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# A Simplified Regret-Based Screening Framework for Vietnam's Power Planning Under Load Uncertainty

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**ABSTRACT**

In the context of the current rapid energy transition, power system planning is crucial. In Vietnam, the decision to approve the national power development plan reflects the increasing pressure to achieve dual objectives. The current planning approach focuses on solving the problem to minimize costs, assuming minimal input variability. Through scenario analysis and robust planning based on regret indices, the study examines power system planning under high uncertainty as variable renewable energy (VRE) sources increase. The results show that the balanced option (PA2) is comprehensive because it avoids the high costs of the renewable energy priority option and the risks associated with a difficult-to-change base structure. This study contributes by introducing a simplified regret-based robust planning framework for data-constrained, policy-driven contexts such as Vietnam.

## 1. INTRODUCTION

The national power system plays a significant role. This is the lifeblood that powers all national activities, serving as the essential foundation for economic and industrial development and improving the quality of life for people throughout society. In the global energy transition, countries with rapid economic growth, such as Vietnam, face pressure to meet rising demand while reducing greenhouse gas emissions. At COP 26, Vietnam committed to reducing greenhouse gas emissions, aiming to achieve net-zero emissions by 2050 [1], thereby setting new constraints for the long-term power system. Power Development Plan VIII adjustment [2], approved in 2025, reflects Vietnam's efforts to achieve this dual goal. Accordingly, the share of high-emission sources, such as coal-fired power, tends to decrease, while renewable and flexible power sources, and the corresponding grid infrastructure, increase in planning scenarios. The rapid growth of variable renewable energy (VRE) sources in the energy mix has increased uncertainty regarding capacity availability and system operation. In addition, factors such as fuel prices, investment costs, interest rates, exchange rates, the development of new construction sources, transmission grids, and policy changes at each stage all affect the initial assumptions. Traditional planning involves forecasting future scenarios and designing actions under assumptions corresponding to those scenarios. As uncertainty factors increase, this approach is no longer suitable [3]. Instead, methods such as scenario analysis, combined with flexible, robust planning, are being researched and proposed to improve adaptability in long-term investment decisions for power sources and power grids. Most of these methods have been researched and applied primarily in countries with stable infrastructure and technology, such as Europe and North America [4]. Approaches to power system planning in regions with high load growth rates, such as Vietnam today, are still limited. Here, input data for planning problems is often approximate and restricted in terms of collection and sharing [5]. The institutional framework and planning decision-making process are highly policy-driven. There remains a significant gap between the analytical framework, comparative scenario evaluation frameworks, and tools supporting national power system planning. This study aims to bridge that gap by simplifying and adjusting the model to suit the data and institutional contexts in Vietnam.

By analyzing sources of uncertainty in Vietnam's power system planning, the study developed robust scenarios using a planning approach in the context of the adjusted Power Development Plan VIII towards the Net Zero goal. The study has three main objectives: First, to identify the main uncertainties in Vietnam's power system planning; second, to analyze the relationship between uncertainty and the increasing share of renewable energy sources in the power system; and finally, to propose policies to improve the sustainability of national power planning in the long term. The structure of the research paper, excluding the introduction, consists of four sections: literature review, methodology, discussion of results after calculation, and policy.

## 2. LITERATURE REVIEW

### 2.1 Traditional power system planning

In the traditional approach, power system planning is often formulated as a total cost assessment problem. The goal is to minimize total investment costs and long-term operating costs while meeting technical constraints and reliability requirements of the national power system [6]. Long-term planning models are often based on assumptions about load growth, fuel prices, technology costs, and policies. This approach is suitable in relatively stable contexts where input assumptions change little over time. However, the assumptions of traditional planning are no longer appropriate when the power system integrates VRE [6]. Research literature has highlighted key questions that traditional planning must address:

(i) Forecasting electricity demand under uncertainty;

(ii) Determining an appropriate generation mix while developing methods to handle the variability and uncertainty from renewable energy sources;

(iii) Upgrading transmission grids to ensure stable and cost-effective electricity distribution.

In power system operation, traditional planning is based on long-term load demand forecasts and predetermined reliability levels. Therefore, when faced with non-linear fluctuations and complex impacts from uncertain factors, the power system struggles to adapt [3]. Additionally, traditional planning uses the electricity cost index as the criterion for comparing power generation technologies in a regulated market context. This approach overlooks many essential system characteristics, remarkably variability, dispatchability, and the technology's contribution to the electricity market under real-time supply-demand balancing conditions [7]. Therefore, recent studies propose using reference cost indices based on the value each technology contributes to the system, aiming to better reflect the energy, capacity, and flexibility it provides to the power system, especially during peak-load hours throughout the year.

