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# Integrated Resource and Resilience Planning in Thailand: Final Report

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**Submitted to:**

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## Acknowledgments

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## Project Background and Context

The USAID and Australia Mekong Safeguards Program (Mekong Safeguards) promotes sustainable development in the Mekong subregion by assisting countries in applying environmental and social standards to infrastructure projects. Jointly funded by USAID and the Australian government, and implemented by The Asia Foundation (TAF), the program aims to minimize the negative impacts of these new infrastructure developments in the region.

In collaboration with TAF, the Stockholm Environment Institute (SEI) contributes to the Mekong Safeguards Program by supporting Thailand's Ministry of Energy (MOEN) in conducting Integrated Resource and Resilience Planning (IRRP) for the country's power system. The IRRP framework, as applied in this project, considers a broad set of objectives beyond conventional least-cost planning. It incorporates greenhouse gas (GHG) emission reductions and other social and environmental goals, evaluated under a range of critical uncertainties, such as climate change and technological advancements. Within this framework, SEI's work aims to support Thailand in making informed, sustainable, and resilient energy-planning decisions that align with its long-term decarbonization targets, including achieving carbon neutrality by 2050 and net-zero GHG emissions by 2065.

SEI's contributions center on three primary objectives:

- 1. Application of IRRP:** develop a detailed optimization model of Thailand's power system and apply it under an IRRP framework to analyze pathways toward net-zero GHG emissions for the power sector.
- 2. Support for the integration of net-zero-compliant scenarios across Thailand's Power Development Plan (PDP) process:** assist MOEN in developing pathways to achieve Thailand's climate-neutral and net-zero GHG targets. This involves reviewing international best practices and supporting the review of updated PDP cases to ensure PDP is consistent with Thailand's long-term decarbonization objectives.
- 3. Capacity building:** provide training to Thailand's energy planners, including government agencies and utilities, on using the modeling tools and the power system optimization model developed for the IRRP.

This report summarizes the assumptions, methods, and results of the IRRP analysis conducted for Thailand. It describes the process for generating and characterizing a large ensemble of model results for the pathways and identifying low-regrets planning decisions. The report concludes with recommendations for Thailand's PDP, based on these findings.

## Power System Planning with Integrated Resource and Resilience Planning

IRRP represents a departure from traditional, deterministic methods in electric utility planning, advancing toward a more adaptive and comprehensive framework. Historically, electric utilities operated under a vertically integrated model that focused primarily on balancing supply to meet demand. However, this model proved insufficient due to vulnerabilities such as fuel price volatility, environmental costs, and the slow adoption of new technologies.

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In response, the 1970s saw the emergence of Integrated Resource Planning (IRP), which aimed to identify the optimal, least-cost strategies to meet future energy needs based on assumed conditions. While IRP represented progress by incorporating demand-side resources and extending planning horizons, it had notable limitations. IRP often lacked explicit consideration of trade-offs among objectives and typically failed to adequately address uncertainties.

IRRP builds on the foundation of IRP by integrating and prioritizing resilience considerations into the planning process, alongside traditional goals such as cost-effectiveness and reliability. It seeks to develop plans that effectively meet multiple social objectives, accounting for a wide array of future uncertainties and risks, thereby reducing the likelihood of undesirable outcomes or regrets associated with unforeseen events. IRRP can empower utilities to make informed decisions that embrace future uncertainties and foster a robust, sustainable, and adaptable power system.

### Key Components in IRRP

Applying the IRRP framework to power systems planning involves identifying and addressing five key components: planning objectives, planning metrics, planning options, critical uncertainties, and planning cases. These components are detailed below.

1. **Planning Objectives:** Desired outcomes of the planning process that broadly cover the interests of multiple stakeholders. For example, system reliability, cost-efficiency, or environmental sustainability.
2. **Planning Metrics:** Quantitative indicators used to assess the extent to which objectives are met. These are calculated by a planning model and are essential for evaluating planning decisions across scenarios.
3. **Planning Options:** Choices within planners' control, which are simulated within the model across scenarios to identify robust strategies that can achieve the objectives.
4. **Critical Uncertainties:** Factors outside planners' control that could significantly impact outcomes and whose future values are uncertain. These uncertainties are sampled by the model to generate diverse future scenarios in which planning options are tested.
5. **Planning Cases:** Narratives or sets of major assumptions outside planners' control that define the external circumstances under which planning decisions are tested. Each planning case comprises a distinct ensemble of scenario runs that share a narrative, while sampling from critical uncertainties.

### An IRRP Process in Practice

The IRRP process begins with a base model that simulates the capacity expansion and operation of a power system. This computer model generates a wide range of future scenarios by stochastically sampling critical uncertainties, informed by their possible values, states, and likelihood distributions. Each scenario is then evaluated to assess planning decisions, using planning metrics to measure performance against established objectives. The process is repeated iteratively for multiple planning cases, as needed. The results for a large scenario ensemble are then analyzed to seek robust (or "low-regrets") strategies that perform well across multiple scenarios rather than focusing solely on optimal solutions.

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# IRRP in Thailand: Methods and Processes

## Modeling Tools

The model that underpins the IRRP for Thailand's power system was constructed by SEI using the Low Emissions Analysis Platform (LEAP) and the Next Energy Modeling system for Optimization (NEMO). These modeling tools, developed by SEI, provide a comprehensive, flexible, and user-friendly system for electricity sector simulation. These tools have been widely used for energy policy analysis and low-emission development strategies.

LEAP serves as the primary user interface, enabling model construction and result visualization through its graphical interface. The supply side of the electricity system is simulated by NEMO, using mixed-integer linear optimization. NEMO co-optimizes the dispatch and expansion of electricity generation, storage, and transmission capacity. The optimization is conducted within a system of constraints, such as maximum and minimum capacities and capacity additions.

In applying LEAP and NEMO under an IRRP framework, the integrated LEAP-NEMO model was paired with an auxiliary tool, the Large Scenario Ensemble Generator. This tool, developed by SEI, automated the modeling process for sampling uncertainties, running the model, and recording results. Results were saved in an SQLite database that was then linked to Excel for data visualization and further analysis.

## Overview of Modeling Scope and Methods

The model developed in LEAP and NEMO is a comprehensive multiregional simulation of Thailand's electricity demand, production, storage, and transmission, exclusively focusing on the electricity sector and excluding the demand and supply for other fuels. It evaluates long-term planning scenarios from 2018 to 2065. Years from 2018 through 2021 represent a historical period in the model, for which results have been calibrated to know historical data. Projections begin in 2022 and extend to 2065, and while any number of years may be calculated, SEI conducted the IRRP analysis by calculating every five years, plus the year 2037 to align with the end year for Thailand's PDP. To capture detailed temporal variations, the model operates with a sub-annual resolution of 576 time slices, which represent (with hourly resolution) a typical weekday and a typical weekend day in each month.

Geographically, the model covers the five electricity-planning regions of Thailand's Electricity Generating Authority (EGAT), namely Northern Area, Northeastern Area, Central Area, Metropolitan Area, and Southern Area. For each region, electricity demand projections within the model are set exogenously, based on the EPPO PDP projections.

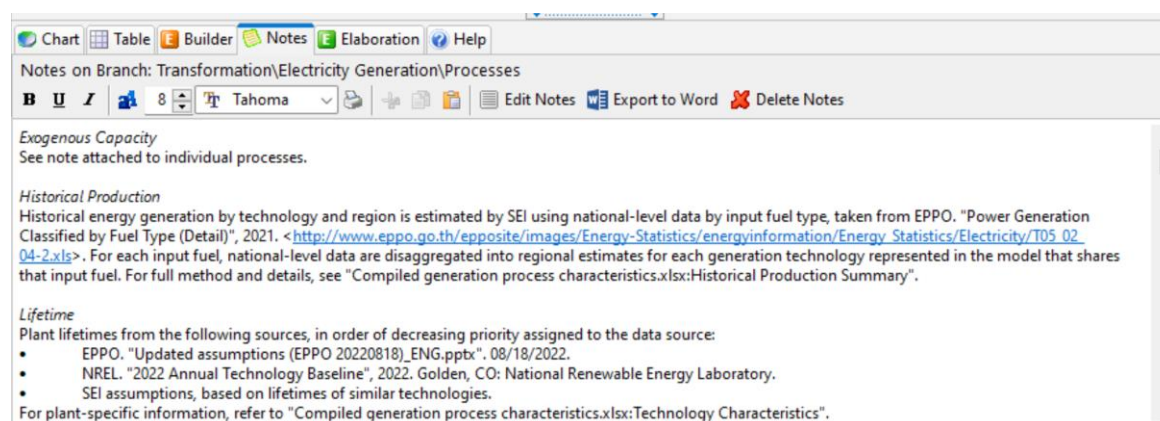
On the supply side, the model includes both current and future options for power generation and storage technologies in each region. Among these are advanced technologies like biomass energy with carbon capture and storage (BECCS), battery storage systems, and the transition of natural gas to gray and eventually green hydrogen. The model also incorporates current, planned, and candidate transmission lines between each adjacent geographic planning region, enabling the model to simulate the flow of electricity among regions.

