more consistent reduction in the value of assets for investors.

This work considers two scenarios to evaluate how an accelerated depreciation schedule may impact the cost of generation. First is an Accelerated Depreciation Schedule Scenario that is based on the 5-year Modified Accelerated Cost Recovery System (MACRS) from the United States Internal Revenue Service as a commonly-used example of an accelerated depreciation schedule (Kiatreungwattana and Lee 2018; NREL 2018; IRS 2018). Second is a Base Scenario with a straight-line 20-year depreciation schedule (Moderate Technical Potential Scenario from Section 2.2).

Figure 16 shows the LCOE results for the Base and the Accelerated Depreciation Schedules for both wind and solar PV. The accelerated depreciation schedule resulted in slight reductions in both wind and solar PV LCOEs for all countries. Table 8 shows the mean solar PV and wind LCOEs and the percentage change from the Base Scenario to the Accelerated Depreciation Schedule Scenario. The accelerated depreciation schedule assumed for all countries resulted in a 4% (Brunei) to a 9% (Indonesia) reduction in the mean LCOE for wind and solar PV for the countries in the region.

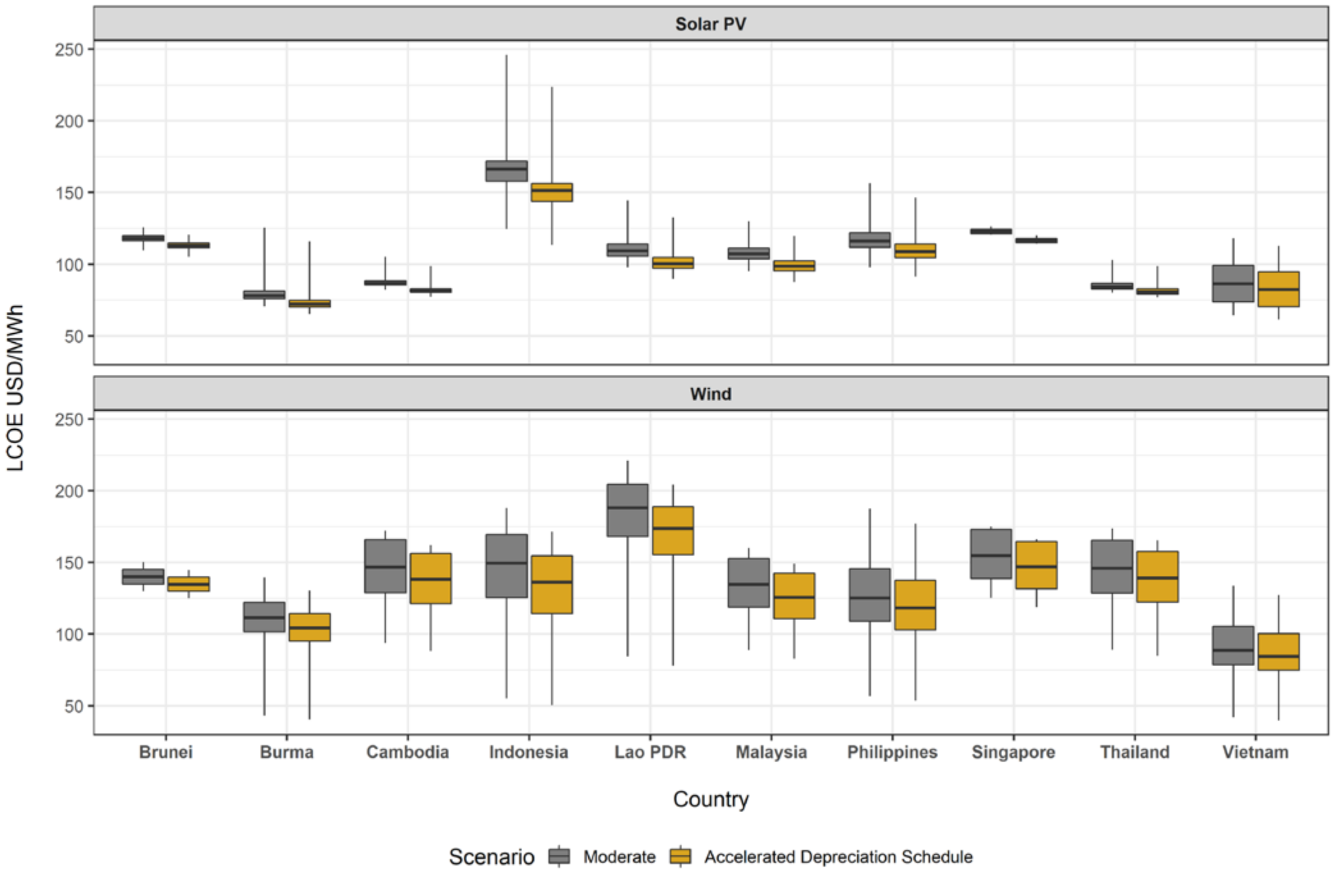


Figure 16. Levelized cost of energy values for depreciation schedule scenarios

Table 8. Mean Solar Photovoltaic and Wind Levelized Cost of Energy and Change from Base Scenario for Accelerated Depreciation Schedule Scenario				
Country	**Technology**	**Base Depreciation Schedule**	**Accelerated Depreciation Schedule**	**Change from Base, Accelerated Depreciation Schedule**
Brunei	Solar PV	117.9	113.1	-4%
	Wind	140.1	134.8	-4%
Burma	Solar PV	79.1	73.0	-8%
	Wind	111.4	104.3	-6%
Cambodia	Solar PV	87.4	82.1	-6%
	Wind	146.6	138.1	-6%
Indonesia	Solar PV	164.8	150.0	-9%
	Wind	145.9	133.0	-9%
Lao PDR	Solar PV	110.5	101.5	-8%
	Wind	186.0	171.8	-8%
Malaysia	Solar PV	107.5	98.9	-8%
	Wind	135.0	125.8	-7%
Philippines	Solar PV	116.8	109.4	-6%
	Wind	127.6	120.6	-6%
Singapore	Solar PV	123.1	116.9	-5%
	Wind	153.6	145.8	-5%
Thailand	Solar PV	84.9	81.3	-4%
	Wind	145.1	138.2	-5%
Vietnam	Solar PV	86.6	82.7	-5%
	Wind	91.6	87.2	-5%

Key Takeaways

Accelerated depreciation lowers LCOE for all countries in the region. Exploring accelerated depreciation schedules in countries where these may not be available could be of interest to policymakers as a tool to support lower renewable generation costs.

2.7 How does the discount rate affect the cost of generation?

This section explores how the discount rate affects the LCOE of solar PV and wind in ASEAN countries. Discount rates determine how long-term projects (such as power generation) are valued by investors and owners. The discount rate is a measure of the time value of money—or the value put on the time that an investor waits for their return on an investment. As $1 USD (or other currency) received today could be invested to start earning interest immediately, it is worth more than a dollar received a year from now. The discount rate is used to compute present values of money as the value of a cash flow depends on the time when the cash flow occurs. Discount rates depend on multiple factors, including the cost of capital and inflation rates, among others) (see LCOE Calculation in Appendix A-1.3.2).[18]

A sensitivity analysis was performed to evaluate the effect of several discount rates compared to the base-case value in each country. The average LCOE in the Base-Case Discount Rate Scenario is compared to the average resulting LCOEs for scenarios with discount rates of 6%, 8%, 10%, and 12% for both wind and solar PV. Figure 17 shows the resulting percentage change in average LCOE from the Base Discount Rate Scenario for each of the alternative discount rate scenarios.

Figure 17 shows how different discount rates can significantly affect the estimated average LCOE in the ASEAN member states for both solar PV and wind. For example, the average solar PV LCOE in Brunei increases from $118 USD/MWh in the Base Discount Rate Scenario to $140 and $215 USD/MWh in the 6% and 12% Discount Rate Scenarios, respectively. With a base discount rate of 4% in Brunei, these scenarios represent increased discount rates for the country. The 12% Discount Rate Scenario resulted in an approximate 82% rise in the LCOE from the Base Scenario in Brunei, which is a significant increase. The average solar PV LCOE in Indonesia decreases from $165 USD/MWh in the Base Discount Rate Scenario to $159 and $113 USD/MWh in the 10% and 6% Discount Rate Scenarios, respectively. Starting from the base assumed discount rate in Indonesia (10.4%), these scenarios represent reduced discount rates.

