Considering Adaptive Power System Planning for Indonesia in the Face of Climate Uncertainties

Hariadi Aji
Faculty of Technology, Policy, Management
Delft University of Technology
PT PLN (Persero)
Jakarta, Indonesia
hariadi.aji@pln.co.id

Nihit Goyal
Faculty of Technology, Policy, Management
Delft University of Technology
Delft, Netherland
nihit.goyal@tudelft.nl

Stefan Pfenninger
Faculty of Technology, Policy, Management
Delft University of Technology
Delft, Netherland
s.pfenninger@tudelft.nl

Igor Nikolic
Faculty of Technology, Policy, Management
Delft University of Technology
Delft, Netherland
i.nikolic@tudelft.nl

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***Abstract*—Climate change impacts the power system globally. It also creates a challenge for Indonesia's energy transition, which aims for net-zero emissions by 2060. Aside from decarbonization efforts, planning for this transition adds a challenge due to the deeply uncertain nature of climate change. This refers to a condition where planners cannot agree on models, probabilities, or even which variables to prioritize. That degree of climate uncertainty has not yet been addressed in Indonesia's current power systems planning approach. Failure to address these uncertainties could bring significant vulnerabilities to Indonesia's future power system. Furthermore, only a small number of studies on power systems planning in Indonesia have addressed these climate uncertainties, and even then, only in a limited way. This paper offers a conceptual recommendation of an adaptive planning approach as one potential method to address these uncertainties. The approach is based on Dynamic Adaptive Pathways Planning (DAPP), which comes from the decision-making under deep uncertainty (DMDU) taxonomy. It supports planners in exploring a range of possible futures, considering policies and uncertainties, and enabling more robust decision-making.**

Keywords—climate change, power system planning, energy transition, adaptive planning, deep uncertainty, Indonesia

I. Introduction

Indonesia has an emerging economy that is expected to continue growing, driving energy demand and infrastructure development in the power sector. In 2023, the fuel mix of power generation consisted of 67% coal, 20% natural gas, and oil [1]. The dominance of fossil fuels will continue to contribute to carbon emissions, peaking around 2038 [2]. The projected rise in carbon emissions over the next few years poses a challenge to achieving the government's Net Zero target by 2060 [3].

To plan for decarbonization, Indonesia has recently developed national long-term plans, named RUKN [2] and RUPTL [4], outlining a roadmap for power infrastructure development. Moreover, in those plans, the concept of "supergrid" is introduced as an enabler for renewable energy access and could be one of the cost-effective options [5].

Designing these plans involves several challenges, particularly in accounting for climate uncertainties. Key uncertainties, such as the variability of renewable energy sources and the impacts of climate change, are expected to influence power system planning and operation [6].

However, the implications of climate-related uncertainties are not clearly explored in the mentioned plan. While the plan optimizes a clear decarbonization goal, they do not address how climate impacts and uncertainties might affect Indonesia's long-term power system development.

Furthermore, while much research discusses Indonesia's power system planning, only limited studies explore the climate uncertainties. Given these gaps, this paper introduces the concept of adaptive planning that could address the uncertainties. The approach is based on the Dynamic Adaptive Pathways Planning (DAPP) approach [7], which falls under the Decision Making under Deep Uncertainties (DMDU) taxonomy [8]. It is well-established in the water sector planning [9] and is an emerging approach in energy system planning [10], [11].

This paper is structured as follows: Section II explores climate uncertainties in the power system globally and in Indonesia. Then, section III focuses on Indonesia's policies and long-term planning research. Finally, an introduction to adaptive power system planning and an outline of its proposed application in Indonesia are presented in Section IV.

II. Climate Uncertainties in the Power System and the Context of Indonesia

A. Climate Change Uncertainties in the Power Systems

This subsection provides a general overview of climate impacts on the power system and their associated uncertainties. The uncertainties in power systems can arise from many sources, including geopolitical, political, technological, and social. However, the mentioned sources could directly affect two main types: technical and economic uncertainties [6]. Technical uncertainties involve operational model limitations, climate-related factors, and the intermittency of renewable energy sources. Economic uncertainties include factors such as fluctuations in fuel prices and financing challenges. Among these, climate uncertainty critically influences the power system's technical and economic aspects in the short and long term [12].

As a major driver of uncertainty, climate change impacts the performance of power systems [13]. Some climate impacts stress system components by reducing their performance without causing disconnection. For example, rising ambient temperature will impact power system elements such as generation, transmission, and distribution at the design and operation stages (see Table I [14], [15], [16], [17], [18]). The increasing temperature can cause transmission and generation efficiency to decrease [19], [20]. It can also increase the load demand simultaneously, thus reducing the system's reserve, which impairs the system's resilience [21].

Another type of climate impact involves shocks that lead to service disconnections. These typically result from damaging events. Such as sea level rise, flooding, landslides, and particularly extreme weather conditions [17], [22].