At the infrastructure planning level, some documents indicate that traditional planning strategies mainly take a "bottom-up" approach, focusing on evaluating individual projects [4]. The challenge is to provide a stable, sustainable long-term investment signal while maintaining the necessary flexibility to respond to future uncertainties. Traditional planning processes have shifted from seeking a single robust solution based on economic forecasts to identifying options that perform well across various future states.

Furthermore, some studies emphasize that investment analysis and decision-making, particularly for long-term infrastructure projects, must be addressed in planning problems with high uncertainty. Based on this, robust methods are proposed with approaches that complement traditional optimal planning.

### 2.2 Planning under uncertainty

To overcome the limitations of traditional planning, many studies have proposed methods for handling uncertainty in power system planning. Scenario analysis considers various development scenarios for the system. At the same time, to assess the impact of each input variable, such as load growth, fuel prices, or technology costs, on planning outcomes, sensitivity analysis can be used. At a higher level, methods such as stochastic assessment and robust planning incorporate uncertainty directly into the decision-making process, rather than treating uncertainty as an external factor. Hallegatte et al. [3] pointed out that for long-term infrastructure investment decisions, especially under high uncertainty, the robust solution is no longer the goal for solving this problem. Decisions need to prioritize flexibility, adaptability, and acceptable performance under various uncertain states.

In another research focused on planning with high uncertainty, aiming to develop flexible approaches. The focus of these studies was to analyze scenarios and find suitable solutions, rather than optimizing a single objective [3, 4]. This approach has enabled planners not only to identify highly adaptable options but also to minimize risks in long-term investment activities. In power system planning, international organizations have widely adopted scenario-based planning methods. According to ENTSO-E's Ten-Year Network Development Plan (TYNDP) report, scenario-based methods are used to assess system demand and infrastructure projects. This helps identify options that minimize regret indices across multiple scenarios [8]. Similarly, IRENA emphasizes the importance of enhancing the power system's overload capacity amid weather fluctuations. IRENA also proposes proactive strategies and legal frameworks to manage natural risks amid increasing climate change [1].

### 2.3 Power system planning with a high proportion of variable renewable energy

The rapid growth of VRE sources has created new challenges for national power system planning. Due to their dependence on weather and the time-varying nature of wind and solar power, the available capacity of these sources is often lower than their installed capacity, especially during peak hours. The planning calculation process, based on assumptions about nominal capacity, has diminished VRE's role in ensuring power system reliability. To more accurately reflect the contribution of VRE, several studies have proposed concepts and indicators such as net load [9], Effective Load Carrying Capability (ELCC) [7], Loss of Load Expectation (LOLE) [5], etc. These indicators help evaluate the VRE's role in ensuring the security of the electricity supply in the current power system. However, the application of these analytical frameworks in the power systems of developing countries, including Vietnam, remains limited. Some studies focus on developing planning methods to address the technical and economic challenges posed by high VRE integration. Recent studies and reports by the IRENA emphasize the role of flexible planning in power systems to cope with increasing variability and uncertainty. IRENA has introduced an approach to assess long-term flexible capacity shortfalls, thereby helping to identify investment needs in flexible power sources, grids, and other supporting solutions [9]. Simultaneously, traditional planning incorporates new analyses such as describing the time-dependent characteristics of wind and solar power, identifying flexible sources like flexible thermal power, energy storage, and load response to mitigate operational challenges [6]. In the global context of moving towards Net Zero targets, many studies indicate that the deployment of clean technologies must be accompanied by improvements in power system flexibility, leading to significant investment in smart grids, storage systems, and demand-side solutions [10]. A limitation of traditional planning is the use of the Levelized Cost of Electricity (LCOE) metric for comparison, which does not account for critical system characteristics such as variability, dispatchability, and the contribution of technology to the reliability and flexibility of the power system.