Significant variations are also seen in the resulting wind LCOEs for the discount rate scenarios. The average wind LCOE for Thailand increases from $145 USD/MWh in the Base Scenario to $260 USD/MWh in the 12% Discount Rate Scenario. This represents a 79% increase from the average LCOE in the Base Scenario for the country. Table A-5 of Appendix A-1.3 shows the base discount rates.

[18] The Asian Development Bank applies a minimum discount rate of 9% for their assessments of projects to identify least-cost options for energy sector investment projects (ADB 2017). IRENA and ACE (2016) assumed a 10% discount rate for select ASEAN member states with a sensitivity analysis that varied this rate from 5% to 15%. A recent LCOE analysis for the Lao PDR explored discount rates of 3%, 6%, and 8% (Kiatreungwattana and Lee 2018).

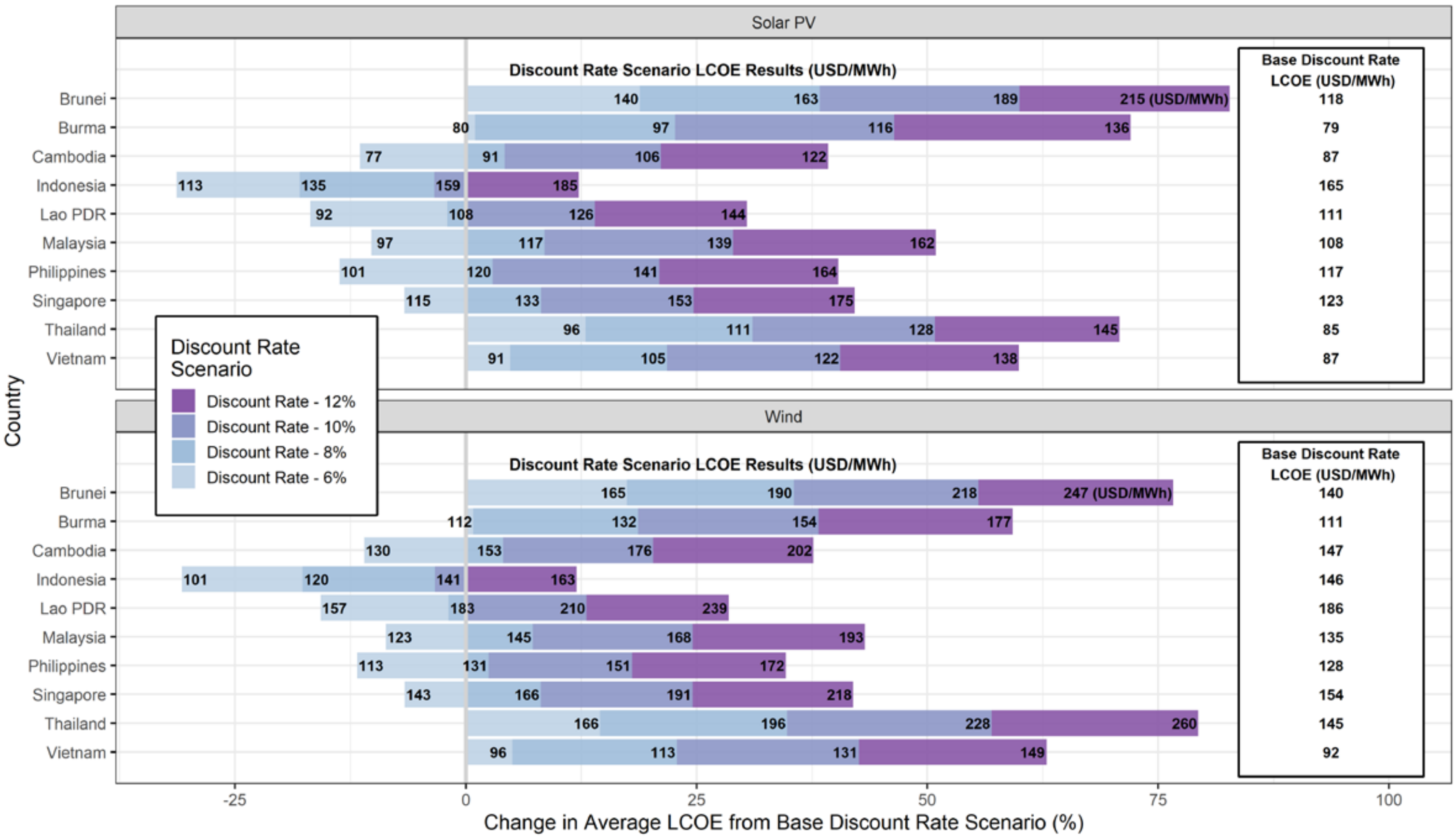


Figure 17. Discount Rate Scenario change in average levelized cost of energy from the Base Discount Rate Scenario

Note: The Base Discount Rate Scenario represents the Moderate Technical Potential Scenario and base assumed discount rates for the countries (see Appendix A-1.3).

Key Takeaways

If the rate assumed in the Discount Rate Scenario is greater than the rate in the Base-Case Scenario, the average estimated LCOE increases. Alternatively, the estimated LCOE decreases where the discount rate assumed in each scenario is less than the Base-Case Scenario rate. An understanding of how the discount rate impacts the LCOE may help decision makers in exploring financial mechanisms that could make renewables more competitive, such as lower interest rates.

The Cost of Energy Mapping Tool allows developers, planners, and policymakers to evaluate how different discount rates scenarios could affect the cost of generation in their country for wind and solar PV.

3 Conclusions

This work estimates the cost of utility-scale, land-based wind and solar PV generation in ASEAN member states through a site-based LCOE approach—addressing a critical gap in spatial data and analytical tools to support clean energy decision making. The analysis is intended to help policymakers, planners, private developers, and other actors in the region assess the cost of renewable-energy-based, utility-scale, land-based wind and solar PV opportunities. This work also highlights the functionality of the Cost of Energy Mapping Tool on RE Data Explorer (see Box 1).

The results of this analysis show there is abundant potential for land-based wind and solar PV development in the ASEAN member states at a range of generation costs. Under the Moderate Technical Potential Scenario, potential solar PV capacity exceeds 41 TW (or 59,386 TWh annually), with an LCOE from $64 to $246 USD/MWh across the region. Potential wind capacity exceeds 1.8 TW (or 3,159 TWh annually) with an LCOE from $42 to $221 USD/MWh. The available potential and costs vary between countries as a result of factors including resource quality (solar PV and wind capacity factors), country-specific economics (such as inflation rates, interest rates, and tax rates, among others), and techno-economic assumptions (such as installed and fixed O&M costs). Results show variations in the cost of generation and available capacity when considering additional technical potential scenarios (Relaxed and Restrictive Scenarios) and land-use constraints for wind and solar PV development in the region.

Using a spatial approach, near-term opportunities for renewables can be assessed in the region to support national and regional renewable energy targets. As an example, total solar PV potential within 20 km of the transmission system in Cambodia exceeded 2 TW (or 3,107 TWh annually) and LCOE ranged from approximately $69 to $105 USD/MWh. Solar PV resources in Cambodia are presented here as an example; however, a similar analysis could be done for wind and solar PV in other countries of the region with geospatial data on transmission systems or other complementary data sets of interest.

Generation costs are sensitive to a number of different factors that could be the focus of future policy interventions to support the scale-up of wind and solar PV in the region through increased competitiveness. This work explored sensitivities to installed costs, fixed O&M costs, debt fractions, depreciation schedules, and discount rates. LCOEs showed the largest sensitivities to the installed costs and discount rates for all countries. The assumed debt fraction could also significantly impact the estimated LCOE for both wind and solar PV.

High-quality renewable resources are not evenly distributed across the region (shown in Figures 1 and 2 for solar and wind potential, respectively). Of note are limitations in wind resource availability across the region given current wind resource data and technology assumptions. Significant areas are excluded in this study due to lower-quality wind resources (capacity factors less than 15% for wind) that would not typically be appealing for commercial development. This significantly limits the potential wind capacity available at lower generation costs in countries such as Indonesia, Malaysia, and Brunei. The estimated capacity available in these countries may change with new wind turbine generation technology assumptions (such as greater hub heights) and resource quality data.

3.1 Potential opportunities and barriers for ASEAN member states

Potential opportunities and barriers for wind and solar PV development in the countries of the region can be identified from this analysis of the cost of generation. The opportunities summarized in Table 9 represent potential wind and solar PV capacity (and suitable land area) available in each country with an LCOE of less than $105 USD/MWh.