B. Climate Change Impact on Indonesia's Power System

Particularly in Indonesia, an archipelagic country with a unique geography, climate change is one important driver already affecting power system planning [23]. In Indonesia, high temperature anomalies have already been observed [24]

TABLE I. TEMPERATURE AND SEA LEVEL RISE IMPACTS ON POWER SYSTEM ELEMENTS

< = decrease | << = significant decrease
> = increase | >> = significant increase

Type	Tech-nology	Temperature Rise	Sea Level Rise (SLR) induced flooding
Generation	Coal	< turbine efficiency, boiler, shutdown because of high water-cooling temp < effectiveness of plant	Power failure, > demand for water drainage pump, and desalination of water
	Gas Turbine / Combined-Cycle	< turbine efficiency, boiler, shutdown because of high water-cooling temp < effectiveness of plant	Affects coastal oil and gas assets
	Nuclear	<efficiency	Power failure
	Biomass	<> Biomass production: water supply, growing season, crop disease	
	Hydro	change in runoff (glacier melt, >evaporation)	
	Solar Panel / PV	< efficiency, panel aging	
	Wind Turbines		Risks to Wind Turbine structures
Transmission	Tower	<< grounding efficiency	Power failure
	Line	overload, << capacity, >> losses	
Load	Trans-formers	overload, << capacity, burnt-out, seal damage	Power failure
	Demand	> load	

and are projected to increase further [25]. These rising temperature stresses affect power system operations by increasing demand and reducing generation output [26].

Indonesia is vulnerable to a range of climate-related shocks and hazards [27], [28]. Furthermore, Indonesia's power system has already experienced those vulnerabilities, such as flooding, sea level rise, and landslides [26]. Sea level rise makes coastal gas and coal power plants more vulnerable to flooding [29]. Landslides have been reported to cause the collapse of transmission towers in certain regions [30]. These examples show that Indonesia's power system is already exposed to climate risks despite uncertainties in the hazards.

To conclude, although Indonesia has a plan to decarbonize, the temperature and sea level rise depend on global mitigation efforts beyond Indonesia's control. In addition, the extreme weather could happen at an unknown time. These climate uncertainties pose significant risks to long-term power system development. Therefore, it is important to account for climate uncertainties in the plan.

III. INDONESIA'S POWER SYSTEM PLANNING IN THE FACE OF UNCERTAINTIES

A. *Limited Attention to Climate Uncertainties in Policy and Planning Documents*

In relation to power planning, Indonesia has had a main energy policy since 2006, called the National Energy Policy or *Kebijakan Energi Nasional* (KEN) [31]. In addition, Law No. 30/2009 on Electricity mandates the development of the General Electricity Plan (RUKN), which is issued by the Ministry of Energy and Mineral Resources (MEMR/ESDM) [32]. The RUKN outlines electricity capacity expansion targets through 2060 [2]. MEMR also issued Ministerial Regulation No. 11/2021 [33] to guide shorter-term planning. It requires electricity business license holders, including Indonesia's utility PLN, to prepare a 10-year electricity supply plan (RUPTL) [4] based on the RUKN.

RUKN was recently published in December 2024. In addition, the ministerial regulation No. 10 / 2025, published in April 2025, explains the energy transition roadmap in the power sector based on the RUKN [34]. The RUKN and the roadmap highlight the planned power generation capacity and emission targets, along with projected fuel mix composition until 2060. The main strategies include: limiting coal-power plant development; planning for its phase down; promoting nuclear power plants; supporting green hydrogen and ammonia production; and developing a supergrid.

Then, to emphasize the plan in detail, the most recent RUPTL 2025-2034 has just been published in May 2025 [4]. The RUPTL serves as a key reference for electricity business license holders in planning and investment. It provides a complete list of upcoming power generation, transmission, and distribution projects that would be a basis for procurement. Designing these plans requires intensive coordination, effort, and extensive simulation work.

In the face of the optimization process, both documents assume that scenario conditions remain constant throughout the entire planning horizon. This is reflected in the use of a simplified single or two optimized scenarios that exist in the plan. It could be said that the plans consider basic scenarios in a static manner. In reality, structural midway shifts can emerge midway, demanding greater flexibility.

However, facing the uncertainties of long-term planning, an effective plan should consider uncertainties [23]. The RUKN and RUPTL have addressed demand uncertainty by addressing several demand projections based on different economic growth assumptions. The RUPTL optimization considers two scenarios: Renewable Energy (RE) base and Accelerated Renewable Energy Development (ARED) scenarios, making a difference in the composition of renewables targeted. That shows both documents suggest a basic recognition of uncertainty. However, again, climate-based uncertainties have not been explicitly addressed to support this long-term energy transition plan.

In relation to climate change and its related uncertainties, existing policy the planning documents in Indonesia only have limited incorporation. The KEN outlines principles of energy management and a general policy toward renewable energy development. However, it does not address climate uncertainties explicitly. Meanwhile, both the RUKN and RUPTL clearly aim for the 2060 net-zero-emissions target, which is a good start in acknowledging climate change. Yet, the documents show limited consideration of the climate uncertainties in the planning process.