Given a projection of electricity demand, and subject to physical limits and other constraints imposed in scenarios, the model finds a capacity (MW for each technology, year, and region) and dispatch (MWh for each technology, year, time slice, and region) solution that minimizes discounted, system-wide electricity production costs. Costs are discounted to 2022 at a 10 percent/year real discount rate.

As one of the main project objectives is to evaluate pathways consistent with Thailand’s long-term decarbonization goals, the model calculates outputs that can be used to compare scenarios, including costs and GHG emission projections from electricity generation in all regions. Emissions of carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), and methane (CH<sub>4</sub>) are considered.

Additional details on modeling methods, data, and assumptions have been incorporated into the model itself, which is being submitted to TAF and MOEN as Appendix 1 to this report. The model is packaged as a data set that can be opened in LEAP and calculated using LEAP and NEMO. Inline documentation, provided through LEAP’s Notes feature (Figure 1), offers detailed descriptions of the data inputs and assumptions used for each model variable.

Figure 1. Example of documentation in LEAP notes.



## Stakeholder Input into Modeling and IRRP

IRRP is intended to be a highly stakeholder-driven process, so stakeholders in Thailand were actively consulted throughout the development of the power system model. Consultations spanned the model design, input data, assumptions, and projection results, as well as the IRRP framework, which included the definition of planning cases, objectives, metrics, and critical uncertainties.

These consultations extended over a period of nearly two years and included representatives from key organizations such as MOEN, EPPO, EGAT, Office of Natural Resources and Environmental Policy and Planning (ONEP), Mekong Safeguards representatives, and other relevant agencies and stakeholders. As the project team received input from stakeholders, the model was continuously refined to incorporate new information, ensuring it accurately reflected Thailand’s power system.

Table 1 summarizes and provides a timeline of the main collaborative interactions between the modeling team and stakeholders in Thailand.

Table 1. Summary of main stakeholder interactions and their role in the development of the model and IRRP scenarios.

Date	Purpose and outcome
18 May 2022	Online project kickoff to present objectives, working approach, and list of data requirements for demand, supply, and transmission modeling.
13 June 2022	Online meeting. Modeling team presented detailed workplan, timeline, data collection schedule, and draft proposal for model scope, structure, and disaggregation.
23 August 2022	Online meeting. Modeling team provided update on modeling progress, collected feedback, and discussed data gaps and approaches for gap-filling.
6 December 2022	Online meeting. Modeling team presented update on modeling data and methods, and preliminary results of baseline scenario. Stakeholders provided feedback and discussed open issues that still required clarification or additional data. Discussed narrative and framing of alternative scenarios (including EPPO's planning cases).
17 January 2023	Online meeting. Modeling team presented results for an updated baseline, and a set of alternative scenarios (EPPO's planning cases). Stakeholders provided feedback.
25 January 2023	Hybrid event: <b>Workshop on Key Questions and Challenges for Carbon Neutral Power Planning</b> . The event involved a wider group of stakeholders beyond EPPO. Modeling team presented and received feedback on preliminary results of baseline and alternative scenarios, and presented key questions and challenges that must be addressed when developing pathways to carbon neutrality for the power sector, and their implications for Thailand's PDP and the LEAP-NEMO model.
9 May 2023	In-person event in Bangkok: <b>IRRP Stakeholders Workshop on Carbon Neutral Planning for Thailand's Power Sector</b> . The event involved a wider group of stakeholders beyond EPPO. Modeling team presented case studies on best practices for carbon-neutral power system planning and introduced the IRRP framework. Collaborative sessions included brainstorming and discussions around IRRP components for Thailand, such as identifying, categorizing, and prioritizing objectives and critical uncertainties, selecting metrics, reflecting on planning cases, and identifying relevant data sources.
10–13 May 2023	In-person event in Pattaya: <b>Training on Thailand Power Model</b> . Training for EPPO and EGAT on the use of LEAP, NEMO, and the model for Thailand. Provided participants with hands-on experience using the model, and allowed for discussions around feedback, data availability, and other model improvements.
23 August 2023	Online follow-up meeting with EPPO and EGAT: <b>Follow-Up Meeting for LEAP/NEMO Training on Developing Carbon Neutral Pathway for Thailand's Power Sector</b> . Modeling team presented a recap of the IRRP inputs gathered during the May workshop, along with the proposed

Date	Purpose and outcome
	methods and data needs for their implementation. Stakeholders provided feedback.
20–22 October 2023	In-person event in Khao Yai: <b>Training on LEAP, NEMO, and Thailand Power Model</b> . Training for EPPO and EGAT on the LEAP-NEMO model for Thailand, and the implementation of IRRP components within it. Provided participants with hands-on experience using the model and allowed for discussions around feedback, data availability, and other improved methods for IRRP implementation.
8 February 2024	Online meeting. Modeling team presented final plan for implementing IRRP metrics and critical uncertainties, and a few examples of IRRP model runs to demonstrate types and ranges of results. EPPO and EGAT provided feedback before running the large scenario ensemble.
9–11 May 2024	In-person event in Hua Hin: <b>Technical Working Session on Thailand LEAP-NEMO model</b> . Modeling team presented final approaches for modeling, analysis, and result interpretation. Close collaboration with the technical stakeholders from EPPO and EGAT, including modeling of PDP cases. Discussion on potential future expansion of the model to include other capabilities.
13 May 2024	In-person event in Bangkok: <b>Integrated Resource and Resilience Planning Pathways Workshop</b> . Modeling team presented results and conclusions from the IRRP process. Representatives from EPPO, EGAT, and other stakeholders reflected on the results and what they may mean for Thailand in the context of the PDP and other planning processes.

## Ingredients for Thailand’s IRRP

The process of determining the IRRP inputs—comprising planning cases, objectives, metrics, and critical uncertainties—was conducted through a collaborative and consultative approach involving a diverse range of stakeholders. This engagement primarily took place during an in-person workshop held in Bangkok on May 9, 2023. During the workshop, the SEI modeling team introduced the concept of IRRP, explaining its components and potential application for Thailand’s power-sector planning. A series of interactive sessions were then conducted around the different IRRP components, during which participants brainstormed, identified, categorized, prioritized, and discussed objectives and critical uncertainties. They also proposed appropriate quantitative metrics, reflected on planning cases, and identified relevant data needs and sources for each component.



The raw inputs collected during the workshop were post-processed by SEI. This involved requesting clarifications as needed, removing duplicates, grouping similar ideas by theme, and prioritizing them based on assigned scores. The proposed draft IRRP components and their implementation methods were then refined and validated through multiple rounds of feedback and consultation with EPPO and EGAT.

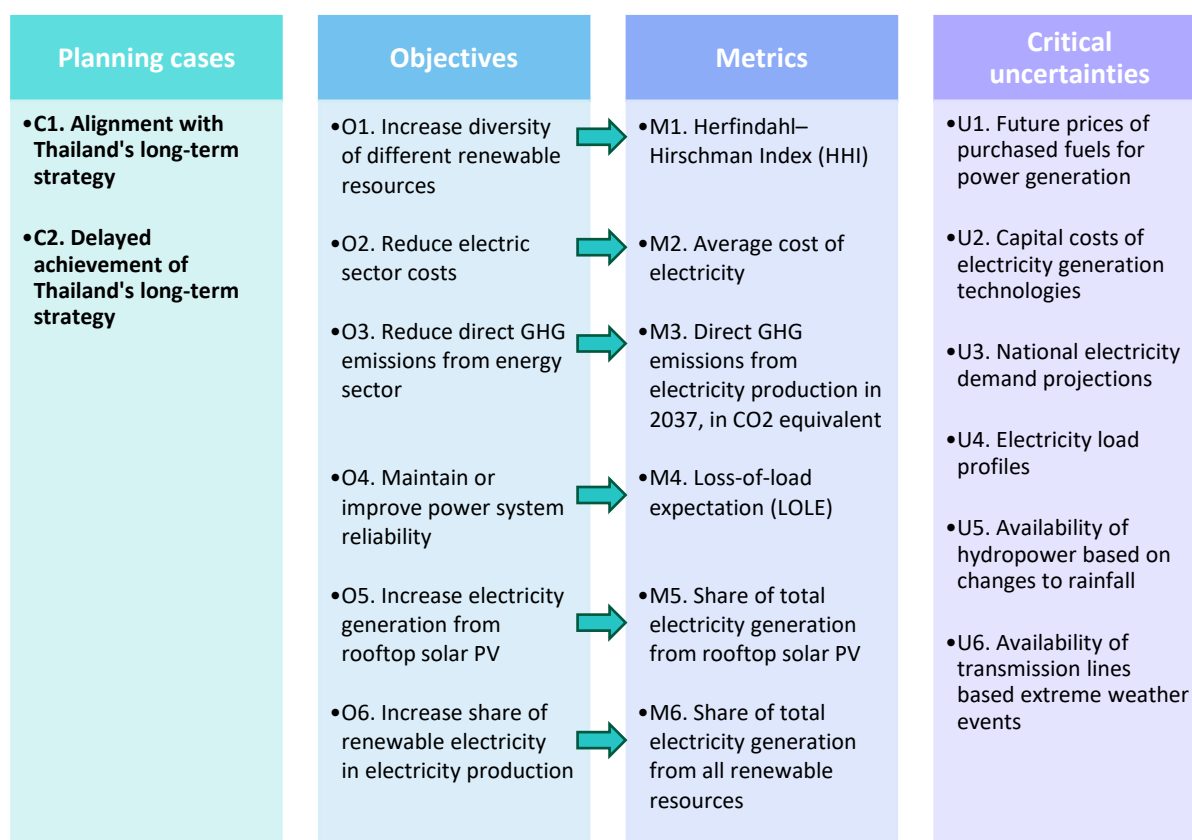
Figure 2 summarizes the final IRRP ingredients used in the analysis. These components, detailed further in the subsequent sections, include two planning cases designed around the achievement of Thailand’s long-term decarbonization strategy, six metrics to assess alignment with power-sector planning objectives, and six critical uncertainties<sup>1</sup> as exogenous inputs to the model.