In the context of the increasing share of VRE in the power system, several studies have proposed the Value-Adjusted Levelized Cost of Electricity (VALCOE) index to capture the energy, capacity, and flexibility values of power generation technologies. The VALCOE index highlights the need to shift from traditional system planning approaches focused on system cost assessment to a comprehensive evaluation of system value [7]. Empirical studies also point to institutional and contractual barriers that can reduce the effectiveness of VRE integration. A case study in Pakistan shows that long-term contracts (for fuel and generation capacity) can reduce operational flexibility. This negates the potential benefits of VRE and increases the need for investment in the grid and forecasting systems [5]. In Vietnam, the development target is for a very high proportion of VRE, with VRE expected to account for approximately 67.5-71.5% of total installed capacity by 2050 according to the revised Power Development Plan VIII [2]. This creates an urgent need to enhance the power system's flexibility and improve the operational flexibility of existing thermal power plants to integrate VRE cost-effectively [11].

Thus, in the context of global energy transition and increasing uncertainty, power system planning based on deterministic scenarios has many limitations. In traditional planning models, methodologies are often designed to handle uncertainty at a low level to optimize system cost. This approach is not suitable when the input assumptions do not accurately reflect actual developments, especially in the context of climate change. Analytical tools and indicators, such as LCOE, limit the ability to provide a comprehensive assessment of VRE system characteristics. The system's dispatchability and operational assessment are reduced due to long-term contracts. The lack of flexibility and failure to keep pace with source development in operations and infrastructure create a significant gap in grid operating capabilities when VRE is high in the power mix. This requires synchronized solutions, including strengthening transmission and distribution grids, investing in energy storage, and leveraging demand-side reserves [9]. Finally, regarding policy and implementation, despite significant commitments, such as JETP and Net Zero targets, there remains a lack of specific policies and measurable short-term goals. Continuing to operate old infrastructure until the end of its life cycle risks exceeding the carbon budget, requiring early implementation and the development of long-term, sustainable planning strategies (Table 1) [12].

**Table 1.** Comparison of approaches

| Approach | Objective |
| --- | --- |
| Traditional planning | Based on the principle of minimizing system costs. The power source is determined to meet a certain load level with a predetermined level of reliability [13].<br>Focus on the supply side, developing supply sources and expanding the power grid [14], while ignoring demand-side power-balancing solutions during the planning process. |
| Uncertain planning | When variables such as load growth, fuel prices, and construction time fluctuate significantly and are difficult to predict using a single scenario in traditional planning, this method considers decisions from the perspective of avoiding the highest risks [14]. |
| Robust planning that takes deep uncertainty into account | Robust planning and high-uncertainty management focus on solutions that ensure system safety even under high-uncertainty conditions, with high reliability and maximum utilization of existing infrastructure [15]. |

### 2.4 Uncertainty and robust planning with Vietnam's Power Development Plan VIII and Net Zero target

2.4.1 Uncertainty in Vietnam's Power Development Plan VIII

According to the adjusted Power Development Plan VIII, a flexible approach will enable adaptation to uncertainty. Vietnam's current plan for the period 2021 to 2030, with a vision to 2050, is not based on a single forecast, but is both dynamic and open. The scenarios developed reflect different levels of economic growth with changes in the energy mix towards the integration of liquefied natural gas and renewable energy. The adjusted Power Development Plan VIII has developed electricity demand forecasts based on macroeconomic scenarios. It assumes a high average growth rate to ensure that the electricity supply stays one step ahead. Average GDP is expected to grow by about 10% per year from 2026 to 2030, then fluctuate at 7.5% per year from 2031 to 2050. The projected demand load range will be 500.4 to 557.8 billion kWh in 2030 and approximately 1,237.7 to 1,375.1 billion kWh in 2050 [1]. The flexible planning under the current revised Power Development Plan VIII scenario integrates different technology pathways to achieve net-zero emissions by 2050. The development of smart grids will facilitate the integration of large-scale, high-reliability renewable energy sources. Back-to-back systems and flexible power transmission equipment will improve transmission capacity, aiming to increase renewable energy (excluding hydropower) from 28% to 36%, then to 74% to 75%, by 2050.