The mentioned documents have not yet integrated climate-related operational uncertainties, such as extreme temperatures or weather disruptions, into their modeling frameworks. These factors can significantly influence system performance and affect core indicators like reserve margin, a key constraint in supply optimization.

In conclusion, the current planning documents open space for research into more adaptive, flexible, and robust planning methods to better handle uncertainty and support long-term decision-making in the power system.

B. *Limited Research on Climate Uncertainty*

Several published studies have analyzed Indonesia's power system planning using modeling approaches to examine long-term developments. We searched for these studies on Scopus with the query: (TITLE-ABS-KEY (indonesia) AND TITLE-ABS-KEY ("power sector" OR

TABLE II. RECENT LONG-TERM PLANNING STUDIES FOR INDONESIA

References	Scope	Objective
Handayani, 2019 [36]	2015-2050 @5 / Java-Bali	Analyze the technological learning of renewable energy's effect on total cost in five scenarios using LEAP.
Handayani, 2022 [37]	2020-2050 / Indonesia, ASEAN	Analyze three scenarios to decarbonize Southeast Asia countries in terms of emissions and costs. LEAP used to highlight renewables and energy storage.
Reyseliani, 2022 [38]	2020-2050 @5 / Indonesia	Analyze Indonesia's system cost and emissions in energy transition strategies to 2050 with three scenarios using TIMES.
Yudiartono, 2023 [39]	2025, 2050 / Indonesia	Evaluate optimal energy mix and emissions in two scenarios: Business as Usual, and Energy Transition using LEAP.
Silalahi, 2023 [40]	2030-2060 @10 /Indonesia	Analyze the usage of 100% renewables and system cost of inter-island transmission in Indonesia using FIRM.
Rahmanta, 2023 [41]	2023-2060 /Indonesia	Analyze the opportunities of nuclear power plants to support net-zero and the effect on emissions and costs using LEAP.
Paiboonsin, 2024 [42]	2030-2070 @20 /Indonesia	Analyze and compare costs, power generation, capacity, and emissions in six scenarios with different energy–fossil fuel composition using OSeMOSYS.
Amiruddin, 2024 [43]	2030-2045 /Indonesia	Analyze Indonesia's 100% renewable energy in three scenarios, focusing on energy storage system configurations affecting cost using PLEXOS.
Hersaputri, 2024 [44]	2015-2050 /Indonesia	Analyze seven decarbonization scenarios, including Coal Phase Out, Carbon Tax, JETP and NDC using OSeMOSYS.
Langer, 2024 [45]	2030-2050 @10 /Indonesia	Analyze the impact of inter-island interconnection on costs and emissions to support 100% renewables, using seven scenarios, using CALLIOPE.
Reyseliani, 2024 [46]	2030-2060 @10 /Indonesia	Compare the costs of three scenarios based on the Coal Power Plant phasing out strategies using TIMES.

"electricity sector" OR electri*) AND TITLE-ABS-KEY (planning OR policy OR roadmap OR pathway* OR scenario*) AND TITLE-ABS-KEY (climate OR "energy transition" OR decarbonization)). From that initial selection, we limit the scope to studies from 2019 until 2024, to studies with the subject area of "Energy," and only include articles and journals. Then we screened the abstracts to include only those that did optimization modeling for Indonesia on the long-term national scale planning, and we did a snowball search.

Table II presents 11 studies from the prior article search strategy. The articles explore long-term planning for decarbonization, focusing on pathways to net-zero emissions. They align with the Paris Agreement's goal by supporting climate change mitigation through emissions reductions and a transition to renewable energy [35].

In relation to climate, most studies focus on long-term plans, reflecting earlier national targets for achieving Net Zero emissions to address climate change. Furthermore, most of the studies seek to determine the relationship between emissions, abatement costs, and total costs with different renewable energy sources using energy system modeling. However, among the resulting articles, the explanation of climate uncertainties has not been rigorously discussed.

To conclude, currently, either policy planning documents or academic research in Indonesia has limited exploration of climate uncertainties. However, given the wide range of uncertainties Indonesia faces, there is a clear need for more uncertainty-aware approaches to power system planning and studies. It will be the focus of the next section.

IV. PROPOSAL FOR AN ADAPTIVE PLANNING APPROACH

Following the previous review, this section proposes a planning approach to address climate uncertainty in the power system. It begins by understanding deep uncertainty, outlining key methodology, and then details the proposed approach.

A. Introduction of Deep Uncertainty

Climate-related uncertainties fall under what is known as deep uncertainty. Deep uncertainty arises when the stakeholders of the problem not only cannot agree on the probabilities used, but also when they cannot agree on an appropriate course of action [47]. That often happens because the problem itself is highly wicked in nature [48]. Uncertainties in public policy can be categorized into different levels [49]. The most certain level is level 1, "clear certainty," while the opposite is level 5, "total unknown". Between those two, there are three recognized levels of uncertainty. Level 2 includes defined alternatives with probabilities, level 3 features ranked scenarios without precise probabilities, and level 4 involves numerous plausible futures.