Table 9. Opportunities and Barriers for Renewable Energy Development Across ASEAN Member States

Country	Potential Opportunities[1] LCOE of Less Than $150 USD/MWh		Potential Barriers[2]
	Solar PV Capacity (GW) (suitable land area [km^2])	Wind Capacity (GW) (suitable land area [km^2])	
Brunei	**16 GW** (431 km^2)	**0.02 GW** (6 km^2)	• Lower-quality wind resources given currently available technologies (and data) • Potentially high installed solar PV and wind costs[3] • Limited suitable land area for wind and solar development
Burma	**7,717 GW** (214,347 km^2)	**482 GW** (160,564 km^2)	• Potentially high installed wind costs[3]
Cambodia	**3,198 GW** (88,830 km^2)	**69 GW** (23,082 km^2)	• Potentially high installed wind costs[3]
Indonesia	**1,052 GW** (29,228 km^2)	**50 GW** (16,551 km^2)	• Lower-quality wind resources given currently available technologies (and data) • High installed solar PV and wind costs
Lao PDR	**1,278 GW** (35,496 km^2)	**13 GW** (4,344 km^2)	• Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Malaysia	**1,965 GW** (54,575 km^2)	**2 GW** (526 km^2)	• Lower-quality wind resources given currently available technologies (and data) • Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Philippines	**1,910 GW** (53,062 km^2)	**217 GW** (72,337 km^2)	• High installed solar PV and wind costs
Singapore	**2 GW** (60 km^2)	**0.02 GW** (7 km^2)	• Lower-quality wind resources given currently available technologies (and data) • Limited suitable land area for wind and solar development • Potentially high installed wind costs[3] • Limited or no existing utility-scale wind development
Thailand	**10,538 GW** (292,713 km^2)	**239 GW** (79,718 km^2)	• High installed wind costs
Vietnam	**2,847 GW** (79,069 km^2)	**311 GW** (103,591 km^2)	• High O&M cost for wind and solar PV

1. Values from estimated technical potential from the Moderate Technical Potential Scenario. The estimated LCOE for solar PV generation ranged from $99 to $200 USD/MWh, and the LCOE for wind generation was approximately $150 USD/MWh in 2018 in ASEAN member states (ACE 2019).
2. Barriers based on the wind and solar PV resource data and techno-economic assumptions used in this analysis.
3. Country data on wind generation costs were not available for this analysis. Regional averages for installed and O&M costs were assumed in the absence of country data. The installed and O&M costs assumed for each country are shown in Appendix A-1.3.1.
4. Installed and O&M costs assumed for each country are shown in Appendix A-1.3.1.

3.2 Future analyses

Policymakers, planners, developers, and other actors in the region are invited to further explore solar PV and wind generation costs for countries in ASEAN with the Cost of Energy Mapping Tool on RE Data Explorer (see Box 1). With the Cost of Energy Mapping Tool, users can construct additional scenarios to estimate the cost of generation in countries across the ASEAN member states. Users can visually explore the spatial results from these scenarios online or download the results for additional analyses. Additionally, users can replicate the scenarios and download all of the results that were presented in this work.

The technical potential analyses that form the basis of this work could be improved for future analyses. This work relied upon a common, representative set of technical potential scenarios for the region as well as global, publicly available land-use data sets. Future analysis could consider technical potential scenarios that reflect specific country land-use designations (where renewables can and cannot be developed) and updated, high-resolution land-use data.

Improvements to the LCOE estimates can also be made for future analyses. The LCOE estimates in this work reflect currently available default, national economic, and techno-economic assumptions and data (see Appendix Section A-1.3). Current assumptions at the national scale will be not representative of all present and future projects; however, they allow for a high-level estimate of LCOE. To further refine LCOE estimates and support decision making, economic and techno-economic assumptions (such as installed and O&M costs) should be updated when data become available. Additionally, future work could also explore regional cost multipliers that would account for intra-country variations in installed and O&M costs for each country as costs in areas near population centers and existing systems likely differ from those in more remote rural areas, for example.

This work shows broad trends in LCOE for the region. It does not attempt to calculate the actual cost of generation at any location. The results are not definitive and should not be used for specific project siting or be adopted into policies without further detailed analyses. Further appropriate studies, long-term data measurement, and validation activities are essential to confirm actual resource availability or project performance for any policy, planning, or project development.

References

ACE. 2016. “Levelised Cost of Electricity of Selected Renewable Technologies in the ASEAN Member States.” Technical Report. Jakarta: Association of Southeast Asian Nations (ASEAN) Center for Energy (ACE). http://www.aseanenergy.org/resources/publications/asean-resp-levelised-cost-of-electricity-of-selected-renewable-technologies-in-the-asean-member-states/.

———. 2019. “Levelized Costs of Electricity (LCOE) for Selected Renewable Energy Technologies in the ASEAN Member States II.” Jakarta: Association of Southeast Asian Nations (ASEAN) Centre for Energy (ACE). http://www.aseanenergy.org/resources/levelised-costs-of-electricity-for-renewable-energy-technologies-in-asean-member-states-ii/.

ACE and IRENA. 2016. “Renewable Energy Outlook for ASEAN.” ASEAN Centre for Energy (ACE), Jakarta and International Renewable Energy Agency (IRENA), Abu Dhabi. https://www.irena.org/publications/2016/Oct/Renewable-Energy-Outlook-for-ASEAN.

ADB. 2017. “Guidelines for the Economic Analysis of Projects.” Manila: Asian Development Bank (ADB). http://dx.doi.org/10.22617/TIM178607-2.

ASEAN Statistics Department of ASEAN Secretariat. 2018. “Indicators.” ASEANStatsDataPortal. 2018. https://data.aseanstats.org/.

Brown, Austin, Philipp Beiter, Donna Heimiller, Carolyn Davidson, Paul Denholm, Jennifer Melius, Anthony Lopez, Dylan Hettinger, David Mulcahy, and Gian Porro. 2016. “Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results.” Technical Report NREL/TP-6A20-64503. Golden, CO: National Renewable Energy Laboratory (NREL). www.nrel.gov/docs/fy15osti/64503.pdf.

Brun, Peter C. 2018. “Current Issues with the Development of Wind Power in Vietnam and Challenges in Supply Chain and Finance: Supply Chain and Financing Challenges.” presented at the Global Offshore Segment, DNV GL, Copenhagen.

Cambodia Ministry of Economy and Finance. 2018. “Flash Report: Socio-Economic Trends November - December 2017.” Phnom Penh: Cambodia Ministry of Economy and Finance. http://www.mef.gov.kh/flash-report/10-p.html.

DTU. 2017. “Global Wind Atlas.” Danish Technical University (DTU), Department of Wind Energy. 2017. http://www.globalwindatlas.com/.

IMF. 2019. “IMF Macroeconomic & Financial Data.” International Monetary Fund (IMF). 2019. http://data.imf.org/?sk=51B096FA-2CD2-40C2-8D09-0699CC1764DA.

IRENA. 2018. “Renewable Power Generation Costs in 2017.” Abu Dhabi: International Renewable Energy Agency (IRENA). http://irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

IRS. 2018. “Publication 946 (2018), How to Depreciate Property: Appendix A: Table A-1.” United States Internal Revenue Service (IRS). 2018. https://www.irs.gov/publications/p946.

Kiatreungwattana, Kosol, and Nathan Lee. 2018. "Task 3 Report – Levelized Cost of Energy of Electricity Generating Technologies: Energy Alternatives Study for the Lao People's Democratic Republic: Smart Infrastructure for the Mekong (SIM) Program (NREL Internal Use Only)." Technical Report NREL/TP-7A40-71549. Golden, CO: National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docx/gen/fy18/71549.pdf.

Kuang, Maggie. 2014. "H2 2014 APAC LCOE Update: A Race Between Renewable Penetration and Fuel Prices." New York: Bloomberg New Energy Finance. https://first.bloomberglp.com/documents/93517_LevelisedCostofElectricityUpdate.pdf.

Lao Ministry of Finance. 2016. "Government Finance Statistics Annual Report for 2014-2015." Vientiane: Lao Ministry of Finance. https://www.mof.gov.la/index.php/en/publications-and-statistics/.

Lee, Nathan, Nick Grue, and Evan Rosenlieb. 2018. "Task 2 Report—A GIS-Based Technical Potential Assessment of Domestic Energy Resources for Electricity Generation: Energy Alternatives Study for the Lao People's Democratic Republic: Smart Infrastructure for the Mekong Program." Technical Report NREL/TP-7A40-70470. Golden, CO: National Renewable Energy Laboratory (NREL). www.nrel.gov/docs/fy18osti/70470.pdf.