The process of conducting the iterative IRRP model runs involved sampling critical uncertainties to project potential future conditions. Planning decisions, including investments and the optimal dispatch of electricity generation, transmission, and storage, were then simulated under these conditions, and outcomes were recorded, focusing on metrics that measure progress toward planning objectives, and other key results that reflect planning decisions. The iterative process was repeated over multiple samples of the uncertainties, each drawn from their respective probability distributions, and for the two selected planning cases.

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<sup>1</sup> SEI agreed to include a seventh critical uncertainty, representing political uncertainty around whether Thailand would meet its 2030 unconditional emission reduction target of 84.2 MTCO<sub>2</sub>e for the power sector as stated in its NDC, or its more ambitious conditional target of 67.7 MTCO<sub>2</sub>e. However, an error in SEI’s Large Scenario Ensemble Generator was discovered after the IRRP results, and this necessitated the removal of this uncertainty. All scenarios in all planning cases obey the unconditional emissions limit in 2030 under Thailand’s Nationally Determined Contribution (NDC).

Figure 2. Main components of Thailand's IRRP.

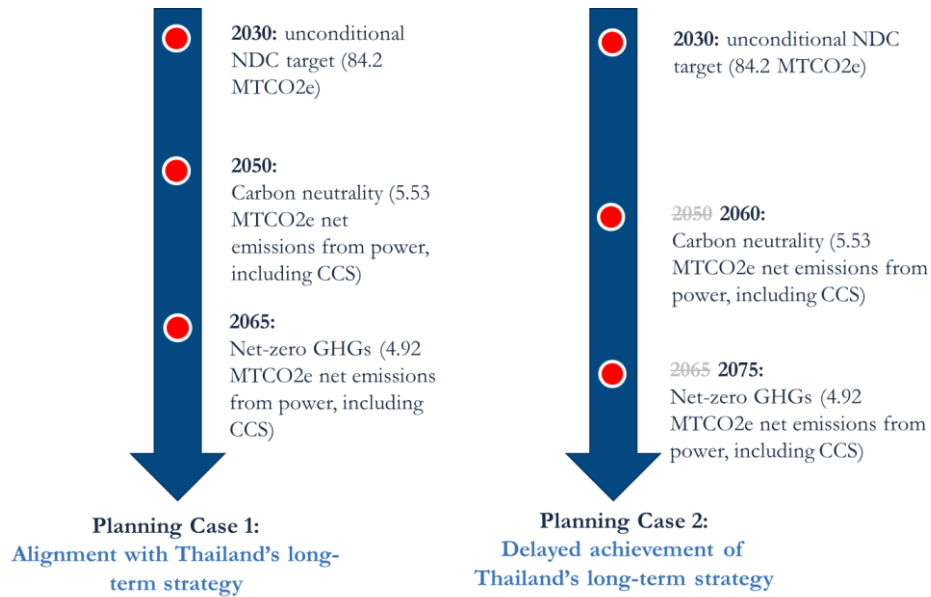


### Planning cases

Two planning cases were defined as follows, based on the achievement or delay of Thailand's long-term decarbonization strategy:

1. *Alignment with Thailand's long-term strategy:* These scenario runs assume that Thailand meets the intermediate and long-term emission reduction targets as stated in their strategy. This includes the unconditional NDC target by 2030 (84.2 MTCO<sub>2</sub>e), reaching carbon neutrality by 2050 (5.53 MTCO<sub>2</sub>e net emissions from power, including Carbon Capture and Storage [CCS]), and net zero by 2065 (4.92 MTCO<sub>2</sub>e net emissions from power, including CCS).
2. *Delayed achievement of Thailand's long-term strategy:* These scenario runs assume that Thailand achieves its unconditional NDC target by 2030 but experiences a ten-year delay in reaching its carbon neutrality and net-zero targets. Consequently, carbon neutrality is attained by 2060, and net-zero emissions are achieved by 2075.

Figure 3. Planning cases for Thailand's IRRP.



## Planning objectives and corresponding metrics

### 1. Increase diversity of different renewable resources for power generation

The Herfindahl–Hirschman Index (HHI)—an index commonly used to quantify the diversity of investment portfolios, energy resources, and religious homogeneity—is used as a metric to measure the diversity of different renewable fuels consumed for power generation. An HHI value close to 1.0 indicates a higher concentration (less diversity), while a lower HHI close to 0.0 signifies a more diverse mix of renewable energy sources. The equation for the HHI is given by the following:

$$HHI = \sum_r s_r^2$$

Above,  $r$  enumerates each renewable resource considered by the index, and  $s$  is the share of annual renewable energy production from that resource.

The renewable resources included in this calculation are large hydro, small hydro, imported hydro, ground-mounted solar, rooftop solar, floating solar, coupled solar with energy storage, wind, municipal solid waste, industrial waste, wastewater digestion, biomass gasification, biogas, and BECCS.

### 2. Reduce electric sector costs

To assess the objective of reducing electric sector costs, the metric used is the average cost of electricity (ACOE). This metric is calculated nationally, averaged over all hours of each year:

$$ACOE = \frac{CC_{g,s,t} + FOM_{g,s,t} + VOM_{g,s,t} + fuel}{kWh}$$

In the preceding formula,  $CC$  represents the debt-servicing obligation, including financing and a portion of capital expenditure;  $FOM$  and  $VOM$  are fixed and variable operation and maintenance costs, respectively; and  $g,s,t$  indices delimit all generation, storage, and transmission assets. The term *fuel* refers to the total expenditure on fuel purchases, including electricity imports. The denominator  $kWh$  is the annual national electricity generation plus imports.

### 3. Reduce direct GHG emissions from energy sector

To measure the objective of reducing direct GHG emissions from the energy sector, the metric used is the total GHG emissions from electricity production, expressed in tonnes of CO<sub>2</sub>-equivalent, using 100-year Global Warming Potential (GWP) values. This metric is calculated nationally by aggregating the GHG emissions from all electricity production sources in each year.

### 4. Maintain or improve power system reliability

To assess the objective of maintaining or improving power system reliability, the metric used is the loss-of-load expectation (LOLE), calculated nationally. For its calculation, each generation technology in the model is assigned a forced outage rate (FOR), and a share of its capacity, which is deemed COPT or non-COPT, indicating which capacity will be used to generate a capacity outage probability table, or COPT. Since only aggregate capacity by technology is represented in the model, and not individual generating units, the number of separate units is estimated by SEI for technologies using an average unit size, before a COPT can be calculated in each year given a set of installed capacities for each technology.

Next, an adjusted electricity load value  $\widetilde{L}_{ts}$  (referred to as “discounted load” by EPPO) is calculated in each time slice from the following equation:

$$\widetilde{L}_{ts} = L_{ts} - \sum_n G_{n,ts} FOR_n - S_{ts}$$

Above,  $L$  is system load,  $G_n$  is electricity generation from each non-COPT technology indexed by  $n$ , and  $S$  is net energy stored (therefore  $S < 0$  when energy is released). Finally, the LOLE can be calculated in any year by summing over the time slices (indexed by  $ts$ , each with duration  $hours_{ts}$ ):

$$LOLE_y = \sum_{ts} P(\widetilde{L}_{ts} > C_{COPT}) hours_{ts}$$

$P(\widetilde{L}_{ts} > C_{COPT})$  is the probability that the adjusted load exceeds capacity, taken from the COPT.

### 5. Increase electricity generation from rooftop solar PV

To evaluate the objective of increasing electricity generation from rooftop solar PV, the metric used is the share of total electricity generation from rooftop solar PV technologies. This metric is calculated nationally by dividing the total electricity generation from rooftop solar PV by the total electricity generation from all resources in that year. The following is the formula for this calculation:

$$S_{rPV} = \frac{g_{rPV}}{\sum_i g_i}$$

Above,  $rPV$  denominates rooftop solar PV,  $i$  enumerates each generation resource, and  $g$  denotes the annual electricity production from that resource.

#### 6. Increase share of renewable electricity in electricity production

To evaluate the objective of increasing the share of renewables in total electricity production, the metric used is the proportion of electricity generation from renewable sources. This metric is calculated nationally by dividing the electricity generation from renewable sources by the total electricity generation in each year. The following formula is used:

$$S = \frac{\sum_r g_r}{\sum_i g_i}$$

Above,  $r$  enumerates each renewable resource (as listed for the HHI metric);  $i$  enumerates each generation resource; and  $g$  represents the annual electricity production from each resource.