Deep uncertainties correspond particularly to level 4 and level 5 uncertainties. Those are situations where multiple plausible futures exist without an evident ability to assign probabilities [49]. Since climate change and mitigation actions manifest over long-term horizons with many uncertain assumptions and conditions, these uncertainties heavily influence future conditions for power systems. As a result, the impacts of climate change on power systems are also subject to deep uncertainty.

B. Shifting the Planning Paradigm: Core Requirements and Overview of Adaptive Planning

Planning the future power system in the context of deep-uncertain climate change is difficult. Due to the level of uncertainty, the climate, such as temperature and sea level, may significantly deviate from historical patterns. To address this, the usage of future climate models provides many scenarios that will complicate the plan. With the deep uncertainty of the climate, a basic plan will break down. This could happen because too many uncertainties lead to too many futures and conditions. The basic plan that never explores those probabilities will not be able to know the risk behind every decision. Given those challenges, it is required that the planning approach account for climate and be robust to remain effective under a range of conditions [50].

Importantly, the resulting plan should leave room for flexibility and include options to respond to different possible futures. This is especially important globally and particularly relevant in countries like Indonesia, where the climate is deeply uncertain, and policy objectives evolve over time. These conditions highlight the limitations of current planning approaches that rely on static assumptions or a fixed pathway, which may fail to anticipate the uncertain climate and policy shifts. It shows a need for planning approaches that are not only robust but also capable of adapting to the goals.

One approach to answer that need is the proposal of the usage of decision-making under deep uncertainty (DMDU) [8]. DMDU, with the use of Robust Decision Making (RDM) [47] addresses situations where future conditions cannot be described using reliable probabilities. Rather than relying on fixed assumptions and probabilities, RDM uses quantitative stress tests to explore a wider range of plausible futures and prepares for different developments [47].

In addition to RDM, which mainly explores and stress-tests plausible futures, another DMDU approach called adaptive planning can add more benefit. It offers a structured approach to developing flexible strategies over time through sequences of actions that can adapt to changing conditions. The approach is named the Dynamic Adaptive Pathways Planning (DAPP) [7]. DAPP is a decision analysis framework that systematically approaches adaptive pathway planning [9]. DAPP has been widely applied and studied, particularly in the water and industrial sectors [9], and how the Netherlands manages its climate adaptation plan for the water sector [7].

The DAPP approach offers two kinds of features: plan creation and operationalization of the plan. The pathways plan creation offers a systematic framework from the beginning of problem analysis, identification of actions, development of pathways, and identification of transfer points. DAPP approach could also identify tipping points, which are critical moments when the existing policy becomes ineffective. The approach could prevent the decision makers from taking a policy that leads to lock-ins before the final goal is achieved [7]. The pathways will be simulated to measure the outcome.

One of the pathway plan visualizations is a metro map in Fig. 1, which explains that several actions can be planned in multiple pathways [9]. The x-axis explains the conditions that will be monitored. The y-axis explains the policies that could be taken. Timely policy shifts can be designed to transition among policies. The score in the box shows is one representation of the simulation results of each path.

The second feature of DAPP is the operationalization of the plan. Besides the plan creation itself, this feature enables the stakeholders to monitor key situations with some indicators and prepare to take specific actions when certain conditions are met. This consists of an implementation framework, monitoring, and evaluation. This allows the assessment of the plan's effectiveness and the adjustment of the plan if needed.

C. *Proposed Approach and Study Plan in Indonesia's Power System*

This section introduces and proposes the DAPP's potential application in Indonesia's power system planning. Given that the DAPP approach enables better handling of uncertainties—an aspect not thoroughly addressed in Indonesia's existing planning documents—it could offer a valuable alternative for improving the country's power system planning. Unlike current planning, which relies on fixed pathways and a limited number of scenarios, DAPP encourages flexible strategies that can change over time depending on how future conditions unfold. This makes it useful in dealing with the wide range of climate-related uncertainties and risks Indonesia faces.

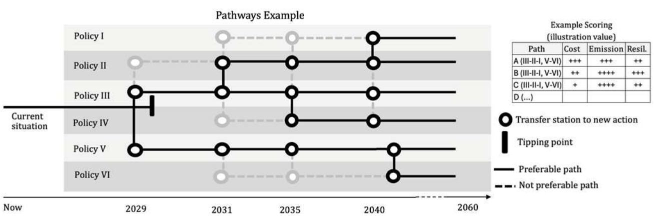

Fig. 1. DAPP's metro map illustration.

To illustrate the usage of DAPP in power system planning, we refer to Indonesia's official power plan as a basis for discussion. Specifically, for example, one interesting case to be discussed is the recent RUKN that introduces the supergrid as part of Indonesia's energy transition stages [2]. In other countries, vastly interconnected grids have shown clear benefits of renewable energy accessibility and building a strong grid. In this context, it is valuable to consider how the super grid plan might perform under various climate-related uncertainties and how different interconnection policy options could influence power system resilience.