Lopez, Anthony, Billy Roberts, Donna Heimiller, Nate Blair, and Gian Porro. 2012. "U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis." Technical Report NREL/TP-6A20-51946. Golden, CO: National Renewable Energy Laboratory (NREL). www.nrel.gov/docs/fy12osti/51946.pdf.

Malaysia Ministry of Finance - Fiscal and Economic Division. 2018. "Key Economic Indicators." Kuala Lumpur: Malaysia Ministry of Finance - Fiscal and Economic Division. http://www.treasury.gov.my/index.php/en/economy/economic-indicators.html.

Mone, Christopher, Maureen Hand, Mark Bolinger, Joseph Rand, Donna Heimiller, and Jonathan Ho. 2017. "2015 Cost of Wind Energy Review." Technical Report NREL/TP-6A20-66861. Golden, CO: National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy17osti/66861.pdf.

NREL. 2018. "Annual Technology Baseline (ATB)." Golden, CO: National Renewable Energy Laboratory (NREL). https://atb.nrel.gov/.

Ong, Sean, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath. 2013. "Land-Use Requirements for Solar Power Plants in the United States." Golden, CO: National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy13osti/56290.pdf.

Open Development Cambodia. 2014. "RE Data Explorer - Southeast Asia: Transmission Lines in Cambodia, Open Development Cambodia." Renewable Energy Data Explorer. 2014. https://maps.nrel.gov/rede-southeast-asia.

World Bank. 2017. "Global Solar Atlas." Global Solar Atlas. 2017. http://globalsolaratlas.info/.

———. 2019a. "Private Participation in Infrastructure Database." World Bank. 2019. http://ppi.worldbank.org/customquery.

———. 2019b. "World Development Indicators." Data Bank. 2019. https://databank.worldbank.org/data/home.

Acronyms

AC	alternating current
ACE	ASEAN Centre for Energy
ASEAN	Association of Southeast Asian Nations
DOE	U.S. Department of Energy
Lao PDR	Lao People's Democratic Republic
LCOE	levelized cost of energy
NREL	U.S. Department of Energy's National Renewable Energy Laboratory
O&M	operation and maintenance
PV	photovoltaics
RE Data Explorer	Renewable Energy Data Explorer
RE SSN	Renewable Energy Sub Sectoral Network
U.S.	United States
USAID CPA	USAID Clean Power Asia
USAID	U.S. Agency for International Development
USD	U.S. dollars

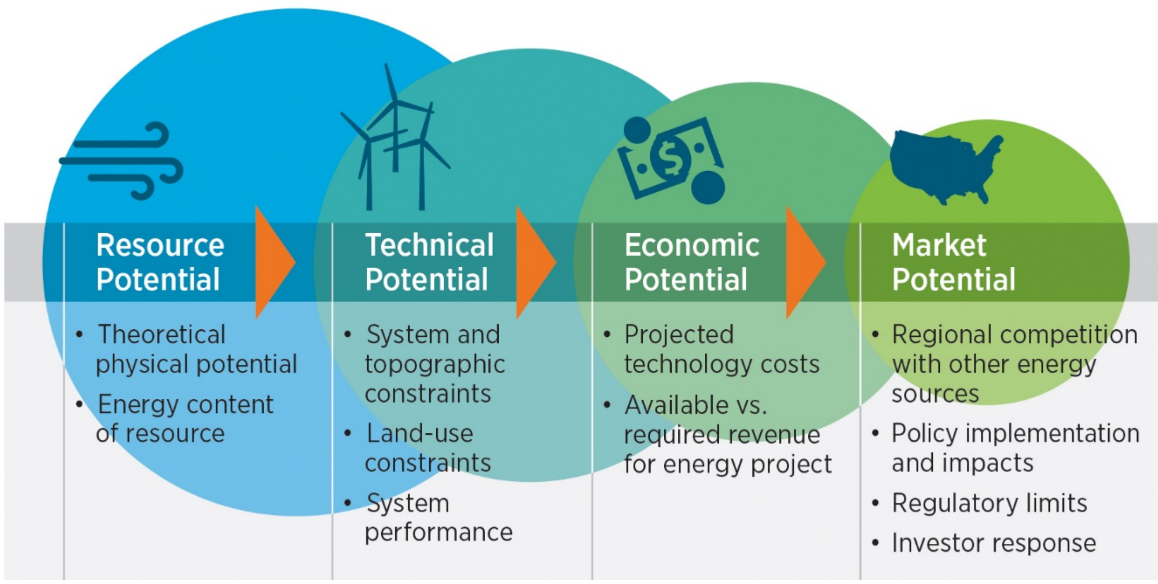
Appendix A. Methodology

This appendix details the methodology used in this work to estimate the LCOE.

A-1.1 Renewable energy potential

Calculation of the site-based LCOE for solar and wind technologies depends on the renewable energy resource potential at the location of a potential generation system, specifically the technical potential. There are different categories of renewable energy potential as depicted in Source: (Brown et al. 2016)

Figure A-1. This work focuses on the technical potential and economic potential of solar and wind technologies.



Source: (Brown et al. 2016)

Figure A-1. Categories of renewable energy potential

Resource potential is the theoretical renewable energy resource that is physically available at a location and represents the upper bound and foundational input to the subsequent analyses of technical, economic, and market potential.

Technical Potential is the achievable electricity generation capacity (MW), generation (GWh), and suitable land area (km^2), given system performance, certain geographic constraints, and technology-specific limitations (such as the need for minimum spacing between solar PV panels or wind turbines). Technical potential reflects the reality that not all physically available solar and wind resources are developable, due in part to technical constraints to siting generation systems in particular areas (such as technical infeasibility of siting utility-scale, land-based wind turbines in water bodies, urban areas, or extremely steep terrains). Technical potential defines the locations at which development of a particular renewable energy technology is technically feasible. This is done through an exclusion-layer analysis to systematically filter out land areas that are not technically feasible from a base layer of resource potential (see Section A-1.2).

Economic Potential is the subset of technical potential in which the cost to generate electricity with a particular renewable energy-based system is below the revenue available in terms of displaced energy (GWh) and capacity (MW) of other systems. LCOE is an initial step in more sophisticated analyses that assess the economic potential of renewable and other energy resources at a location or within a region. Site-based LCOE represents the cost of generating electricity at technically-feasible sites. Site-based LCOE represents the cost of electricity at the point of interconnection and does not include additional transmission interconnection or access road costs.

This work first estimates technical potential, within different potential development scenarios, before calculating the site-based LCOE for wind and solar PV based on data and assumptions for each of the ASEAN member states. This methodology is detailed in the following sections.

A-1.2 Estimating technical potential

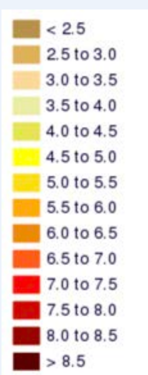
In addition to generation system assumptions, technical potential results (and subsequent LCOE and economic potential analyses) are highly sensitive to the exclusions (or constraints to development) assumed for generation system siting. Scenario analyses allow for assessment of technical potential that could result from different plausible land-use designation and related policies for renewable energy development. A technical potential scenario is a pre-defined set of assumptions that establish the land-use, topographical, and other constraints that are excluded from development. As an example, Box A-1 illustrates example results for three hypothetical technical potential scenarios for fixed-tilt solar PV generation in Vietnam.

For this work a set of applicable technical potential scenarios and generation system assumptions for the ASEAN member states were developed in coordination with the ACE for both solar PV and wind. These scenarios and assumptions were then confirmed with ACE's Renewable Energy Sub Sectoral Network (RE SSN) Focal Points in the ASEAN member states. The sections that follow detail the generation system assumptions as well as the technical potential scenarios considered for both solar PV and wind.

Box A-1. Technical Potential Scenarios

Technical potential scenarios are pre-defined sets of assumptions that establish the land-use, topographical, and other constraints that may be excluded from development. Using technical potential scenarios allows for an assessment of the sensitivities that could result from different plausible land-use designation and related policies for renewable energy development. Technical potential scenarios often reflect progressively more restrictive constraints for renewable energy-based generation development for a particular system such as fixed-tilt solar PV systems.

As an example, three different technical potential scenarios for fixed-tilt solar PV generation in Vietnam are presented below. Scenario 1, the least restrictive, considered exclusions for designated protected areas as well as waterbodies, which include water, wetlands, and ice. Scenarios 2 and 3 are increasingly restrictive with exclusions for urban areas, slopes, as well as agricultural and forest lands—common constraints to renewable energy-based generation development. Depending on the exclusions considered, generation potential ranges from 847 million MWh/year in the most restrictive case (Scenario 3) to 12 billion MWh/year in the least restrictive case (Scenario 1).