#### Critical uncertainties

##### 1. Future prices of purchased fuels for power generation

A critical uncertainty in power generation planning is the future prices of purchased fuels, which can significantly impact cost projections and decision-making. To model this uncertainty, upper and lower limits were selected for the average annual growth rate (AAGR) of the mean price for each fuel. The future price of each fuel is then modeled using a mean-reverting stochastic process to introduce volatility. This method accounts for both the uncertainty in the AAGR and the year-to-year price fluctuations. For each fuel, all possible AAGRs between the defined limits (shown in Table 2) are considered with equal probability.

Table 2. Lower and upper limits for AAGR in fuel prices. Fuels not listed here were assumed to follow deterministic fuel cost trajectories in all scenarios.

Fuel or fuel type	AAGR lower limit	AAGR upper limit
Natural Gas	-2.4%	0.5%
Coal	-1.09%	-0.96%
Oil	-3.58%	1.11%
Biogas	-0.85%	1.85%
Gray Hydrogen	-2.4%	0.5%
Electricity Imports	-0.38%	0.94%

## 2. Capital costs of electricity generation technologies

The capital costs of electricity generation technologies also pose an important uncertainty for power generation planning, particularly as the systems transition toward newer and more sustainable technologies that haven't been on the market as long as traditional generation technologies. As technologies evolve, the capital costs could either decrease due to technological advancements and economies of scale or increase due to unforeseen materials scarcity or other geopolitical factors. To model this uncertainty, a linear interpolation method was implemented to project future capital costs. Starting from the current known capital cost, the model linearly interpolated between the lower and upper bounds of capital costs projected for 2050, assuming equal probability across this range. This approach allows for a gradual adjustment of capital costs over time until 2050, after which the costs are held constant.

*Table 3. Lower and upper boundaries for overnight capital costs. Technologies not listed here were assumed to follow deterministic capital cost trajectories in all scenarios.*

Selected technologies	Overnight capital cost (thousand USD/kW)		
	2022 Value	Lower Boundary for 2050	Upper Boundary for 2050
Large Hydro	6,314.0	6,236.8	8,261.7
Small Hydro	6,397.0	6,236.8	6,429.8
Imported Laos Hydro	3,872.0	3,738.6	6,236.8
Ground Mount PV	1,050.0	436.8	704.7
Rooftop PV	2,370.0	528.1	975.5
Floating PV	981.0	408.0	658.2
PV Storage Hybrid	1,711.0	572.2	1,000.4
Onshore Wind	1,255.0	484.9	830.5
Nuclear LWR	6,632.0	4,500.0	6,632.0
Nuclear SMR	6,011.0	4,086.1	6,022.0
Lithium Battery Small	993.0	486.9	993.3
Biomass BECCS	7,923.5	4,845.5	6,707.8

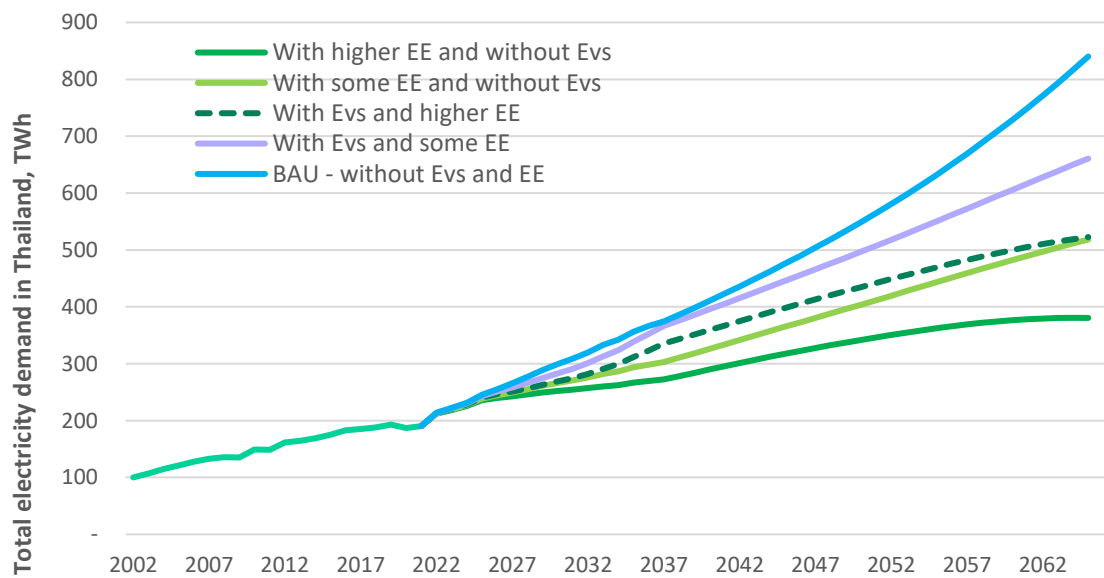
## 3. National electricity demand projections

Projections of future electricity demands are crucial for power system planning, influencing both the required capacity and energy needs of the system. These projections can be uncertain, as they are influenced by factors that introduce variability, including population, economic growth, levels of energy efficiency (EE) improvements, and the adoption of electric vehicles (EVs). To model this uncertainty, five distinct exogenous demand projections were considered, each reflecting different assumptions about baseline demand growth, the impact of vehicle electrification, and levels of EE savings. These exogenous demand projections, sourced from EPPO for the period 2022–2037, were extended beyond 2037 based on population projections, and trends in the final energy intensities (GWh/person). Table 4 and Figure 4 illustrate the five demand scenarios used to capture the range of possible future demands in the IRRP runs, along with the probability distribution used for the large scenario ensemble. The demand projection with the highest probability (40 percent) corresponds to the draft PDP demand projections.

Table 4. Demand scenarios used for Thailand's IRRP.

#	Demand scenarios	AAGR		Probability distribution
		2022–2037	2038–2065	
1	With higher EE and no EVs	1.6%	1.1%	10%
2	With some EE and no EVs	2.2%	1.8%	20%
3	With higher EE + EVs	2.9%	1.5%	40%
4	With some EE + EVs	3.4%	2.0%	20%
5	BAU - without EVs and EE	3.6%	2.8%	10%

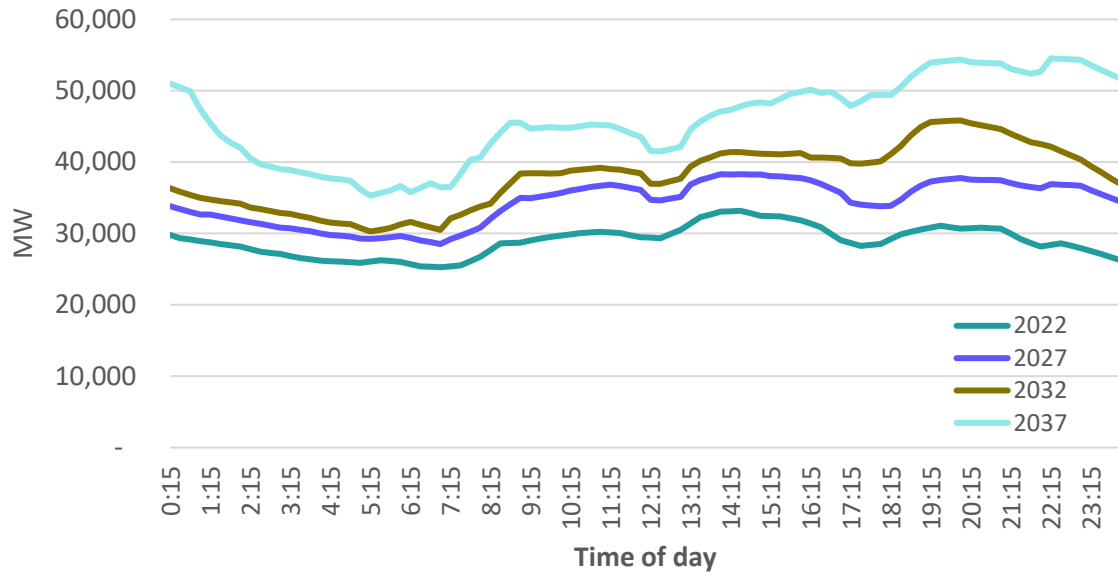
Figure 4. Electricity demand projections for Thailand.



#### 4. Electricity load profiles

This uncertainty relates to the variability in future annual and intra-day electricity consumption patterns, which can be influenced by end uses and behaviors. These load profiles are crucial for accurate power system planning, as they directly impact both the required capacity and the energy that the system must supply throughout the day. To address this uncertainty, the model incorporated a range of future annual load profiles sourced from EPPO’s draft PDP, spanning the period from 2022 to 2037. These projections consider alternative intra-day distributions of electricity demand, transitioning from a daytime peak in 2022 to a nighttime peak starting in 2028. For each scenario run in the IRRP, the load shape for 2037 is selected randomly from projected shapes for 2022, 2027, 2032, and 2037, with equal probability assigned to each. Load shapes for the years 2022–2036 are interpolated based on the historical 2021 load shape and the selected shape for 2037. After 2037, the applied load profile is assumed to remain constant.