The structuring tool named XLRM framework is used to do the DMDU approach [47], [49]. XLRM helps to frame the situations and also helps for modeling purposes later on. XLRM stands for X: eXogenous uncertainties, about what cannot be controlled, L: policy Levers, about what can be controlled. R: system Relation and Resources, about what system could relate the X and L. Finally, M: performance Metrics indicate what the goal entails.

One example of structuring XLRM in the case of Indonesia is presented here in Fig. 2. While this provides a conceptual example as a starting point, a more rigorous or participatory approach could be employed to refine and validate each component in practice. The first step involves identifying X, which in this case is defined by assessing the climate uncertainty and vulnerability of Indonesia's power system to climate impacts. For L, Indonesia's proposed super grid can be used as a base plan, and other policies can be registered as other levers. R in this framework is defined by the geographical scope and model used to represent Indonesia's national power system infrastructure. Meanwhile, M represents the performance objectives of the adaptive pathways, such as cost, emission, and system resiliency.

The XLRM framework will then be quantitatively operationalized using computational tools to do RDM's stress testing. One tool is the Exploratory Modeling and Analysis Workbench (EMA-WB) [51]. EMA-WB enables exploring a wide range of scenario space combinations across XLRM through large-scale simulations. It also supports integrating multiple models [52], allowing for the simulation and evaluation of pathway performance across a diverse set of plausible future scenarios. Moreover, it enables the systematic exploration of multiple plausible futures and policy robustness [53].

This XLRM-based EMA-WB tool can be integrated with any Python-based model, such as energy system models, power flow simulations, and other relevant models that align with the framework, such as a climate model to map the impact on the power system spatially. Through this setup, deep uncertainties can be systematically explored by running a large ensemble of scenarios across different combinations of policy levers and exogenous uncertainties. The result of the

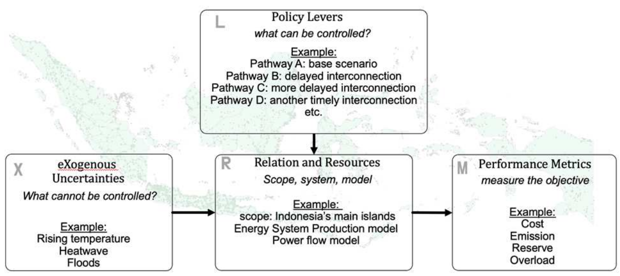

Fig. 2. XLRM framework explanation and example.

run is some futures that can be categorized as successful or unsuccessful scenarios. The result is a structured representation of plausible future pathways under varying climate conditions. The simulation output, evaluated against predefined performance metrics, provides a clear picture of which pathways remain robust across many futures.

In summary, from this DAPP approach, Indonesia can take a more flexible approach to power system planning. Instead of sticking to fixed plans, decision-makers can explore different options as new conditions emerge. This makes it easier to prepare for changes without locking into decisions too early.

V. Conclusions and Future Work

A. Conclusions

Climate change introduces significant uncertainties that challenge the effectiveness of power system planning in Indonesia. Rising temperatures and sea level rise have already begun to affect the performance and resilience of power generation, transmission, and demand. These impacts are subject to deep uncertainties, where the probability, timing, and magnitude of future change cannot be reliably predicted. Such conditions limit the usefulness of current planning approaches. While difficult to predict, these deeply uncertain climate-related stresses and shocks are critical factors that must be addressed in long-term planning.

To address these deep uncertainties, the paper proposes the use of Dynamic Adaptive Pathways Planning (DAPP) as an alternative planning approach. Rather than aiming to maintain a fixed path, DAPP supports the planning of many future strategies that can respond to changing conditions and evolving conditions and objectives over time in a flexible manner. This approach allows planners to explore multiple goals and pathways from the initial conditions and adjust the course of action as circumstances change. In doing so, it could provide a more responsive and robust foundation for power system planning in Indonesia. That is why addressing such climate-related uncertainties within long-term planning is essential to ensure the resilience and reliability of future power systems.

B. Future Work

Future work related to this paper will begin with a climate vulnerability assessment of Indonesia's power system to identify how climate-related stressors and shocks may affect generation, transmission, and demand. This assessment will help define key climate uncertainties (X) and some part of the relation (R) of the deep uncertainty work. The findings will guide the development of an adaptive planning approach that considers these uncertainties and prepares input for a model.

The model to demonstrate DAPP is proposed to be built using the Exploratory Modeling and Analysis Workbench (EMA-WB) alongside a production optimization and power flow model. The model setup will be structured with the XLRM framework to explore a range of scenarios using possible multi-model [52] setups of the models. A demonstration of the DAPP approach will follow, using a case study based on Indonesia's plan. It intends to demonstrate how DAPP can explore many plausible futures for climate-resilient planning in Indonesia's power system.