Although Vietnam's revised Power Development Plan VIII has demonstrated flexibility in integrating renewable energy and aims for Net Zero by 2050, the current planning approach reveals significant shortcomings amid the energy transition and rising uncertainty. The first is that it relies primarily on deterministic planning, with centralized load forecasts and static comparison scenarios. There is currently no analytical framework to assess the robustness of planning decisions amid high uncertainty stemming from rapid growth in electricity demand, volatility of fuel prices, climate change, and the evolving nature of renewable energy. The lack of multi-scenario assessment tools and decision-effectiveness testing across scenarios increases risk. The second, the assessment of power generation technologies in the revised Power Development Plan VIII, still relies mainly on traditional indicators. Quantitative indicators have not been fully integrated into the system to reflect the actual value of VRE (such as its contribution to reliability, available capacity, and system flexibility). This is a significant gap given that wind and solar power are expected to dominate Vietnam's long-term power mix. The third, Vietnam's current Power Development Plan, has not established an integrated assessment framework that links long-term planning to the flexible operational requirements of energy storage, demand response, and the flexible operation of existing power sources. This lack of linkage limits the ability to identify critical infrastructure investment needs to ensure the power system operates safely and efficiently as the share of VRE increases.

2.4.2 Identifying sources of uncertainty and establishing a robust planning framework for Vietnam

In the context of the energy transition, Vietnam’s power system is facing significant sources of uncertainty:

(1) Load uncertainty: Vietnam’s current revised Power Plan 8 is based on a GDP growth scenario of 6.5 to 7.5% per year; consequently, the range of commercial electricity demand is

projected to fluctuate significantly between 500.4 and 557.8 billion kWh by 2030 [2]. Additionally, according to the energy outlook report, the pace and process of economic restructuring under a green growth scenario in the energy transition context will alter future electricity demand [11].

(2) Uncertainties regarding the timeline and risks associated with thermal power sources. Unlike the assumptions in previous plans, Vietnam is currently facing significant obstacles, as coal-fired power projects (Nam Dinh I, Quang Tri, Vinh Tan III, Song Hau II) are encountering difficulties in implementation, with investors requesting project suspensions and the Ministry of Industry and Trade terminating BOT contracts. LNG-fired power projects (Long Son, Ca Na, Bac Lieu) are also at risk of delays. On the other hand, the risk of stranded assets is projected to be very high if additional coal-fired power plants are built before 2030, as they will operate only as baseload plants to compensate for system shortages for a very short period before transitioning to a flexible role [2].

(3) Uncertainty regarding the integration of offshore wind power. The 2025 technical assessment report on offshore wind energy potential indicates a potential of up to 1,068 GW; however, its development and operation depend heavily on transmission capacity and marine spatial planning [16]. Therefore, according to PDP 8, the development target is set at 6,000-17,032 MW by 2030 under favorable conditions and reasonable Costs [2].

Recognizing the uncertainties in traditional forecasting methods, Vietnam is gradually shifting toward a robust planning approach through policies that enhance flexibility and reliability. Specifically:

- Energy storage requirements: To address the uncertainty of VRE, centralized solar power projects in Vietnam must install storage batteries with a minimum capacity of 10% of the power output for a duration of 2 hours [2].
- Instead of using a reserve margin (PRM), the planning requires the 500 kV and 220 kV transmission systems to meet the N-1 criterion for critical load areas and the N-2 criterion for particularly critical load areas [2].
- To mitigate the risk of localized power shortages, inter-regional transmission capacity must be expanded from 27 GW to 48 GW by 2030 [11].

## 3. METHODOLOGY

### 3.1 Approach

The study applies a scenario-based approach to robust decision-making under high uncertainty. With this approach, the study evaluates cost changes, calculates regret indices, and assesses robustness to measure trade-offs among planning options across different scenarios.

### 3.2 Overall research design

The research methodology framework consists of the following main steps (Figure 1):

(1) First, identify and recognize the primary sources of uncertainty in Vietnam's power system planning, including load, generation sources, costs, transmission grids, and policies.

(2) Next, develop scenarios reflecting different assumptions about load growth, renewable energy (VRE) penetration, and policy conditions. Simultaneously, identify corresponding power system planning options for different development paths, such as prioritizing base load, prioritizing VRE, and balanced options.

(3) Modeling under conditions of sufficient capacity.

(4) Calculating system costs.

(5) Using the regret index to evaluate the sustainability of the planning options proposed in the previous step.

(6) Finally, analyzing and evaluating the effectiveness of each option in each scenario based on economic and reliability criteria.