Figure 5. Projected load profiles for Thailand.



#### 5. Availability of hydropower based on changes to rainfall

Climate change impacts, such as rising temperatures, extreme rainfall patterns, and increased frequency of severe weather events, can significantly alter the future seasonal availability of both domestic and imported hydropower resources. This uncertainty poses challenges for the power system planning, since the changing hydropower availability requires adjustments from non-hydro resources to meet energy demands throughout the year. To address this uncertainty, the model incorporates nine scenarios based on a study by the Mekong River Commission (Mekong River Commission for Sustainable Development 2018), which used water resource modeling to estimate the monthly impact of climate change on hydropower potential in the Lower Mekong Basin under various climate scenarios. These scenarios combine three Representative Concentration Pathways (RCPs)—RCP 2.6, RCP 4.5, and RCP 8.5—with three General Circulation Models (GCMs) representing a drier climate, a wetter climate, and increased seasonality. Each of these nine scenarios informs monthly correction factors applied to baseline availability curves for hydropower stations in Thailand, and those based geographically in Laos but serving the Thai grid. For the IRRP runs, probabilities for each RCP were informed by Huard et al. (2022), and were set at 8 percent for RCP 2.6, 58 percent for RCP 4.5, and 34 percent for RCP 8.5, while the probability of each GCM within an RCP is assumed to be equal. Figure 6 and Figure 7 illustrate the projected monthly availability factors for hydropower plants in Thailand and Laos under each of the nine scenarios, compared to baseline values.

Figure 6. Monthly hydropower availabilities for Thailand.

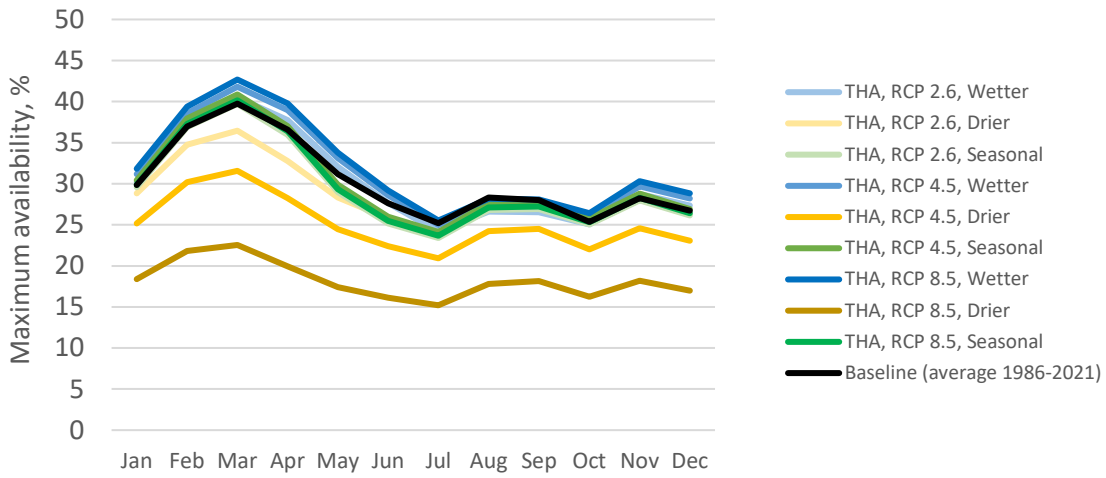
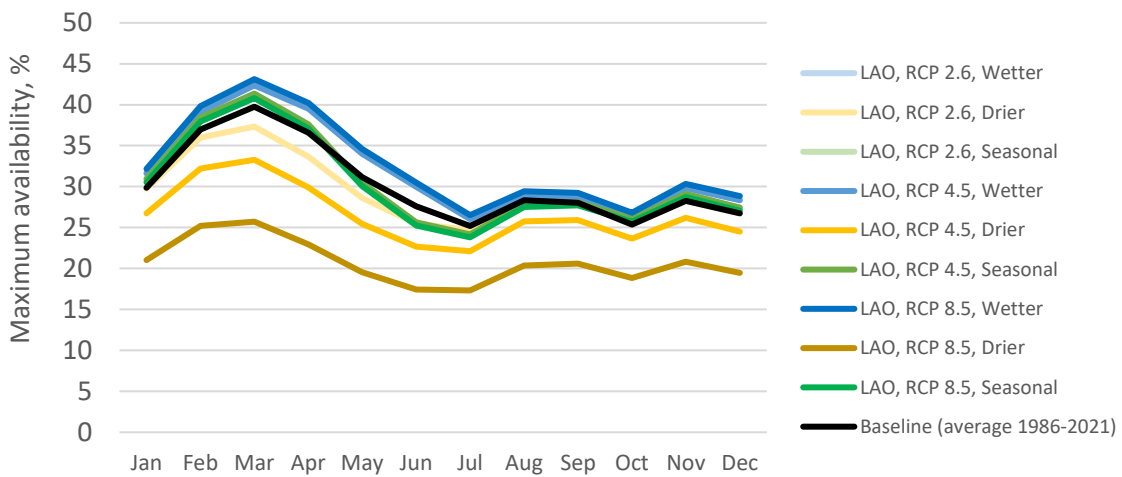


Figure 7. Monthly hydropower availabilities for Laos. These availability profiles are assigned to hydropower stations based geographically in Laos, but which export their electricity to Thailand.



### 6. Availability of transmission lines—based extreme weather events

Extreme weather events, and the resulting potential impairment of interregional transmission lines, pose a critical uncertainty for power system planning. Extreme weather can affect the availability of transmission and distribution lines, and with them, overall system reliability. To model this uncertainty, historical data on tropical cyclone occurrence (from the IBTRACS database [User Engagement and Services Branch 2010]) was used as a proxy for occurrences of extreme weather events. The database contains information about the frequency of tropical cyclones making landfall in each region of Thailand between 1950 and 2021, which reveals that the Northeastern region has been particularly vulnerable, experiencing on average two severe tropical storms and typhoons every ten years. This critical uncertainty therefore assumes that future extreme weather events will impact only the North-Northeast and Central-Northeast transmission lines, causing two randomized outage events every ten years. Based on narrative descriptions of observed impacts on infrastructure from similar events in other countries, SEI assumes that each outage completely

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disrupts one 300 MW conductor in a transmission line for three days (cumulatively), randomly selecting disrupted time slices from across the year.

## Identification of Low-Regrets Decisions

In an IRRP process, many individual scenarios are modeled for each planning case, sampling from the set of critical uncertainties introduced in the previous section. The distribution of model results, together with the planning metrics that quantify how well each objective is satisfied, is used to identify planning decisions that are “low-regrets”: that is, they are decisions likely to be made under most circumstances, they do not foreclose other decisions that may be made later and with new information, and they tend to correlate with model runs that yield desirable planning metrics. To capture how well each run performed using a single statistic (rather than six separate planning metrics), SEI calculates an “aggregate metric” by:

- a) expressing each metric as a normalized value between zero and one, where zero is assigned to the run with the poorest achievement of the planning objective, and one is assigned to the run with the best achievement of the objective, then
- b) calculating a weighted sum of the resulting normalized metrics, using the following weights (based on in-person feedback during the Technical Working Session in Hua Hin, Thailand, 11–13 May 2024):
  - a. 1/12 for the Herfindahl–Hirschman Index
  - b. 1/3 for the ACOE
  - c. 1/12 for the direct GHG emissions from electricity production in 2037, in CO<sub>2</sub>-equivalent
  - d. 1/3 for the LOLE
  - e. 1/12 for the share of total electricity generation from rooftop solar PV
  - f. 1/12 for the share of total electricity generation from all renewable resources

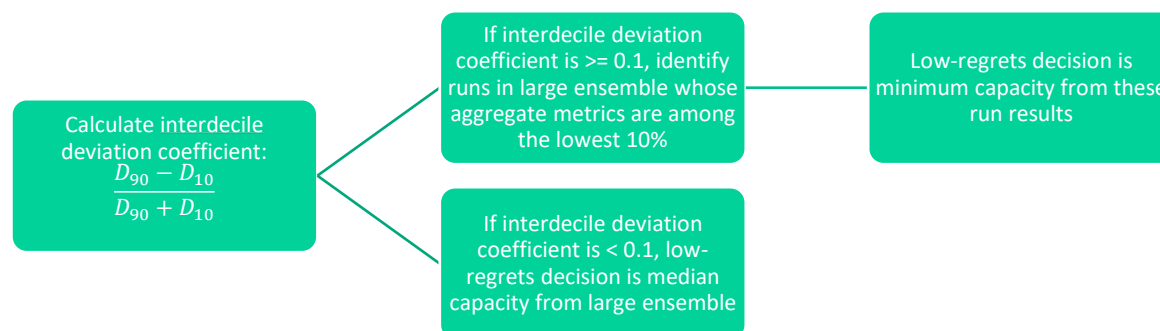
Having formed an aggregated metric that can be calculated for each year and each scenario, SEI adopts three principles to identify low-regrets decisions from the Thailand IRRP model:

1. **Look for similarities.** Where results from all runs are highly clustered together, the low-regrets decision should be drawn from that cluster.
2. **Plan for the worst.** Where results are more dispersed, the low-regrets decisions should anticipate values for uncertainties that lead to poor satisfaction of planning objectives (as measured by the aggregated metric described above).
3. **Don’t overcommit.** When “planning for the worst,” low-regrets decisions should not overcommit to a single technology because of a small number of outlier runs.