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References

[1] PT PLN (Persero), "PLN Annual Report 2023," PLN, Indonesia, Annual Report, 2024. Accessed: Nov. 21, 2024. [Online]. Available: https://web.pln.co.id/statics/uploads/2024/07/AR-PLN-2023-final_compressed.pdf

[2] Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMR/ESDM), "Rencana Umum Ketenagalistrikan Nasional (RUKN) 2024," Minsitry of Energy and Mineral Resources Republic of Indonesia, 2024. Accessed: Oct. 22, 2024. [Online]. Available: https://gatrik.esdm.go.id/assets/uploads/download_index/files/2f251-rukn-2024.pdf

[3] Ministry of Environment and Forestry of the Republic of Indonesia (KLHK), "Enhanced Nationally Determined Contribution Republic of Indonesia," Ministry of Environmental and Forestry Republic of Indonesia, 2022. Accessed: May 08, 2025. [Online]. Available: https://unfccc.int/sites/default/files/NDC/2022-09/23.09.2022_Enhanced NDC Indonesia.pdf

[4] Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMR/ESDM), "Rencana Umum Penyediaan Tenaga Listrik (RUPTL) 2025-2034," Ministry of Energy and Mineral Resources of the Republic of Indonesia (MEMR/ESDM), 2025. Accessed: July 01, 2025. [Online]. Available: https://gatrik.esdm.go.id/assets/uploads/download_index/files/b967d-ruptl-pln-2025-2034-pub-.pdf

[5] C. Wu, X.-P. Zhang, and M. J. H. Sterling, "Economic Analysis of Power Grid Interconnections Among Europe, North-East Asia, and North America With 100% Renewable Energy Generation," IEEE Open J. Power Energy, vol. 8, pp. 268–280, 2021, doi: 10.1109/OAJPE.2021.3085776.

[6] A. R. Jordehi, "How to deal with uncertainties in electric power systems? A review," Renewable and Sustainable Energy Reviews, vol. 96, pp. 145–155, Nov. 2018, doi: 10.1016/j.rser.2018.07.056.

[7] M. Haasnoot, J. H. Kwakkel, W. E. Walker, and J. Ter Maat, "Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world," Global Environmental Change, vol. 23, no. 2, pp. 485–498, Apr. 2013, doi: 10.1016/j.gloenvcha.2012.12.006.

[8] V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen, and S. W. Popper, Eds., Decision Making under Deep Uncertainty: From Theory to Practice. Cham: Springer International Publishing, 2019. doi: 10.1007/978-3-030-05252-2.

[9] M. Haasnoot, V. Di Fant, J. Kwakkel, and J. Lawrence, "Lessons from a decade of adaptive pathways studies for climate adaptation," Global Environmental Change, vol. 88, p. 102907, Sept. 2024, doi: 10.1016/j.gloenvcha.2024.102907.

[10] W. Ton, "Gridmaster HIC Rotterdam," Nov. 2022. Accessed: July 01, 2025. [Online]. Available: https://gridmaster.nl/wp-content/uploads/2022/11/20221124-report-GridmasterHICRdam_public_final.pdf

[11] H. A. M. Wurth, J. N. G. van Dinther, J. H. Kwakkel, I. Nikolic, J. J. Steringa, R. Calon, et al., "The Gridmaster-toolbox, a step towards a new infrastructure investment paradigm," presented at the CIGRE Session 2022, Paris, France, 2022.

[12] K. Zhu, M. Victoria, G. B. Andresen, and M. Greiner, "Impact of climatic, technical and economic uncertainties on the optimal design of a coupled fossil-free electricity, heating and cooling system in Europe," Applied Energy, vol. 262, p. 114500, Mar. 2020, doi: 10.1016/j.apenergy.2020.114500.

[13] Z. Ma, Z. Zhao, C. Liu, F. Yang, and M. Wang, "The Impacts and Adaptation of Climate Extremes on the Power System: Insights from the Texas Power Outage Caused by Extreme Cold Wave," Chn. J. Urb. Environ.Stud, vol. 10, no. 01, p. 2250004, Mar. 2022, doi: 10.1142/S234574812250004X.

[14] M. Panteli and P. Mancarella, "Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies," Electric Power Systems Research, vol. 127, pp. 259–270, Oct. 2015, doi: 10.1016/j.epsr.2015.06.012.

[15] J. Ebinger and W. Vergara, Climate Impacts on Energy Systems: Key Issues for Energy Sector Adaptation. The World Bank, 2011. doi: 10.1596/978-0-8213-8697.

