VERSION 1

TZ-APG model

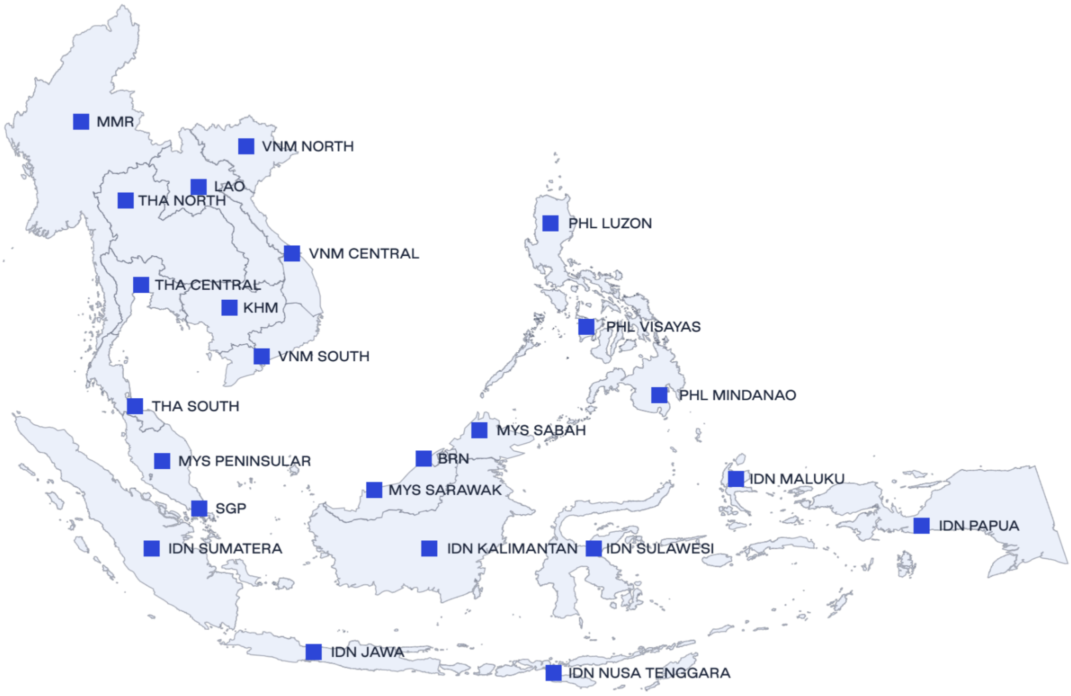
Technical Annex

Updated: 2 December 2024

Geographic scope

TransitionZero's ASEAN Power Grid model, or TZ-APG, is a power systems model covering ten member states of the Association of Southeast Asian Nations (ASEAN). In the first iteration, TZ-APV v1, five countries are represented at the national level and the remaining five at the subnational level. As a result, TZ-APG v1 is a 24-node model.

Below is the geographic scope and representation of the model.



Input data

Demand projection

In this first iteration, TZ-APG v1 has used a simple demand projection methodology. Power demand growth in the modelling period between 2023-2035 was derived primarily from national policy documents. In cases where such data was not available, such as Brunei Darussalam, Lao PDR, Malaysia and Myanmar, we applied neutral growth rates that were estimated based on historical trends, and future population and economic growth rates as projected by the World Bank, International Monetary Fund (IMF), and International Institute for Applied Systems Analysis (IIASA).

For countries represented at the sub-national level, we assumed that node-level demand growth would share the same pace with the national growth. We also assumed that the share of each node's demand in overall national demand would remain the same as in the latest year where such data is available (2023 for Vietnam, Malaysia, Indonesia, and the Philippines; and 2020 for Thailand).

A linear growth rate for demand was applied throughout the modelling period. The base demand values, which are actual data for the year 2022 or 2023 depending on the country, was collected from official government statistics.

All data and results in this study are presented on an annual timescale.