	Vietnam Scenario 1	Vietnam Scenario 2	Vietnam Scenario 3
	Exclude: • Protected Areas • Waterbodies	Exclude: • Protected Areas • Waterbodies • Urban Areas • Area with slope exceeding 5% grade	Exclude: • Protected Areas • Waterbodies • Urban Areas • Agricultural Lands • Forest Lands • Area with slope exceeding 3% grade
Irradiation kWh/m²/day	**Scenario 1 Results**	**Scenario 2 Results**	**Scenario 3 Results**
			
Figures from RE Data Explorer (See Box 1)	**Suitable Land Area**: 273,231 km² **Generation Potential** (AC): 12 billion MWh/year **Nameplate Capacity**: 10 million MW	**Suitable Land Area**: 108,250 km² **Generation Potential** (AC): 5 billion MWh/year **Nameplate Capacity**: 4 million MW	**Suitable Land Area**: 18,441 km² **Generation Potential** (AC): 847 million MWh/year **Nameplate Capacity**: 663,890 MW

A-1.2.1 Utility-scale solar photovoltaics

Utility-scale solar PV includes land-based, urban and rural deployed systems that are connected at the transmission system level. [19] This work assumes a fixed-tilt solar PV system with a power density of 36 MW per km^2 (Ong et al. 2013). A contiguous land-area constraint for a minimum generation system size was not applied due to restrictions in the resolution of the current land-cover and land-use data (Lee, Grue, and Rosenlieb 2018).[20]

Spatial solar resource data for the ASEAN member states were obtained from the Global Solar Atlas, from the World Bank Group and provided by SolarGIS (World Bank 2017). No resource quality exclusions were applied. Capacity factors were determined by the ratio of the PV output over the modeled installed capacity (in kWh/kW/day) with the use of spatial data. Results are limited to locations with net capacity factors greater 10% for solar PV as locations with lower-quality resources have a higher cost and are less likely to be developed.

This study considers four technical potential scenarios for solar PV as depicted in Table A-1. This common set of technical potential scenarios is used across all of the ASEAN Members States to estimate LCOE (see Appendix A-1.3). The first three scenarios represent progressively more restrictive exclusions to development. The first, *Relaxed*, scenario excludes development in designated protected areas, water bodies, and urban areas. The second, *Moderate*, scenario further excludes agricultural areas and areas with slope greater than 5%. The third, *Restricted*, scenario adds an exclusion to development in forested areas. The fourth, *Urban Emphasis*, scenario constrains development to urban areas with a slope that is less than 3% grade.

Table A-1. Solar Photovoltaic Technical Potential Scenarios

Scenario	Protected Areas	Water-bodies	Forested Areas	Urban Areas	Agricultural Areas	Slope Exclusion
Relaxed	*Exclude*	*Exclude*	*Include*	*Exclude*	*Include*	*None*
Moderate	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Include*	**> 5% Slope**
Restricted	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Exclude*	**> 5% Slope**
Urban Emphasis	*Exclude*	*Exclude*	*Exclude*	*Include*	*Exclude*	**> 3% Slope**

[19] This work only considers land-based systems. It does not include floating solar PV systems.

[20] The land area requirements for utility-scale, fixed-tilt PV systems are highly dependent on the technology; however, 27,000 m^2 could allow for a 1-MW system, roughly. These Constraints are often applied with higher resolution data and in larger countries such as the US, where a contiguous area exclusion would not eliminate a significant portion of available land area (Lopez et al. 2012).

A-1.2.2 Utility-scale wind power

Utility-scale wind power consists of land-based wind power systems connected at the transmission system level.[21] A 100-m hub height system was assumed with a power density of 3 MW/km^2. A contiguous land-area constraint for a minimum generation system size was not applied.

Spatial wind resource data were obtained from the Global Wind Atlas from the Danish Technical University (DTU 2017). Capacity factors were calculated assuming 98% availability and 15% losses, which included wind farm wiring, transformer, and other losses. A Weibull probability distribution, assuming a K=2 following Mone et al. (2017), was used for wind speed distributions. Results are limited to locations with net capacity factors greater 15% for wind as locations with lower-quality resources have a higher cost and are less likely to be developed. The best turbine configuration to utilize the available wind resources at each location was selected.

This work considers three technical potential scenarios for wind that reflect progressively more restrictive development exclusions as shown in Table A-2. This common set of scenarios is used across all of the ASEAN member states. The first, *Relaxed*, scenario excludes development in designated protected areas, water bodies, and urban areas. The second, *Moderate*, scenario further excludes agricultural areas and areas with slope greater than 20%. The third, *Restricted*, scenario adds an exclusion to development in forested areas.

Table A-2. Wind Technical Potential Scenarios

Scenario	Protected Areas	Water-bodies	Forested Areas	Urban Areas	Agricultural Areas	Slope Exclusion
Relaxed	*Exclude*	*Exclude*	*Include*	*Exclude*	*Include*	*None*
Moderate	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Include*	> 20% Slope
Restricted	*Exclude*	*Exclude*	*Exclude*	*Exclude*	*Exclude*	> 20% Slope

[21] This work only considers land-based systems. It does not include offshore wind.

A-1.3 Estimating levelized cost of energy

Economic potential is a metric used to quantify the amount of economically viable renewable generation capacity and generation potential that is available at a location or within a region. The results from economic potential analyses can be used to inform renewable energy target setting and other policies to incentivize the deployment of renewable energy. Furthermore, such results can help renewable energy developers by identifying favorable sites for more detailed on-the-ground resource measurement and validation.

A key initial step in the assessment of economic potential within a region is estimating LCOE, which represents the net present value of the unit cost of electricity during the lifetime of a particular electricity generation system in USD/MWh.

Site-based LCOEs for wind and solar PV utility scale systems (greater than 1 MW) were calculated for each location on a 1 km by 1 km grid using the capacity factors that resulted from the technical potential scenarios. This "site-based" approach considers the electricity generated at the site of the generator and does not include any transmission interconnection or access road costs. This work does not use any regionally specific cost increments or regional cost multipliers.

A-1.3.1 LCOE Data Collection

Calculating site-based LCOE requires local economic and techno-economic data. To ensure accurate inputs to the calculation, local data were collected for each of the ASEAN member states that reflected actual renewable energy system projects. ACE led the data collection efforts, relying on their Renewable Energy Sub Sectoral Network (RE SSN) Focal Points in each ASEAN member state.[22] Table A-3 shows the data sets collected by ACE.

[22] For more information on organizations and institutions in the RE SSN Focal Points, please refer to ACE's homepage at http://www.aseanenergy.org/.

Table A-3. Association of Southeast Asian Nations Member State Input Data for Calculation of Levelized Cost of Energy	
Input*	**Level of data aggregation**
Installed cost	One value for each technology (wind and solar PV) for each ASEAN member state provided by ACE that represents the average for the project data shared for the years 2015 to 2018.
Debt fraction	One value for each ASEAN member state
Discount rate	One value for each ASEAN member state
Economic lifetime	One value for each technology for each ASEAN member state
Fixed O&M cost	One value for each technology (wind and solar PV) for each ASEAN member state provided by ACE that represents the average for the project data shared.
Inflation rate	One value for each ASEAN member state
Interest rate	One value for each ASEAN member state
Rate of return on equity (RROE)	One value for each ASEAN member state
Tax rate	One value for each ASEAN member state
Variable O&M cost	One value for each technology for each ASEAN member state
Weighted average cost of capital (WACC)	One value for each ASEAN member state
*Refer to Section A-1.3.2 for methodology to calculate LCOE and additional description and units for each input. These values were collected and shared by ACE.	

To collect data, ACE first sent a data request to their RE SSN Focal Points. ACE then analyzed the data provided by RE SSN focal points, identified missing data, and hosted a meeting with focal points to clarify missing data. ACE then compiled the data and aggregated (simple average) renewable energy system project data, ensuring that project-specific data was anonymous to respect concerns about proprietary data. ACE then reviewed and shared the compiled data for this LCOE analysis with the authors of this work.