[16] C. Wang, P. Ju, F. Wu, X. Pan, and Z. Wang, “A systematic review on power system resilience from the perspective of generation, network, and load,” Renewable and Sustainable Energy Reviews, vol. 167, p. 112567, Oct. 2022, doi: 10.1016/j.rser.2022.112567.
[17] A. C. R. Gonçalves, X. Costoya, R. Nieto, and M. L. R. Liberato, “Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures,” Sustainable Energy res., vol. 11, no. 1, p. 4, Jan. 2024, doi: 10.1186/s40807-023-00097-6.
[18] M. A. Russo, D. Carvalho, N. Martins, and A. Monteiro, “Future perspectives for wind and solar electricity production under high-resolution climate change scenarios,” Journal of Cleaner Production, vol. 404, p. 136997, June 2023, doi: 10.1016/j.jclepro.2023.136997.
[19] M. D. Bartos and M. V. Chester, “Impacts of climate change on electric power supply in the Western United States,” Nature Clim Change, vol. 5, no. 8, pp. 748–752, Aug. 2015, doi: 10.1038/nclimate2648.
[20] IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors. doi: 10.1109/IEEESTD.2023.10382442.
[21] X. Ke, D. Wu, J. Rice, M. Kintner-Meyer, and N. Lu, “Quantifying impacts of heat waves on power grid operation,” Applied Energy, vol. 183, pp. 504–512, Dec. 2016, doi: 10.1016/j.apenergy.2016.08.188.
[22] M. Panteli and P. Mancarella, “Modeling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events,” IEEE Systems Journal, vol. 11, no. 3, pp. 1733–1742, Sept. 2017, doi: 10.1109/JSYST.2015.2389272.
[23] D. Prasetijo, “An Approach for Planning Under Uncertainties for Indonesia’s Long-Term Energy Transition,” in 2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS), Denpasar Bali, Indonesia: IEEE, Aug. 2023, pp. 466–470. doi: 10.1109/ICHVEPS58902.2023.10257551.
[24] Meteorology, Climatology, and Geophysics Agency of the Republic of Indonesia (BMKG), “Anomali Suhu Udara Rata-Rata Tahun 2024.” Accessed: Mar. 21, 2025. [Online]. Available: https://www.bmkg.go.id/iklim/anomali-suhu-udara/anomali-suhu-udara-rata-rata-tahun-2024
[25] IPCC, “IPCC Sixth Synthesis Report,” 2023. Accessed: Mar. 21, 2025. [Online]. Available: https://www.ipcc.ch/report/ar6/syr/
[26] K. Handayani, T. Filatova, and Y. Krozer, “The Vulnerability of the Power Sector to Climate Variability and Change: Evidence from Indonesia,” Energies, vol. 12, no. 19, p. 3640, Sept. 2019, doi: 10.3390/en12193640.
[27] National Disaster Management Authority of the Republic of Indonesia (BNPB), “InaRisk.” Accessed: Mar. 24, 2025. [Online]. Available: https://inarisk.bnpb.go.id/about
[28] Asian Development Bank (ADB), “Climate Risk Country Profile: Indonesia,” Asian Development Bank, World Bank Group, 2021. Accessed: Mar. 24, 2025. [Online]. Available: https://www.adb.org/sites/default/files/publication/700411/climate-risk-country-profile-indonesia.pdf
[29] Beritasatu.com, “Gardu Induk Terdampak Banjir, PLN Pastikan Suplai Listrik di Kudus Aman.” Accessed: Mar. 24, 2025. [Online]. Available: https://www.beritasatu.com/nusantara/2805605/gardu-induk-terdampak-banjir-pln-pastikan-suplai-listrik-di-kudus-aman
[30] PLN, “Lebih Cepat dari Target, PLN Berhasil Membangun Tower Emergency di Pulau Timor NTT.” Accessed: Mar. 24, 2025. [Online]. Available: https://web.pln.co.id/media/siaran-pers/2021/04/lebih-cepat-dari-target-pln-berhasil-membangun-tower-emergency-di-pulau-timor-ntt
[31] Government of Indonesia, Presidential Regulation No. 5/2006 on the Kebijakan Energi Nasional. [Online]. Available: https://jdih.esdm.go.id/dokumen/view?id=187
[32] Government of Indonesia, Law No. 30/2009 on Electricity. 2009. Accessed: Mar. 24, 2025. [Online]. Available: https://gatrik.esdm.go.id/assets/uploads/download_index/files/9ef73-03.uu-30-2009-tentang-ketenagalistrikan.pdf
[33] Ministry of Energy and Mineral Resources of the Republic of Indonesia, Ministrial Regulation No. 11/2021 on Preparation of Electricity Supply Business Plan, vol. 11/2021. 2021.
[34] Ministry of Energy and Mineral Resources of the Republic of Indonesia, Ministrial Regulation No. 10/2025 on Road Map of Power Sector Energy Transition, vol. 10/2025. 2025. Accessed: Mar. 24, 2025. [Online]. Available: https://jdih.esdm.go.id/dokumen/view?id=2567