The table below shows the compound annual growth rates (CAGR) applied to each country and the official policy documents or sources they were derived from:

Country	CAGR 2023-2035 (%)	Sources
Brunei Darussalam	2.4	TransitionZero's estimates
Cambodia	8.1	Power Development Master Plan 2022-2040 (Low case, without energy efficiency measures)
Indonesia	5.8	Comprehensive Investment and Policy Plan (CIPP) under the Just Energy Transition Partnership (JETP)
Lao PDR	5.6	TransitionZero's estimates
Malaysia	3.0	TransitionZero's estimates

Myanmar	1.6	TransitionZero's estimates
Philippines	6.7	Power Development Plan 2020-2040 (Low scenario)
Singapore	2.6	Energy 2050 Committee Report
Thailand	3.0	Power Development Plan 2018-2037 (Rev. 1)
Vietnam	7.7	Power Development Plan 2020-2030 (Base scenario)

Renewable energy potentials and profiles

Potentials

We computed renewable potentials and profiles (capacity factors) for utility-scale solar PV, onshore wind and offshore wind. In short, our methodology to compute the potential considers the following:

1. Application of land use constraints.
2. Assumptions around dual land use possibilities.
3. Assumptions around installation density.

We also computed capacity factors globally for the aforementioned technologies, making use of 2013 weather data to simulate the performance of wind turbines and solar PV panels.

Both the potentials and the capacity factors were computed with the intention to be used as input for the long term capacity expansion model OSeMOSYS. Indeed, this use case informed the modelling process as will be explained in detail later.

Below we summarise the data inputs and give more detail on the methodology used to compute both the potential and capacity factors.

Renewable Potentials

Renewable potentials were computed for each admin 1 node for the following technologies: utility-scale solar PV, onshore wind and offshore wind.

Data Inputs

- For land cover information we made use of the Copernicus Global Landcover Dataset (CGLS) from 2019.
- For bathymetry and height data we use the GEBCO global terrain data
- For wildlife restrictions we made use of the WDPA protected area list

Land Use Restrictions Applied

We applied a combination of physical and social restrictions to exclude land from renewable energy development. These are listed in the table below.

Type	Constraint	Technology	Value
Physical	Elevation	Onshore Wind	< 2500m
		Offshore Wind	Max depth 500m
Social	Distance to Urban Area	Onshore Wind	> 500 m
		Solar PV	> 500 m
	Nature Conservation	Onshore Wind	No building on WDPA land and no deforestation
		Solar PV	No building on WDPA land and no deforestation
		Offshore Wind	No building on WDPA sea

Dual Land Use Assumptions

We assumed only a certain percentage of each land type was suitable for renewable energy development based on figures from the PhD thesis of Hoogwijk from 2004. Note these factors are driven more by physical suitability assumptions but could also be adjusted to incorporate political or social preferences (e.g. the suitability factor for cropland could be reduced if a government decides not to use cropland for RE).

Land Type	Technology	Suitability Factor
Cropland	Onshore Wind	0.7
	Solar PV	0.15
Bare	Onshore Wind	0.9
	Solar PV	0.9
Shrub	Onshore Wind	0.5
	Solar PV	0.4
Water	Offshore Wind	0.9

RE Density Assumptions

We assumed one could install 30 MW per KM2 of Solar PV and 5 MW per KM2 for wind turbines. These figures are from NREL. For Singapore and Brunei Darussalam, we used technical potentials from other modelling studies as the methodology above is constrained in population-dense city states. Technical potentials were taken from Accenture[1], USAID-NREL[2] and EMA[3].

RE Profiles

RE Profiles for onshore wind, offshore wind, and solar PV were extracted from renewables ninja. This platform utilises the VWF model to convert wind speed data from NASA MERRA reanalysis data into power output and computes solar profiles using the GSEE model (Global Solar Energy Estimator). The wind profile references[4], leveraging NASA MERRA reanalysis data[5], while the solar profile references[6] and utilises solar radiation data from[7] . For each node, a representative latitude and longitude were selected, and the 2013 profile at this point was employed as the node's profile.