For economic parameters and some techno-economic parameters, one value per country was requested. For technology specific parameters such as capital and O&M cost, one value per generation technology per country was requested. Only projects completed in the period between 2015 and 2018 were included in developing the techno-economic parameters (such as capital costs, O&M costs, and rate of return on equity) for the ASEAN member states to account for recent falling costs for wind and solar power systems. Older project data were filtered out to minimize the impacts of inflation, exchange rates, and declines in the costs of renewables on estimated LCOE results.

ACE also collected techno-economic data for six wind power projects and 30 solar PV projects across the 10 ASEAN member states. Table A-4 shows the number of solar PV and wind projects represented in the data collected by ACE for each of the ASEAN member states.

Table A-4. Number of ASEAN Solar and Wind Projects Represented in the Data Collected by the ASEAN Centre for Energy

ASEAN member state	Number of solar PV projects represented in data	Number of wind projects represented in data
Brunei Darussalam	1	-
Burma	1	-
Cambodia	1	-
Indonesia	3	1
Lao PDR	7	-
Malaysia	13	-
Philippines	1	1
Singapore[1]	1	-
Thailand	Aggregate number of 523 very small power plants (VSPPs)[2]	3
Vietnam	1	1

1. Additional solar PV project data for Singapore is available on the National Solar Repository of Singapore (www.solar-repository.sg); however, this data was not included in the original aggregated data for the current work and therefore it is not reflected in this analysis. Readers are invited to reference this database for up-to-date inputs for their LCOE calculations (for example, using the Cost of Energy Mapping Tool).

2. Aggregate value of VSPPs is treated as 1 project

Table A-5 shows the values for the techno-economic inputs used in the calculation of the Moderate Technical Potential Scenario LCOE, by country. Table A-6 below lists the sources for the techno-economic inputs. Actual installed and O&M costs for utility-scale wind projects were not available for all countries in the region. In the absence of project-specific data (or country value) an average regional representative value was assumed for the country.

Table A-5. ASEAN Member State Economic and Techno-Economic Inputs											
Country	Inflation Rate (-)	Interest Rate - Real (-)	Debt Fraction (-)	Rate of Return on Equity – Real (-)	Tax Rate (-)	Economic Lifetime (Years)	Discount rate [calculated] (-)	Solar PV Installed Costs (USD/MW)	Solar PV Fixed Operation and Maintenance Costs (USD/MW/year)	Wind Installed Costs (USD/MW)	Wind Fixed Operation and Maintenance Costs (USD/MW/year)
Brunei	-0.001	0.0052	0.700	0.126	0.185	20	0.040	1,810.0	18.1	2,100.0	36.0
Burma	0.040	0.0249	0.730	0.043	0.250	20	0.059	1,600.0	5.0	2,100.0	39.0
Cambodia	0.023	0.0907	0.740	0.001	0.200	20	0.075	1,250.0	16.0	2,100.0	36.0
Indonesia	0.036	0.0655	0.680	0.121	0.250	20	0.104	1,837.6	18.5	2,027.8	25.0
Lao PDR	0.001	0.1114	0.800	0.070	0.240	20	0.083	1,146.0	11.0	2,100.0	39.0
Malaysia	0.034	0.0339	0.750	0.090	0.240	20	0.071	1,695.0	5.9	2,100.0	39.0
Philippines	0.033	0.0323	0.690	0.093	0.200	20	0.077	1,746.6	13.5	2,299.1	52.5
Singapore	0.003	0.0437	0.730	0.150	0.170	20	0.070	1,400.0	16.0	2,100.0	25.0
Thailand	0.008	0.0206	0.700	0.086	0.200	20	0.045	1,268.0	25.4	2,629.2	25.0
Vietnam	0.028	0.0315	0.825	0.052	0.200	20	0.054	1,117.4	24.6	1,990.1	35.0

Table A-6. Sources for ASEAN Member State Economic and Techno-Economic Inputs	
Input	**Source**
Inflation Rate	(ASEAN Statistics Department of ASEAN Secretariat 2018) Values provide by ACE.
Interest Rate	Brunei D.: World Development Indicators (World Bank 2019b) Cambodia: (Cambodia Ministry of Economy and Finance 2018) Indonesia: World Development Indicators (World Bank 2019b) Lao PDR: (Lao Ministry of Finance 2016) Malaysia: (Malaysia Ministry of Finance - Fiscal and Economic Division 2018) Burma: World Development Indicators (World Bank 2019b) Philippines: World Development Indicators (World Bank 2019b) Singapore: World Development Indicators (World Bank 2019b) Thailand: World Development Indicators (World Bank 2019b) Vietnam: World Development Indicators (World Bank 2019b)
Debt Fraction	Brunei D: ACE RE SSN Focal Point Cambodia: ACE RE SSN Focal Point Indonesia: ACE RE SSN Focal Point Lao PDR: ACE RE SSN Focal Point Malaysia: ACE RE SSN Focal Point Burma: Average regional representative value assumed Philippines: (IMF 2019) Singapore: Average regional representative value assumed Thailand: ACE RE SSN Focal Point Vietnam: (Brun 2018)
Rate of Return on Equity	All countries except Lao PDR: (IMF 2019) Lao PDR: ACE RE SSN Focal Point
Tax Rate	All countries: ACE RE SSN Focal Point
Economic Lifetime	All countries: (ACE 2016)

Table A-6. Sources for ASEAN Member State Economic and Techno-Economic Inputs	
Solar PV Capital Expenditure	Brunei D: ACE RE SSN Focal Point Cambodia: ACE RE SSN Focal Point Indonesia: ACE RE SSN Focal Point Lao PDR: ACE RE SSN Focal Point Malaysia: ACE RE SSN Focal Point Burma: ACE RE SSN Focal Point Philippines: (World Bank 2019a) Singapore: ACE RE SSN Focal Point Thailand: (World Bank 2019a) Vietnam: (World Bank 2019a)
Solar PV Fixed Operation and Maintenance Costs	Brunei D.: Average regional representative value assumed Cambodia: Average regional representative value assumed Indonesia: (ACE 2016) Lao PDR: ACE RE SSN Focal Point Malaysia: ACE RE SSN Focal Point Burma: ACE RE SSN Focal Point Philippines: ACE RE SSN Focal Point Singapore: Average regional representative value assumed Thailand: ACE RE SSN Focal Point Vietnam: ACE RE SSN Focal Point
Wind Capital Expenditure	Brunei D.: Average regional representative value assumed Cambodia: Average regional representative value assumed Indonesia: (World Bank 2019a) Lao PDR: Average regional representative value assumed Malaysia: Average regional representative value assumed Burma: Average regional representative value assumed Philippines: Average regional representative value assumed Singapore: Average regional representative value assumed Thailand: (World Bank 2019a) Vietnam: (Kuang 2014)
Wind Fixed Operation and Maintenance Costs	Brunei D.: Average regional representative value assumed Cambodia: Average regional representative value assumed Indonesia: (Kuang 2014) Lao PDR: Average regional representative value assumed Malaysia: Average regional representative value assumed Burma: Average regional representative value assumed Philippines: Average regional representative value assumed Singapore: Average regional representative value assumed Thailand: (Kuang 2014) Vietnam: (Kuang 2014)

The depreciation fractions were calculated from two different assumed depreciation schedules (see Section A-1.3.2). The default depreciation schedule assumes a 20-year straight-line depreciation schedule for generation systems shown in Table A-7. This was assumed following ACE (2016) and in the absence of specific applicable depreciation schedules for each country in the region. As a policy alternative, an accelerated depreciation assumes a 5-year depreciation schedule based on the Modified Accelerated Cost Recovery System (MACRS) from the United

States Internal Revenue Service, presented in Table A-8. Although depreciation schedules were not available for each country in the region, the example schedules used in this work represent common approaches to representing depreciation schedule policy alternatives for utility-scale projects.