[35] UNFCCC, “Adoption of The Paris Agreement,” UNFCCC, Dec. 2015. Accessed: Apr. 16, 2024. [Online]. Available: https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf
[36] K. Handayani, Y. Krozer, and T. Filatova, “From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning,” Energy Policy, vol. 127, pp. 134–146, Apr. 2019, doi: 10.1016/j.enpol.2018.11.045.
[37] K. Handayani, P. Anugrah, F. Goembira, I. Overland, B. Suryadi, and A. Swandaru, “Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050,” Applied Energy, vol. 311, p. 118580, Apr. 2022, doi: 10.1016/j.apenergy.2022.118580.
[38] N. Reyseliani, A. Hidayatno, and W. W. Purwanto, “Implication of the Paris agreement target on Indonesia electricity sector transition to 2050 using TIMES model,” Energy Policy, vol. 169, p. 113184, Oct. 2022, doi: 10.1016/j.enpol.2022.113184.
[39] Y. Yudiartono, J. Windarta, and A. Adiarso, “Sustainable Long-Term Energy Supply and Demand: The Gradual Transition to a New and Renewable Energy System in Indonesia by 2050,” Int. J. Renew. Energy Dev., vol. 12, no. 2, pp. 419–429, Mar. 2023, doi: 1701064095.
[40] D. F. Silalahi, A. Blakers, and C. Cheng, “100% Renewable Electricity in Indonesia,” Energies, vol. 17, no. 1, p. 3, Dec. 2023, doi: 10/gtqxnz.
[41] M. A. Rahmanta, A. C. Adhi, H. B. Tambunan, W. Digwijaya, N. Damanik, and R. A. Al Hasibi, “An Analysis of National Position, Opportunity, and Challenge of Indonesia’s Nuclear Program to Support Net-Zero Emissions by 2060,” Energies, vol. 16, no. 24, p. 8089, Dec. 2023, doi: 10.3390/en16248089.
[42] P. Paiboonsin, G. Oluleye, M. Howells, R. Yeganyan, C. Cannone, and S. Patterson, “Pathways to Clean Energy Transition in Indonesia’s Electricity Sector with Open-Source Energy Modelling System Modelling (OSeMOSYS),” Energies, vol. 17, no. 1, p. 75, Dec. 2023, doi: 10.3390/en17010075.
[43] A. Amiruddin, A. Liebman, R. Dargaville, and R. Gawler, “Optimal energy storage configuration to support 100 % renewable energy for Indonesia,” Energy for Sustainable Development, vol. 81, p. 101509, Aug. 2024, doi: 10.1016/j.esd.2024.101509.
[44] L. D. Hersaputri et al., “Reducing Fossil Fuel Dependence and Exploring Just Energy Transition Pathways in Indonesia Using OSeMOSYS (Open-Source Energy Modelling System),” Climate, vol. 12, no. 3, p. 37, Mar. 2024, doi: 10.3390/cli12030037.
[45] J. Langer, F. Lombardi, S. Pfenninger, H. P. Rahayu, M. I. Al Irsyad, and K. Blok, “The role of inter-island transmission in full decarbonisation scenarios for Indonesia’s power sector,” Environ. Res.: Energy, vol. 1, no. 2, p. 025006, June 2024, doi: 10.1088/2753-3751/ad53cb.
[46] N. Reyseliani, Y. W. Pratama, A. Hidayatno, N. Mac Dowell, and W. W. Purwanto, “Power sector decarbonisation in developing and coal-producing countries: A case study of Indonesia,” Journal of Cleaner Production, vol. 454, p. 142202, May 2024, doi: 10.1016/j.jclepro.2024.142202.
[47] R. J. Lempert, Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis. Erscheinungsort nicht ermittelbar: RAND Corporation, 2003.
[48] H. W. J. Rittel and M. M. Webber, “Dilemmas in a general theory of planning,” Policy Sci, vol. 4, no. 2, pp. 155–169, June 1973, doi: 10.1007/BF01405730.
[49] W. E. Walker, R. J. Lempert, and J. H. Kwakkel, “Deep Uncertainty,” in Encyclopedia of Operations Research and Management Science, S. I. Gass and M. C. Fu, Eds., Boston, MA: Springer US, 2013, pp. 395–402. doi: 10.1007/978-1-4419-1153-7_1140.
[50] J. H. Kwakkel and M. Haasnoot, “Supporting DMDU: A Taxonomy of Approaches and Tools,” in Decision Making under Deep Uncertainty, V. A. W. J. Marchau, W. E. Walker, P. J. T. M. Bloemen, and S. W. Popper, Eds., Cham: Springer International Publishing, 2019, pp. 355–374. doi: 10.1007/978-3-030-05252-2_15.
[51] J. H. Kwakkel, “The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making,” Environmental Modelling & Software, vol. 96, pp. 239–250, Oct. 2017, doi: 10.1016/j.envsoft.2017.06.054.
[52] I. Nikolic et al., “Multi-Model Ecology and Interface for transition models,” Delft University of Technology, 2019. doi: 10.4233/UUID:1AA3D16C-2ACD-40CE-B6B8-0712FD947840.
[53] J. H. Kwakkel, M. Haasnoot, and W. E. Walker, “Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world,” Climatic Change, vol. 132, no. 3, pp. 373–386, Oct. 2015, doi: 10.1007/s10584-014-1210-4.