Hydropower profiles were obtained from the PLEXOS World model data[8]. This in turn consolidated location-specific monthly capacity factors for every hydro power plant (7155 in total) from the Global Reservoir and Dam Database (GRAND)[9] and a study by Gernaat and colleagues[10] . In this latter study, the authors identified over 60,000 potential new locations for hydropower plants and developed monthly water discharge profiles for every new location, as well as for every existing location as identified in the GRAND database based on 30-years of runoff data.

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[1] Accenture (2022). *System Value Analysis: BRUNEI DARUSSALAM*. https://www3.weforum.org/docs/WEF_Brunei_System_Value_Analysis_2022.pdf
[2] USAID-NREL (2020). *EXPLORING RENEWABLE ENERGY OPPORTUNITIES IN SELECT SOUTHEAST ASIAN COUNTRIES*. https://www.nrel.gov/docs/fy19osti/71814.pdf
[3] Energy Market Authority (2023). *What is the potential of solar energy in Singapore?* https://www.ema.gov.sg/resources/faqs/energy-supply/solar/what-is-the-potential-of-solar-energy-in-singapore
[4] Staffell, Iain, and Stefan Pfenninger. "Using bias-corrected reanalysis to simulate current and future wind power output." Energy 114 (2016): 1224-1239.
[5] Rienecker, Michele M., Max J. Suarez, Ronald Gelaro, Ricardo Todling, Julio Bacmeister, Emily Liu, Michael G. Bosilovich et al. "MERRA: NASA's modern-era retrospective analysis for research and applications." Journal of climate 24, no. 14 (2011): 3624-3648.
[6] Pfenninger, Stefan, and Iain Staffell. "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data." Energy 114 (2016): 1251-1265.
[7] Müller, Richard, Uwe Pfeifroth, Christine Träger-Chatterjee, Jörg Trentmann, and Roswitha Cremer. "Digging the METEOSAT treasure—3 decades of solar surface radiation." Remote Sensing 7, no. 6 (2015): 8067-8101.
[8] https://dataverse.harvard.edu/dataverse/PLEXOS-World
[9] B. Lehner, C.R. Liermann, C. Revenga, et al., High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management, Front. Ecol. Environ. 9 (2011) 494–502, https://doi.org/10.1890/100125.
[10] D.E.H.J. Gernaat, P.W. Bogaart, D.P.V. Vuuren, et al., High-resolution assessment of global technical and economic hydropower potential, Nature Energy 2 (2017) 821–828, https://doi.org/10.1038/s41560-017-0006-y.

Scenario design

The main goal of this study was to assess the impact of different grid expansion pathways on the development and operation of the power systems of the 10 ASEAN countries. Taking into account the most recent climate policy and power development plans in the region, TZ-APG v1 set out to model four grid scenarios, starting from the most constrained (status quo) and progressing to the most ambitious regional grid network currently envisioned. Even in the most ambitious scenario, all the transmission candidates that were included came from regional and/or national-level policy discussions. For the purpose of this research, we assumed that these transmission projects would be built by the modelled year 2035. This does not necessarily reflect our assessment of the development outlook of these projects.

Specifics on the four scenarios are provided in the table below.

	Grid scenario	Description
1	Business-as-usual (BAU)	Includes all existing domestic and cross-border interconnectors only, with their capacity remaining unchanged.
2	Enhanced BAU	Includes all existing domestic and cross-border interconnectors only, but their capacity can be expanded to the optimal level, as decided by the model.
3	Regional Interconnection	Apart from the existing lines, new interconnectors were added, including the remainder of the 18 AIMS III interconnectors, as well as the newly proposed lines between Singapore and Vietnam, Cambodia. Their capacity is expandable to the optimal level, as decided by the model.
4	Indonesia Super Grid	Includes all the lines in the “Regional Interconnection” scenario with the addition of four inter-island transmission lines that are part of Indonesia’s Super Grid concept. Their capacity is expandable to the optimal level, as decided by the model.