The full set of planning decisions, from which low-regrets decisions may be drawn, includes the capacity of each generation or storage technology, in each region and each year, as well as the capacity of transmission lines connecting each pair of regions. With 28 generation and storage technologies, ten calculated years through 2065 (every five, plus 2037), and five pairs of connected regions, a total of 1,450 individual planning decisions must be made. For each individual planning

decision, SEI followed the process diagram shown in Figure 8, which codifies the principles above, to identify a low-regrets decision (if it exists<sup>2</sup>).

Figure 8: Quantitative process for identifying low-regrets decisions. The process refers to an interdecile deviation coefficient, which is an expression of the dispersion of a data set. Its calculation involves the first ( $D_{10}$ ) and ninth ( $D_{90}$ ) deciles from the ensemble results for each planning decision.



## Results from Large Ensemble Analysis

This section includes a sampling of results derived from the large ensemble runs for Planning Case 1. The full set of results, with the full set of results for Planning Case 2, is included as Appendix 2 of this report.

For Planning Case 1, the large ensemble consists of 228 model runs, each with an average runtime of 22.4 minutes. The large ensemble of Planning Case 2 includes 233 runs, each with an average runtime of 21.9 minutes. The number of runs for each case was largely determined by the available server time that SEI could devote to the computations, and a qualitative judgment that subsequent runs appear to show diminishing returns—meaning that they were not adding substantially to the diversity of the results obtained.

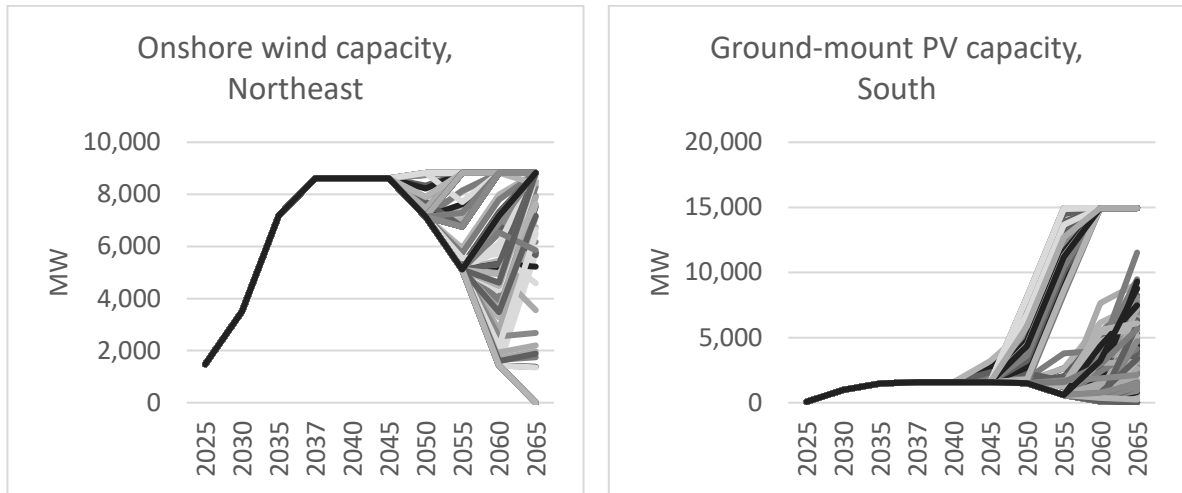
### Planning Decisions and Metrics

Full results for all planning decisions, all model runs, and both planning cases are provided as Appendix 2. Results for selected planning decisions (onshore wind in the Northeast region, and ground-mount solar in the South region) are shown below for Planning Case 1.

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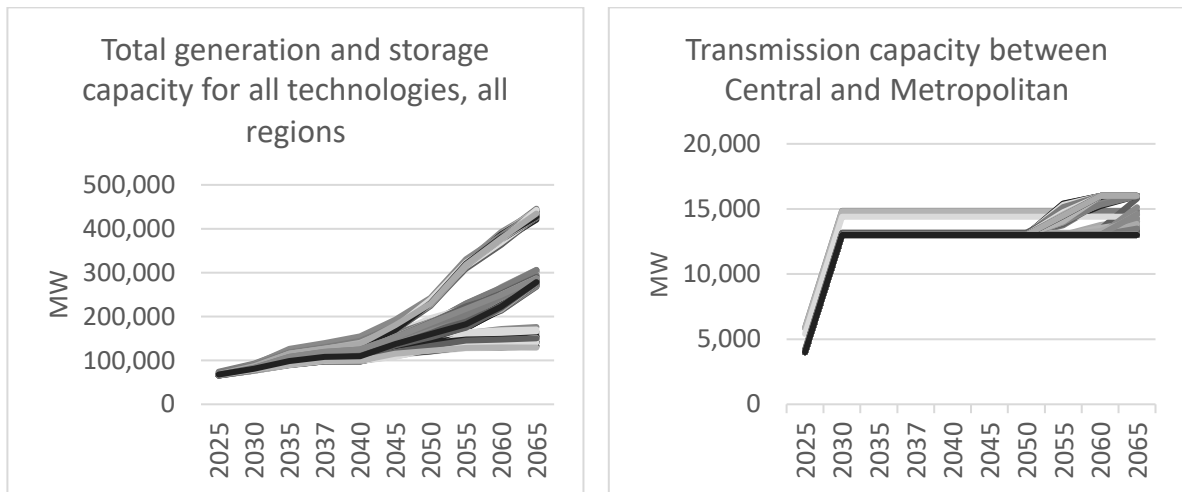
<sup>2</sup> It is possible that in some modeled years, in some regions, and for some capacity types, no capacity is added in any of the individual runs. In these cases, SEI does not identify a specific low-regrets decision. One could equivalently conclude that a low-regrets capacity recommendation could be “at least zero megawatts,” but SEI does not highlight such recommendations.

Figure 9: Example planning decisions for two technologies. Each line represents an individual model run in the Planning Case 1 ensemble.



Total generation and storage capacity across all regions and for all technologies is shown below (left), with a sample of transmission capacity results connecting the Central and Metropolitan region (right).

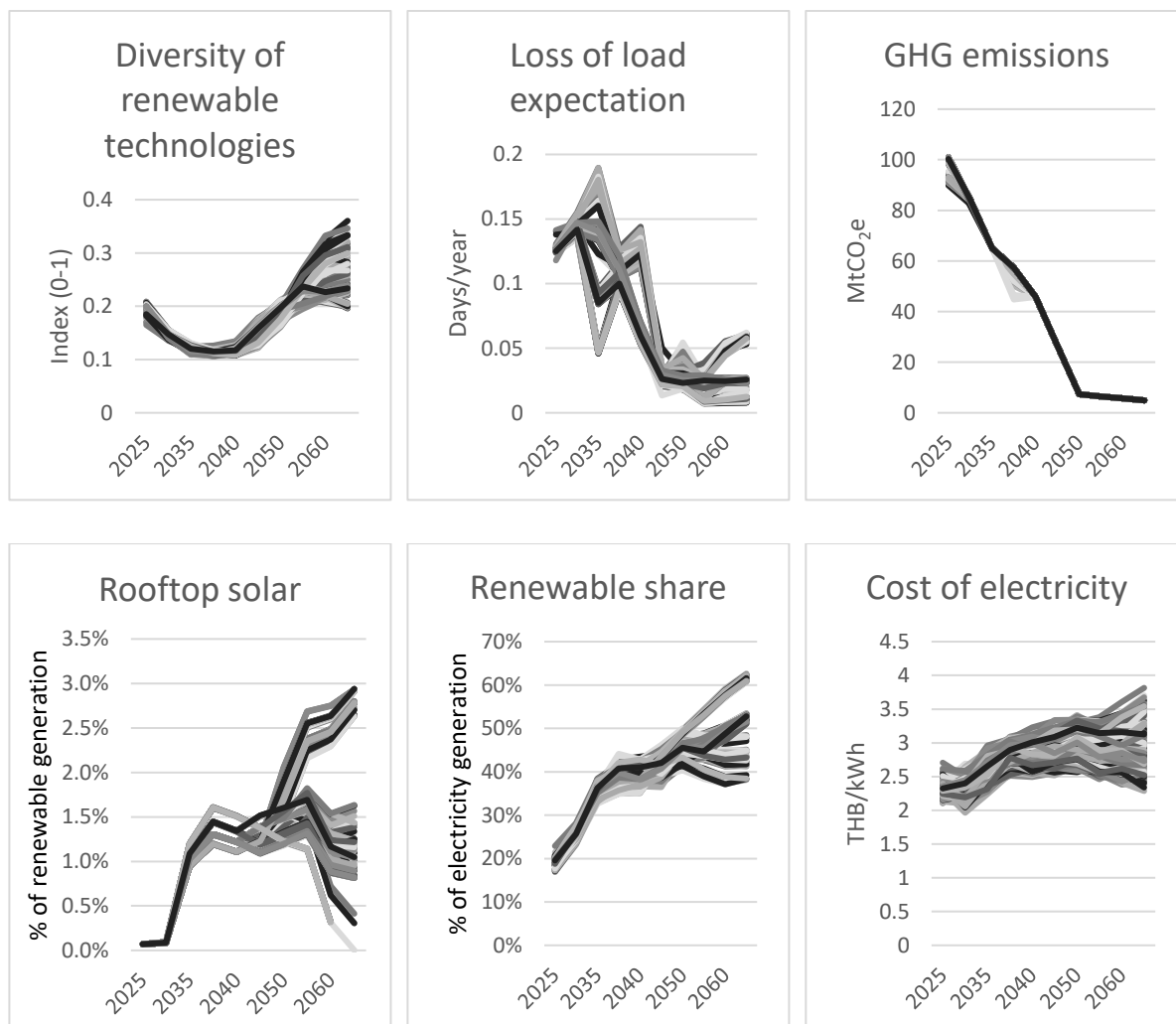
Figure 10: Example planning decisions. Each line represents an individual model run in the Planning Case 1 ensemble.