Table A-7. Default, 20-Year Straight-Line Depreciation Schedule

Year	1	2	3	4	5	6	7	8	9	10
Depreciation Fraction	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Year	11	12	13	14	15	16	17	18	19	20
Depreciation Fraction	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table A-8. Accelerated, 5-Year (MACRS) Depreciation Schedule

Year	1	2	3	4	5	6
Depreciation Fraction	0.2000	0.3200	0.1920	0.1152	0.1152	0.0576

Source: IRS (2018)

A-1.3.2 Levelized Cost of Energy Calculation

The LCOE was calculated following an approach established in NREL's Annual Technology Database shown in Equation 1 (NREL 2018). The equations used to calculate terms in Equation 1 are further detailed below in Equation 2 to Equation 10. Definitions of terms used in the equations are defined below.

$$LCOE = \frac{(Fixed\ Charge\ Rate \times Installed\ Cost + Fixed\ O\&M\ Cost) \times 1{,}000}{Capacity\ Factor\ \times 8{,}760\ hours/year} + Variable\ O\&M\ Cost + Fuel\ Cost$$

Equation 1

$$Fixed\ Charge\ Rate\ = Capital\ Recovery\ Factor \times Project\ Finance\ Factor$$

Equation 2

$$Capital\ Recovery\ Factor\ = \frac{WACC_{real}}{1-(1+WACC_{real})^{t}}$$

Equation 3

$$Project\ Finance\ Factor\ = \frac{1 - Tax\ Rate \times Present\ Value\ of\ Depreciation}{1 - Tax\ Rate}$$

Equation 4

$$WACC_{real} = \frac{1 + ((1 - DF) \times \left((1 + RROE_{Real}) \times (1 + i) - 1\right)) + (DF \times \left((1 + IR_{Real}) \times (1 + i) - 1\right) \times (1 - Tax\ Rate))}{1 + i} - 1$$

Equation 5

$$Present\ Value\ of\ Depreciation = \sum_{y=1}^{y=M+1} Depreciation\ Fraction_y \times f_y$$

Equation 6

$$f_y = \frac{1}{d_{nominal}^{y}}$$

Equation 7

$$d_{nominal} = \left((1 + WACC_{real}) \times (1 + i)\right) - 1$$

Equation 8

$$RROE_{real} = \frac{1 + RROE_{nominal}}{1 + i} - 1$$

Equation 9

$$IR_{real} = \frac{1 + IR_{nominal}}{1 + i} - 1$$

Equation 10

Fixed Charge Rate (-) represents the amount of revenue per dollar of investment that has to be collected annually to repay the investment.
Installed Cost (USD/kW) (or capital cost) is the total for capital work including generation system and machinery, civil work, erection and commissioning, financing and interest during construction, and infrastructure to connect generation to interconnection point.
Fixed O&M Cost (USD/kW) is the total annual expenditures to operate and maintain a generation system, which are not incurred on a per-unit-energy (/MWh) basis. These include costs for labor, equipment, spare parts, insurance, and other costs associated with operating the project that are proportional to generation system size, but not annual energy output.
Variable O&M Cost (USD/MWh) is the total expenditures to operate and maintain a generation system incurred on a per-unit-energy basis. Variable O&M costs are proportional to energy output and are avoided when the system is not generating energy. Variable O&M cost is assumed to be $0 USD/MWh for wind and solar for this work.
Fuel Cost (USD/MWh) is the total cost for fuel incurred on a per-unit-energy basis.
Capacity Factor (-) is the ratio of the estimated annual system generation and its nameplate output. This factor is specific to the technology and the energy resources of the location at which it operates. Capacity factor is determined as the ratio of the annual generation (MWh) to the nameplate capacity (MW) and annual operating hours at each location.
Capital Recover Factor (-) is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time.
Project Finance Factor (-) is a technology-specific financial multiplier that accounts for any applicable differences in the depreciation schedule and tax policies.
Tax Rate (-) is the applicable tax rate (often corporate tax rate) that the system owner or operator pays on the net revenues from the operation of the generation system.
Weighted Average Cost of Capital (-) is the average expected rate that is paid to finance assets.
Debt Fraction (DF) (-) is the fraction of capital financed with debt. The difference between 100 (%) and the debt fraction (%) is assumed to be financed with equity. The debt-to-equity ratio (D/E) indicates the relative proportion of generation system shareholders' or owners' equity and debt used to finance project assets.
Inflation Rate (i) (-) is the assumed inflation rate based on historical data.
Interest Rate (IR) (-) is the assumed interest rate on debt.
Rate of Return on Equity (RROE) (-) is the assumed rate of return on the share of assets financed with equity.
Present Value of Depreciation (-) is the product of the depreciation fraction and depreciation factor, which depend on a depreciation schedule (unitless).
Depreciation Fraction (-) is the fraction of capital depreciated in each year, 1 to M.
Depreciation Factor (-) is a function of the discount rate (f_y).
Discount Rate (-) is a measure of the time value of money expressed as an annual rate. The discount rate depends on the cost of capital, including the balance between debt-financing and equity-financing, and an assessment of the financial risk.

A-1.3.3 Additional Levelized Cost of Energy Scenarios

Sensitivities were conducted for several LCOE analysis scenarios. A LCOE analysis scenario is a predefined set of assumptions for the financial parameters used in the calculation of the LCOE. Comparing results under different assumptions for installed costs, tax rates, depreciation schedules, and other financial parameters helps policymakers identify where they could potentially focus their efforts to increase the economic deployment of renewable energy. Likewise, developers can use the results from LCOE analysis studies to determine which projects might be attractive under different economic scenarios. For each of the questions regarding

LCOE in Section 2, the resource availability for the Moderate Technical Potential Scenario was used. Table A-9 lists the assumptions made in each of these LCOE analysis scenarios.

Table A-9. Description of Levelized Cost of Energy Analysis Scenarios Considered

Question Addressed	Assumptions
What is the cost of utility-scale wind and solar generation across the ASEAN member states? (Section 2.1)	Default economic and techno-economic inputs from Table A-5 are assumed together with the wind and solar PV resources available from the Moderate Technical Potential Scenarios for wind (Table A-2) and solar PV (Table A-1).
How does technical potential for wind and solar resources affect the cost of generation? (Section 2.2)	Default economic and techno-economic inputs from Table A-5 are assumed together with the wind and solar PV resources available from the Relaxed and Restricted Technical Potential Scenarios for wind (Table A-2) and solar PV (Table A-1). The Urban Technical Potential Scenario is also considered for solar PV.
What are the near-term opportunities for solar PV development? (Section 2.3)	Solar PV resources limited to those within a 20-km distance of the transmission system in Cambodia are considered.
How do installed costs affect generation costs? (Section 2.4)	Capital costs for wind and solar were set to be no higher than $1,500 and $1,000 USD/kW respectively.
How do installed costs and operation and maintenance costs affect generation costs? (Section 2.4)	Capital costs for wind and solar were set to be no higher than $1,500 and $1,000 USD/kW respectively. Additionally, fixed O&M costs were set to be no more than $60 and $10 USD/kW/year for wind and solar, respectively.
How does debt fraction impact the cost of generation? (Section 2.5)	The debt fraction for both wind and solar projects in all countries is assumed to be 95%.
How does a shorter depreciation schedule impact the cost of generation? (Section 2.6)	The accelerated 5-year depreciation schedule shown in Table A-8 was used instead of the 20-year straight-line depreciation schedule shown in Table A-7.
How does the discount rate affect the cost of generation? (Section 2.7)	Discount rates of 6%, 8%, 10%, and 12% for all countries for wind and solar PV projects were assumed.

Appendix B. Supplementary Levelized Cost of Energy Results

Tables B-1 and B-2 present the technical potential results (i.e., suitable land area, capacity, and generation) within the available LCOE ranges for each of the technical potential scenarios considered for solar PV and wind, respectively. LCOE ranges are only shown for ranges with technical potential results.

Table B-1. Solar Photovoltaic Technical Potential within Available Levelized Cost of Energy Ranges

Country	Scenario	LCOE (USD/MWh)*	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
Brunei	Relaxed	100 to 150	2,885.2	103.9	142.3
	Moderate	100 to 150	430.6	15.5	21.4
	Restricted	100 to 150	42.6	1.5	2.1
	Urban	100 to 150	54.6	2.0	2.7
Burma	Relaxed	50 to 100	717,657.5	25,835.7	37,616.9
		100 to 150	13,231.6	476.3	518.4
	Moderate	50 to 100	214,307.2	7,715.1	11,573.8
		100 to 150	40.2	1.5	1.6
	Restricted	50 to 100	45,569.2	1,640.5	2,387.2
		100 to 150	40.2	1.5	1.6
	Urban	50 to 100	476.3	17.2	25.4
Cambodia	Relaxed	50 to 100	133,439.2	4,803.8	7,135.3
		100 to 150	615.8	22.2	28.3
	Moderate	50 to 100	88,525.1	3,186.9	4,760.1
		100 to 150	305.3	11.0	14.0
	Restricted	50 to 100	26,645.5	959.2	1,424.7
		100 to 150	197.1	7.1	9.0
	Urban	50 to 100	206.6	7.4	11.1
		100 to 150	2.5	0.1	0.1
Indonesia	Relaxed	100 to 150	91,785.9	3,304.3	5,075.3
		150 to 200	1,332,157.4	47,957.7	62,631.4
		200 to 250	14,358.9	516.9	533.3
	Moderate	100 to 150	29,227.8	1,052.2	1,613.1
		150 to 200	314,871.1	11,335.4	14,944.5
		200 to 250	27.6	1.0	1.1
	Restricted	100 to 150	1,166.6	42.0	63.9
		150 to 200	17,012.3	612.4	802.6
		200 to 250	2.3	0.1	0.1
	Urban	100 to 150	2,263.9	81.5	123.7
		150 to 200	4,408.6	158.7	216.7
		200 to 250	0.24	0.01	0.01
Lao PDR	Relaxed	50 to 100	3,873.4	139.4	208.4
		100 to 150	217,275.6	7,821.9	10,497.6