Interconnectors

Interconnector candidates

TZ-APG v1 works with a predetermined set of interconnector routes, as specified in each modelled scenario. With respect to the new interconnectors that were added to scenarios "Regional Interconnection" and "Indonesia Super Grid", the candidates were derived from the following official documents:

- ASEAN Interconnection Masterplan Study (AIMS) III
- Singapore Energy Market Authority's project announcements: Vietnam, Cambodia
- Indonesia Super Grid initiative

We acknowledge that some ASEAN countries have existing interconnectors with other non-ASEAN countries, such as China. However, such links were not included in TZ-APG v1.

Interconnector database

For details on the capacities of existing and planned interconnectors between the 24 nodes, we referenced different sources including the Global Transmission Database[11], ASEAN Centre for Energy, and other public records.

Interconnector centre-points

For assigning the start- and end-points of transmission lines in the context of interconnectors between nodes in this study, we follow a 'centre-of-gravity' approach from Zappa et al.[12], taking urban-area-weighted centers resulting in a single point for each customized node. This approach not only simplifies the spatial and internal grid complexity in multi-region study but is also useful for policy analysis, such as evaluating the impact of existing and new cross border transmission lines for power trade. The capacity of each interconnector acts as a combined interface rather than individual lines. World Cities Database[13] (last updated on March 31, 2023) was the main reference to retrieve longitude, latitude and population datasets to determine the urban-area-weighted centers.

[11] Brinkerink, M., Sherman, G., Osei-Owusu, S., Mohanty, R., Majid, A., Barnes, T., Niet, T., Shivakumar, A., & Mayfield, E. (2024). Global Transmission Database (1.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10870602

[12] Zappa W, Junginger M, van den Broek M (2019). Is a 100% renewable European power system feasible by 2050? Applied Energy 233–234: 1027–1050

[13] Pareto Software, LLC (2023), World Cities Database, https://simplemaps.com/data/world-cities, accessed 11/01/2023.

The straight-line distance between centre-points is calculated based on the radius of the Earth with an Excel formula as:

$$ACOS\,(COS(RADIANS(90 - Lat1)) \times COS(RADIANS(90 - Lat2)) + SIN(RADIANS(90 - Lat1)) \times SIN(RADIANS(90 - Lat2)) \times COS(RADIANS(Long1 - Long2))) \times 6371$$

Interconnector costs and losses

There are two types of transmission lines incorporated in this study, which are high voltage alternating current (HVAC) for line-based and shorter transmission distances and high voltage direct current (HVDC) for longer transmission distances, including subsea lines. Baseline costs and losses are taken from Zappa et al[14] and Droste-Franke et al[15] with the incorporation of inflation and conversion to USD2020 value. Interconnector's cost and losses also vary depending on the distance and technology type aligned with Brinkerink et al[16]. Due to that reason, HVDC subsea cables have a higher cost per unit of distance.

According to the aforementioned costs assumption, the cost-efficiency threshold for land-based HVDC, which is more cost-efficient than HVAC, is identified as 374 km, excluding considerations for transmission losses, variable costs and wheeling charges. In the model, we assume that land-based transmission lines with straight-line distance exceeding the break-even distance threshold are classified as HVDC, while those below this distance are designated as HVAC.

[14] Zappa W, Junginger M, van den Broek M (2019). Is a 100% renewable European power system feasible by 2050? Applied Energy 233–234: 1027–1050.
[15] Droste-Franke B, et al (2012). Balancing Renewable Electricity. Springer Berlin Heidelberg, Berlin, Heidelberg, doi: 10.1007/978-3-642-25157-3, ISBN: 978-3-642-25156-6.
[16] Brinkerink, M. et al (2022). Assessing global climate change mitigation scenarios from a power system perspective using a novel multi-model framework. Environmental Modelling & Software 150, 105336.

Power plant data

Power plant data was collected and validated by TransitionZero's Analysis team. We started with the power plant list of Global Energy Monitor (GEM), then reviewed and updated detailed information about each power plant, as well as added new assets based on the latest official national documents and other public records deemed reliable.