The results in Figure 9 and Figure 10 convey the breadth of the results found in the large ensemble analysis. For some planning decisions, results are highly dispersed, while for others, they tend to be much more concentrated during most years. In some cases, the charts also reveal clustering around two or more modes. It is important to note that many of the decisions are bounded by model inputs: from below, due to specific existing or planned capacity that is not retired, and also from above, due to maximum resource potentials or other capacity limits. Some of the planning decisions reveal a wide range of different outcomes, but by far the largest predictor of installed capacity in each run comes from the electricity demand uncertainty. This is shown most clearly in Figure 10, where the total capacity shows a trimodal distribution, with trajectories that are not unlike the different realizations of the electricity demand uncertainty shown in Figure 4.

In addition to the planning decisions, the six planning metrics can be evaluated for all modeled years of each run. These reveal both trends over time in how well each planning objective is satisfied, and diversity among runs in the large ensemble.

Figure 11: Planning metrics for all runs conducted under Planning Case 1.



### Low-Regrets Decisions

Applying the method described in Figure 8, SEI analyzed the set of modeled planning decisions to arrive at low-regrets decisions. Since the full set of low-regrets decisions can include up to 1,450 separate capacity recommendations, the full set is included in table format as Appendix 3. A brief graphical overview is presented here for groups of similar technologies, and for two important years in the planning horizon: 2037, corresponding to the final year of Thailand’s most recent PDP, and 2065, the final year for each scenario.

Figure 12: Low-regrets capacity for years 2037 and 2065 under Planning Case 1. The full set of technologies represented in the model has been aggregated to improve the chart's legibility.

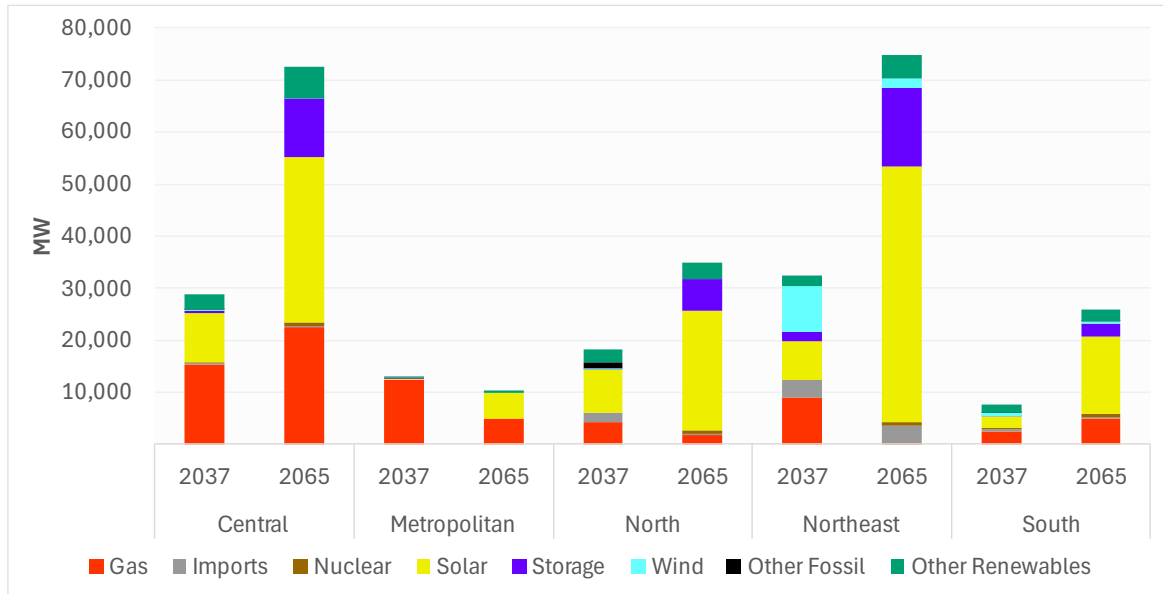


Figure 13: Low-regrets capacity for years 2037 and 2065 under Planning Case 2. The full set of technologies represented in the model has been aggregated to improve the chart's legibility.

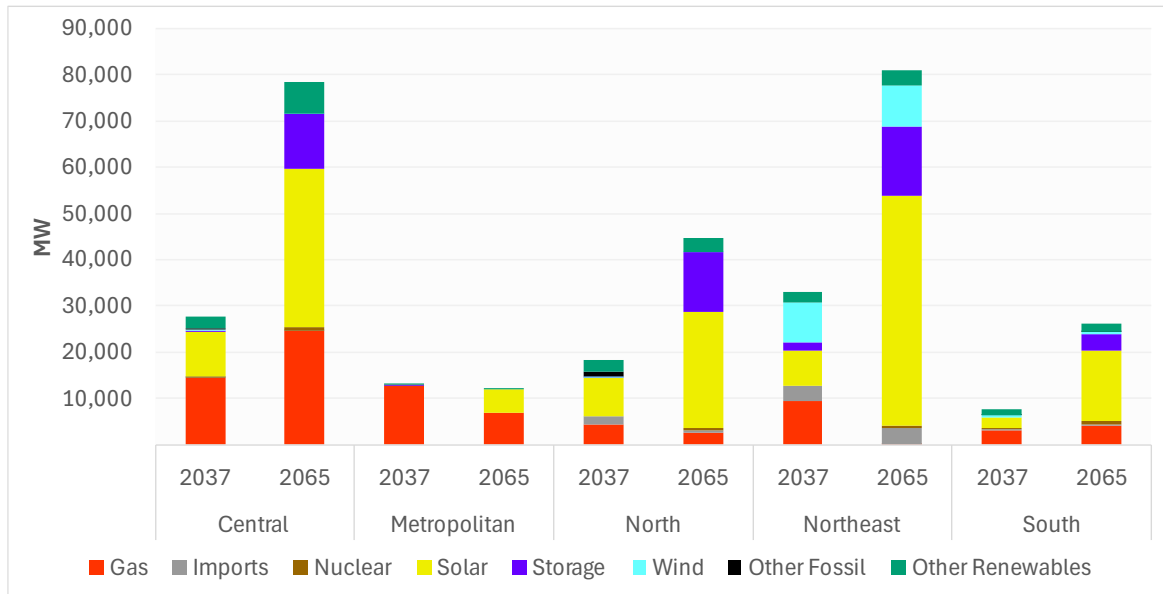


Figure 12 and Figure 13 illustrate the extensive capacity investment that would be recommended by the low-regrets decisions, particularly for solar and energy storage technologies. Wind is less attractive, with low-regrets wind capacity found almost entirely in the Northeast region, where the wind resource is marginally better than other regions. Natural gas capacity (partially blended with hydrogen after 2030) is included in the low-regrets decisions, but there is little or no use of other fossil-fueled technologies. Looking in more detail, the four technologies with the largest low-regrets capacities in each region are shown below in Table 5.

Table 5: Low-regrets capacity for key generation and storage technologies in each region, for year 2065.

Low-regrets capacity [MW]		Planning Case 1	Planning Case 2
Central	Floating PV	20,150	20,150
	Ground Mount PV	8,843	12,028
	Natural Gas	22,588	24,675
	Lithium Battery	11,196	11,509
South	Floating PV	11,050	11,050
	Ground Mount PV	1,256	2,729
	Natural Gas	4,962	4,054
	Pumped Storage Hydro	1,981	2,770
North	Floating PV	7,800	7,800
	Ground Mount PV	12,382	15,176
	Pumped Storage Hydro	115	4,047
	Lithium Battery	5,927	8,842
Northeast	Floating PV	25,350	25,350
	Ground Mount PV	23,330	23,249
	Onshore Wind	1,875	8,824
	Lithium Battery	12,386	13,236
Metropolitan	Rooftop PV	3,200	3,200
	Ground Mount PV	1,869	1,869
	Natural Gas	4,934	6,983
	Industrial Waste and MSW	249	249

While Planning Case 1 and 2 are broadly similar, low-regrets wind capacity under Planning Case 2 is slightly higher than Planning Case 1, notably for wind, natural gas, and energy storage. While this does not mean that installed capacities are higher under Planning Case 2 (in fact, installed capacities found in individual runs under Planning Case 2 tend to be smaller than under Planning Case 1), it does reflect a higher degree of consensus among runs, and translating into higher low-regrets capacity recommendations.