Table B-1. Solar Photovoltaic Technical Potential within Available Levelized Cost of Energy Ranges					
Country	Scenario	LCOE (USD/MWh)*	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
	Moderate	50 to 100	2,858.4	102.9	153.9
		100 to 150	32,637.7	1,175.0	1,674.2
	Restricted	50 to 100	1,366.8	49.2	73.5
		100 to 150	13,834.5	498.0	699.1
	Urban	50 to 100	3.3	0.1	0.2
		100 to 150	93.1	3.4	4.7
Malaysia	Relaxed	50 to 100	6,608.4	237.9	347.1
		100 to 150	258,848.6	9,318.6	12,436.0
	Moderate	50 to 100	2,068.2	74.5	108.5
		100 to 150	52,506.9	1,890.3	2,538.2
	Restricted	50 to 100	123.5	4.5	6.5
		100 to 150	5,387.5	194.0	260.0
	Urban	50 to 100	64.9	2.3	3.4
		100 to 150	898.9	32.4	43.7
Philippines	Relaxed	50 to 100	1,164.2	41.9	68.0
		100 to 150	220,322.5	7,931.6	10,762.7
		150 to 200	765.6	27.6	29.0
	Moderate	50 to 100	464.8	16.7	27.2
		100 to 150	52,597.0	1,893.5	2,667.8
		150 to 200	0.49	0.02	0.02
	Restricted	50 to 100	142.2	5.1	8.3
		100 to 150	9,366.6	337.2	470.9
		150 to 200	0.50	0.02	0.02
	Urban	50 to 100	102.9	3.7	6.0
		100 to 150	4,568.4	164.5	237.3
Singapore	Relaxed	100 to 150	103.1	3.7	4.7
	Moderate	100 to 150	60.0	2.2	2.8
	Restricted	100 to 150	2.9	0.1	0.1
	Urban	100 to 150	108.9	3.9	5.0
Thailand	Relaxed	50 to 100	424,293.0	15,274.6	22,325.0
		100 to 150	73.7	2.7	3.3
	Moderate	50 to 100	292,699.2	10,537.2	15,564.9
		100 to 150	14.0	0.5	0.6
	Restricted	50 to 100	16,255.5	585.2	850.0
		100 to 150	0.35	0.01	0.02
	Urban	50 to 100	1,899.7	68.4	99.5
Vietnam	Relaxed	50 to 100	218,032.2	7,849.2	10,061.3
		100 to 150	68,504.7	2,466.2	2,447.6
	Moderate	50 to 100	73,576.7	2,648.8	3,520.2
		100 to 150	5,492.7	197.7	198.7
	Restricted	50 to 100	17,302.3	622.9	818.4
		100 to 150	2,948.9	106.2	106.3

Table B-1. Solar Photovoltaic Technical Potential within Available Levelized Cost of Energy Ranges					
Country	Scenario	LCOE (USD/MWh)*	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
	Urban	50 to 100	3,888.3	140.0	167.9
		100 to 150	291.1	10.5	10.6

*LCOE ranges are only shown for ranges with technical potential results.

Table B-2. Wind LCOE and technical potential for land-use constraint scenarios					
Country	Scenario	LCOE (USD/MWh)*	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
Brunei	Relaxed	100 to 150	7.2	0.02	0.03
		150 to 200	1.3	0.004	0.005
	Moderate	100 to 150	6.3	0.02	0.03
	Restricted	100 to 150	5.7	0.02	0.03
Burma	Relaxed	40 to 100	36,304.1	108.9	214.3
		100 to 150	193,967.6	581.9	914.1
	Moderate	40 to 100	28,106.2	84.3	164.5
		100 to 150	132,458.0	397.4	635.2
	Restricted	40 to 100	3,857.2	11.6	23.0
		100 to 150	23,546.4	70.6	107.9
Cambodia	Relaxed	40 to 100	17.4	0.05	0.12
		100 to 150	25,656.1	77.0	131.5
		150 to 200	25,620.7	76.9	106.3
	Moderate	40 to 100	25.6	0.1	0.2
		100 to 150	23,056.0	69.2	118.2
		150 to 200	22,363.2	67.1	92.6
	Restricted	40 to 100	26.4	0.08	0.18
		100 to 150	5,348.7	16.0	27.4
		150 to 200	4,740.4	14.2	19.9
Indonesia	Relaxed	40 to 100	3,308.0	9.9	27.5
		100 to 150	28,110.0	84.3	160.7
		150 to 200	43,326.4	130.0	189.4
	Moderate	40 to 100	2,023.7	6.1	17.0
		100 to 150	14,526.8	43.6	83.0
		150 to 200	22,021.5	66.1	96.2
	Restricted	40 to 100	119.3	0.4	1.0
		100 to 150	1,943.1	5.8	11.1
		150 to 200	2,193.6	6.6	9.7
Lao PDR	Relaxed	100 to 150	5,757.5	17.3	34.5
		150 to 200	53,187.4	159.6	261.0
		200 to 250	28,449.5	85.3	118.1
	Moderate	40 to 100	3.4	0.01	0.03
		100 to 150	4,340.3	13.0	25.8
		150 to 200	18,072.4	54.2	90.8
		200 to 250	6,914.9	20.7	28.7

Table B-2. Wind LCOE and technical potential for land-use constraint scenarios					
Country	Scenario	LCOE (USD/MWh)*	Suitable Land Area (km^2)	Capacity (GW)	Generation (TWh)
	Restricted	40 to 100	3.4	0.01	0.03
		100 to 150	618.0	1.9	3.7
		150 to 200	9,596.4	28.8	47.2
		200 to 250	5,006.2	15.0	20.8
Malaysia	Relaxed	40 to 100	4.3	0.01	0.03
		100 to 150	996.9	3.0	4.9
		150 to 200	543.9	1.6	2.2
	Moderate	100 to 150	525.5	1.6	2.6
		150 to 200	347.5	1.0	1.4
	Restricted	40 to 100	1.9	0.01	0.01
		100 to 150	85.0	0.3	0.4
		150 to 200	22.0	0.1	0.1
Philippines	Relaxed	40 to 100	13,601.0	40.8	114.0
		100 to 150	109,768.4	329.3	645.3
		150 to 200	45,979.5	137.9	205.4
	Moderate	40 to 100	7,144.5	21.4	59.5
		100 to 150	65,192.8	195.6	383.3
		150 to 200	22,177.3	66.5	99.1
	Restricted	40 to 100	3,180.8	9.5	27.0
		100 to 150	20,584.5	61.8	120.9
		150 to 200	8,157.4	24.5	36.5
Singapore	Relaxed	100 to 150	11.2	0.03	0.06
		150 to 200	22.4	0.07	0.10
	Moderate	100 to 150	7.0	0.02	0.04
		150 to 200	12.8	0.04	0.06
	Restricted	100 to 150	0.5	0.002	0.003
		150 to 200	1.5	0.005	0.007
Thailand	Relaxed	40 to 100	139.1	0.4	1.0
		100 to 150	84,081.3	252.2	435.6
		150 to 200	55,141.9	165.4	228.6
	Moderate	40 to 100	61.7	0.2	0.4
		100 to 150	79,656.8	239.0	412.5
		150 to 200	51,216.8	153.7	212.0
	Restricted	40 to 100	3.6	0.01	0.03
		100 to 150	3,362.9	10.1	17.6
		150 to 200	2,288.5	6.9	9.5
Vietnam	Relaxed	40 to 100	131,237.0	393.7	852.2
		100 to 150	80,395.0	241.2	369.1
	Moderate	40 to 100	80,608.8	241.8	530.7
		100 to 150	22,981.9	69.0	105.4
	Restricted	40 to 100	25,253.6	75.8	162.0
		100 to 150	13,941.2	41.8	64.0

**LCOE ranges are only shown for ranges with technical potential results.*

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