We acknowledge that there remains gaps between the aggregated national-level capacities in the dataset and those announced by each country's authorities. By technology type, the problem was most visible in the case of solar PV assets, as our dataset has not yet fully captured rooftop and small-scale solar PV systems.

The dataset that was used in TZ-APG v1 is valid as of March 2024. Power plants that were included in the model were those with the following statuses:

(i) **Operating:** power plants that have been successfully commissioned and are currently in operation

(ii) **Under construction:** power plants where the construction process, such as land clearance or equipment installation, is underway in which the expected commissioned dates are based on the official announcement or other reliable sources.

Technology palette

In the first iteration, TZ-APG v1 had a modelling horizon of 2035. As a result, the model worked with a conservative technology palette, considering only technology choices that are common and commercially viable in ASEAN today. We've also assigned constraints to each technology expansion based on the current market view. Details on TZ-APG v1 technology constraints are provided in the table below.

Technology	Constraints
Coal	Only plants in operation and under construction in the base year (2023) are eligible
Gas	No constraints
Oil	No constraints
Renewable energy	Includes solar PV, wind, hydropower (including pumped storage hydropower), geothermal, bioenergy
Battery storage	Includes lithium-ion battery

TZ-APG v1 does not yet consider technologies such as nuclear power, ammonia and hydrogen co-firing, or carbon capture and storage.

National policies and targets

TZ-APG v1 was designed for a least-cost outcome. However, some constraints were forced upon the model to drive system development. This includes selective national decarbonisation policies and targets, as detailed in the table below. The application of these targets by the model does not reflect our view on the feasible implementation of the targets by the respective timeline.

Country	System development constraints	Sources
Brunei Darussalam	Minimum 30% solar penetration (by installed capacity) by 2035	NDC 2020
Cambodia	Hydropower capacity at least 1558MW by 2030	Power Development Master Plan 2022-2040
	Solar capacity at least 1005MW by 2030	
Indonesia	Emissions peak at 290 MtCO2eq by 2030	National Energy Policy (Government Regulation No. 79/2014), JETP Indonesia CIPP 2023
	Minimum 31% renewable energy penetration (by generation) by 2030	
Lao PDR	Hydropower capacity at least 13000MW by 2030	NDC 2021
Malaysia	Minimum 40% renewable energy penetration (by installed capacity) by 2035	Malaysia Renewable Energy Roadmap MyRER
Myanmar	Renewable energy at least 2000MW by 2030	NDC 2021
	Coal capacity at 3620MW by 2030	
Philippines	Minimum 35% renewable energy penetration (by generation) by 2030	National Renewable Energy Programme
Singapore	Solar capacity at least 1600MWac by 2030	Singapore Green Plan 2030
	Emissions target at 60 MtCO2eq in 2030	

Thailand	Minimum 36% renewable energy penetration (by installed capacity) by 2037	Power Development Plan 2018-2037 (Rev. 1)
Vietnam	Coal peak at 30127MW by 2030	Power Development Plan 2020-2030
	Onshore wind at least 21880MW, and offshore wind at least 6000MW by 2030	

In the case of Thailand, the renewable energy target was set for the year 2037. However, as TZ-APG v1 was modelled for the year 2035, the above target was not implemented.

We note that this is not an exhaustive list of each country's power sector decarbonisation targets currently in place. Future iterations of TZ-APG can be updated and supplemented with other constraints, as needed.

Technology costs

Technology capital and fixed operating costs were sourced from the following catalogues developed by the Danish Energy Agency (DEA):

- EREA and DEA: Vietnamese Technology Catalogue for power generation technologies 2023 (2023)
- Technology Data for the Indonesian Power Sector: Catalogue for Generation and Storage of Electricity (March 2024)

We derived an average of the technology costs found in Vietnam and Indonesia, as provided in the documents above, and applied these across the countries in the model. The DEA data assumes some technology costs will reduce through time from learning-by-doing, R&D, etc.