Low-regrets transmission capacities are given in

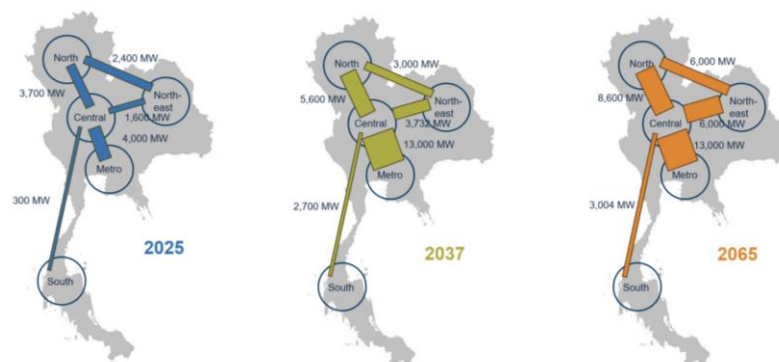
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Figure 14 and Figure 15 below. Low-regrets capacities in each of the planning cases are similar, reflecting the fact that important transmission corridors (such as that connecting the Central and Metropolitan regions) are reaching their maximum allowed capacities in all, or nearly all, model runs.

Figure 14: Low-regrets transmission capacity for years 2025, 2037, and 2065 under Planning Case 1.



Figure 15: Low-regrets transmission capacity for years 2025, 2037, and 2065 under Planning Case 2.



## Conclusions and Policy Lessons for Thailand

This IRRP analysis is intended to help Thailand navigate investments in electricity generation, storage, and transmission in a way that avoids poor outcomes, outcomes in which planning objectives are not well satisfied, and outcomes that are “locked in” due to decisions around long-lived infrastructure choices. Rather than promoting a set of optimal planning decisions, IRRP recognizes that different decisions perform differently across a range of metrics, and they respond differently to a range of future uncertainties; it seeks “good-enough” decisions that assume an uncertain future, rather than perfect decisions anticipating a deterministic future.

It is important not to misinterpret low-regrets recommendations as a recipe for a complete set of capacities that would satisfy the country’s full electricity needs in the future. Instead, they represent the outcomes of a process that searches for similarities and selects either the median or minimum capacities (see Figure 8) from an ensemble of model runs; in this sense, they are more akin to minimum capacity recommendations, recognizing that additional capacity will be required as future conditions change and come into focus.

An interesting feature of the planning metrics shown in Figure 11 is that there are no clear anticorrelations among how well planning objectives are satisfied. A correlation analysis shows that runs that tend to yield “good” values for one planning metric (where “good” may be either high or low, depending on the planning objective) also yield “good” values for other planning metrics. In

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other words, among the planning objectives considered in this IRRP, there are no clear trade-offs that would force planners to decide to improve one objective while worsening another.

## Application to Thailand's PDP Process

Thailand's current (2022–2024) PDP process has unfolded in parallel, but mostly independently, from the IRRP analysis, as EPPO is the lead agency responsible for revising the PDP, without direct input from Mekong Safeguards and SEI. However, there are connections between the processes. For example, at multiple occasions the electricity model that serves as the basis for IRRP was used to explore draft PDP scenarios and feed information back to EPPO, based on input assumptions carefully selected to align with PDP cases. In addition, the previous PDP (revision 1, from 2018) was used as a source of input assumptions for the IRRP model, with the 2022 Alternative Energy Development Plan (AEDP) providing specific planned capacity expansion for renewable technologies. As the PDP and IRRP analyses have mostly kept pace with one another, the IRRP model provided input for EPPO to consider incorporating in the draft PDP. In June 2024, EPPO released a public draft of Thailand's upcoming PDP, and is currently revising the PDP based on public feedback, allowing EPPO to consider the final IRRP results in the revision. There are several recommendations that can be drawn from this analysis that can have a bearing on Thailand's upcoming PDP, or the country's power planning processes generally:

- a) Thailand's IRRP analysis reveals that significant amounts of new solar capacity are considered low-regrets, with large amounts of either ground-mount, floating, or rooftop PV (or some of each) recommended for each region except Metropolitan. Balancing the daily variation in electricity production that would arise, the IRRP analysis further recommends large amounts of energy storage (battery or pumped hydropower). These recommendations hold for all regions, with additional low-regrets transmission capacity recommended for most pairs of connected regions—and in particular between the Metropolitan and Central regions. In fact, between these regions the low-regrets capacity is equal to the maximum capacity allowed by the model, implying that planners should consider evaluating scenarios with even higher levels of regional interconnection under consideration.
- b) Another notable feature of the low-regrets decisions is the amount of natural gas-fired capacity that would continue to exist even in 2065, even under Planning Case 1, where Thailand achieves net-zero GHG emissions. While counterintuitive, it is important to remember that all planning cases assume 20 percent by volume of hydrogen co-fired with natural gas by 2036, and that negative-emission technologies would balance the remainder of the power sector's emissions: the low-regrets capacity recommendation for BECCS is between 3.6 GW and 4.6 GW by 2065, depending on planning case.
- c) In Planning Case 1, the IRRP analysis describes a set of low-regrets installed capacities for the year 2037 (the PDP end year) *and beyond*, consistent with achieving the country's long-term GHG targets in 2050 and 2065. These could be compared to the PDP's planned capacity in 2037 to compare planned capacity with low-regrets capacity, to confirm whether capacity projected in the PDP in harmony with the country's long-term GHG goals, or potentially used as the basis for another PDP scenario.
- d) Examination of the full set of planning decisions across each large ensemble of results shows that some technologies have very similar installed capacities during the first half (or more) of the scenario period, aligning roughly with the PDP time period.

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Examples of this are seen for wind and solar capacity in Figure 9, which do not tend to diverge among model runs until 2040 or later. This is largely due to the model's exogenously specified capacity assumptions through 2037 from the AEDP and 2018 PDP, which are large enough that little additional capacity is needed until later. This itself is revealing, and it suggests that more capacity is planned than might be needed.

- e) As noted previously, the most impactful planning uncertainty in the IRRP analysis was the electricity demand forecast. A lesson from this analysis is that the PDP would do well to consider at least a variety of electricity demand scenarios, and to adopt as planning recommendations the resulting minimum capacities of each major technology found among these scenarios.
- f) Under Planning Case 1, a small amount of BECCS capacity is considered low-regrets as early as 2030. While the IRRP process did not consider it, the future scalability and availability of BECCS is still unknown—and yet all runs, regardless of planning case, include some BECCS capacity in 2037. Power planners in Thailand should consider contingency plans, such as further reducing the role of fossil natural gas or looking to other carbon dioxide-removal technologies, in case BECCS is not available as envisioned in the model.

SEI and the Mekong Safeguards Program presented the IRRP results to EPPO, EGAT, and members of the stakeholder community on 13 May 2024 in Bangkok during the project's Integrated Resource and Resilience Planning Pathways Workshop. Through a facilitated discussion, SEI heard from EPPO that the most directly applicable part of the IRRP analysis to Thailand's power planning processes is the Thailand model itself, which EPPO staff viewed as an important tool for contributing to their core energy modeling and forecasting capabilities. EPPO staff have demonstrated a clear interest in continuing to use the model, to develop new scenarios, and to expand its capabilities, and SEI will continue to provide all possible support during this process.

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# Appendices

## Appendix 1

The attached LEAP file “*thailand irrp\_1\_40.leap*” is the latest version of the Thailand IRRP model at the time of writing, although SEI anticipates further collaborative work on the model together with EPPO staff. It is attached here as a source of data sources and modeling assumptions, all of which are documented within the model itself.

## Appendix 2

The attached Excel files “*appendix\_2\_irrp\_analysis\_pc1.xlsx*” and “*appendix\_2\_irrp\_analysis\_pc2.xlsx*” contain the full set of modeled planning decisions (see worksheets *Transmission Data* and *Generation & Storage Data*) for Planning Case 1 and 2, respectively. They also contain a set of spreadsheet tools developed by SEI to organize and explore the large ensemble of results.

## Appendix 3

The attached Excel file “*appendix\_3\_low\_regrets\_decisions.xlsx*” contains the full set of low-regrets decisions identified by SEI for both planning cases. It contains six worksheets:

- *Introduction*: The set of weights used to determine the aggregate planning metrics that were used for identification of low-regrets decisions.
- *PC1 Gen & Storage*: Low-regrets capacity recommendations for electricity generation and storage technologies in each region and modeled year, taken from Planning Case 1.
- *PC1 Transmission*: Low-regrets capacity recommendations for electricity transmission lines connecting each pair of Thailand’s planning regions, taken from Planning Case 1.
- *PC2 Gen & Storage*: Low-regrets capacity recommendations for electricity generation and storage technologies in each region and modeled year, taken from Planning Case 2.
- *PC2 Transmission*: Low-regrets capacity recommendations for electricity transmission lines connecting each pair of Thailand’s planning regions, taken from Planning Case 2.

*Reporting Categories*: Categories used to aggregate technologies for display in

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- Figure 12 and Figure 13.

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