Fuel prices

TZ-APG v1 represents fuel prices as a static input for each energy carrier. Unlike other energy system models, such as TZ-OSeMOSYS, TZ-APG v1 does not represent upstream fuel supply in detail and therefore we use a single price for each fossil fuel (coal, gas, oil) across all countries. Modelling fossil fuel prices in ASEAN in TZ-APG v1 provides a significant challenge given heterogeneity amongst countries in terms of domestic resource endowment and fossil fuel import dependency. For example, Malaysia is a net exporter of gas whilst Singapore is reliant on imports for 100% of fossil consumption[17].

The fuel price for each fossil fuel is consistent across all countries in TZ-APG v1. In short, this means the relative difference between competing fossil fuels (coal, oil and gas) is the same for each country. Fossil fuel prices are derived as a weighted average of regional supply cost curves[18,19] for gas and oil. A supply cost curve, or cumulative extraction curve, reflects that fossil fuels (generally) become more expensive as a resource is depleted. It should be noted that the fuel prices input into TZ-APG v1 reflect a weighted average marginal cost of production across ASEAN countries, rather than observed market prices which are subject to price formation mechanisms, international geopolitical forces, etc.. For oil, a 20% premium was added to the weighted average cost of crude oil to reflect a refining mark-up, i.e. oil consumption in the power sector is in the form of refined petroleum products (e.g. diesel, fuel oil). For coal, we used

[17] Energy Institute (2024). *Statistical Review of World Energy.* https://www.energyinst.org/statistical-review/resources-and-data-downloads
[18] Mutitt et. al. (2023). Socio-political feasibility of coal power phase-out and its role in mitigation pathways. *Nature Climate Change.* 13, 140–147
[19] Welsby et. al (2021). Unextractable fossil fuels in a 1.5°C world. *Nature.* 597, 230–234

prices taken from OSeMOSYS Global[20] with an Indonesian proxy taken for all countries.

Fuel prices for coal, gas and oil products are shown in the table below.

Fuel	Fuel cost, $/MWh
Coal	8
Gas	15
Oil products	33

In future releases of TZ-APG we aim to improve on the fuel price methodology we use by:

- Represent depletion of domestic resources in a more robust way. For example, whilst Indonesia has large gas resources, much of the reserve base has been depleted and future production could be subject to smaller marginal fields and fields with significant technical challenges (e.g. East Natuna with a CO_2 content > 70%).[21]
- Taking into account differences in, and inter-linkage between, domestically produced fossil fuels and those purchased on international markets (e.g. by using projections of internationally traded gas prices from the IEA and other sources).

[20] Barnes et. al (2023). Global Interconnector Grid Study. https://blog.transitionzero.org/hubfs/TransitionZero_InterconnectorsStudy_TechnicalAnnex_Final.pdf
[21] Offshore Technology (2007). *Natuna Gas Field - Greater Sarawak Basin*. https://www.offshore-technology.com/projects/natuna/

Model framework

TZ-APG is developed using the PyPSA[22] modelling framework and serves as an open access tool for dispatch modelling. It enables power system optimization for 24 nodes across ASEAN with a high temporal resolution of two hours. Its detailed network modelling provides the flexibility to analyze complex challenges in cross-border or interconnected power systems.

As an open access, flexible, and scalable tool, TZ-APG allows users to adapt, expand, and reproduce it for various use cases. The model optimizes capacity expansion and system operations to minimize system costs while adhering to technical constraints, such as generator ramp rates, transmission line capacities, technology and fuel costs, and renewable energy profiles. Its two-hour temporal resolution facilitates the analysis of intra- and intercountry power system dynamics over short intervals, enabling a detailed understanding of generation and power flow patterns to meet demand and policy goals.

TZ-APG v1 uses 2023 data (e.g., existing capacity and generation) as a baseline and projects least-cost options for 2035. As a live model, it is regularly updated to reflect the latest energy, power, and climate policies in each country, ensuring its ongoing relevance to ASEAN's evolving power sector. The model structure and inputs, including all assumptions, are openly available at transitionzero.org/tz-apg promoting transparency and collaborative development.

[22] https://pypsa.readthedocs.io/en/latest/