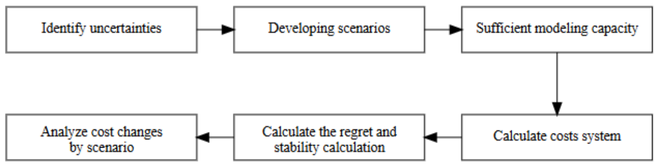


**Figure 1.** Main steps of the research process

### 3.3 Data and information sources

The study primarily uses secondary data from official and reliable sources, including the adjusted Power Development Plan VIII, reports from the Ministry of Industry and Trade, EVN, IEA, IRENA, and UNDP. These sources provide information on load forecasts, power source structure, technology costs, and fuel prices.

### 3.4 Quantitative modeling of power source planning

Based on the identified scenarios and planning options, the study calculates and evaluates the load-response capacity and economic efficiency of each option in each scenario. This is done by determining peak power requirements, system capacity, investment costs, operating costs, and power loss costs. From there, the study calculates the regret index and selects the most sustainable planning option.

The study develops options S1, S2, and S3 representing the uncertain states of Vietnam's power system (Table 2).

**Table 2.** Description of the scenarios

| Scenario | Scenario Description |
|---|---|
| S1 | Low-growth scenario: Slow load growth, favorable development of VRE, but may face risks due to excess capacity. |
| S2 | Base-case scenario: Load growth aligns with the adjusted Plan VIII forecast. This scenario serves as the reference. |
| S3 | Rapid growth scenario: Rapid load growth, high peak power demand. Risk of power shortages. |

Options PA1, PA2, and PA3 reflect different priorities between renewable energy and baseload sources. Based on the research objectives and established research framework, the paper develops three power generation planning options (PA1, PA2, PA3) in the context of energy transition and increasing uncertainty. Uncertainties include load growth and the power factor of VRE sources (Table 3).

Option PA1 is developed using a planning approach that prioritizes a rapid transition to renewable energy, with a high share of VRE sources, such as wind and solar power, in the energy mix. In this option, the share of traditional dispatchable generation sources gradually decreases. PA1 reflects a scenario pursuing high-level emission-reduction and energy-transition goals while accepting a high degree of dependence on load uncertainty.

**Table 3.** Description of the options

| Option | Description of the Plan |
|---|---|
| PA1 | High VRE share: prioritizes rapid transition, high VRE share, low baseload |
| PA2 | Balanced Option: Balancing transition and ensuring electricity supply security, balanced VRE and baseload power generation. |
| PA3 | System security priority option: high proportion of baseload power source. |

Scenario PA2 is a balanced scenario in which the power source structure is designed to balance energy transition goals with the requirement for electricity supply security. The share of VRE and dispatchable generation sources is allocated at a relatively balanced level, allowing the system to both leverage the long-term cost benefits of renewable energy and maintain sufficient capacity to meet peak load under uncertain conditions. PA2 has the potential to minimize extreme trade-offs between cost, reliability, and transition speed.

Option PA3 is designed to ensure system security and power supply reliability. It features a high proportion of dispatchable and baseload sources. In this option, the proportion of VRE in the source mix is kept at a safe level to limit operational risks and ensure peak load response capability. PA3 focuses on minimizing the risk of power shortages and short-term cost volatility. However, the biggest challenge in this plan is achieving long-term energy transition goals. Each plan is evaluated across the entire set of scenarios from S1 to S3, forming a table that maps scenarios to plans. Based on that, the regret index is used to assess the robustness of each plan against possible outcomes.

Determining peak power requirements and reserve margins [17]:

$$P^{demand} = P^{capacity}(1 + PRM) \quad (1)$$

where,

PRM = reserve margin.

PRM = (10-15%) to ensure system reliability against load fluctuations and risks [18]:

Available capacity and capacity contribution factor [19]:

$$P_i^{avail} = k_{VRE}.Cap_i^{VRE} + k_{base}.Cap_i^{base} \quad (2)$$

where,

$P_i^{avail}$ = available capacity of a power generation portfolio

$Cap_i^{VRE}$, $Cap_i^{base}$ = the installed capacity of VRE and the capacity of base sources

$k_{VRE}$ , $k_{base}$ = the power contribution factor of the renewable and base sources (Table 4)

According to Vietnam's latest planning documents and energy reports, the coefficients have been calibrated to account for the specific characteristics of Vietnam's power system [20, 21].

$$a(i,j) = CAPEX_{ij} + OPEX_{ij} + Penalty_{ij} \quad (3)$$

$$Penalty_{ij} = \begin{cases} VOLL.E_{ij}^{shed} & \text{If } \Delta P_{ij} > 0 \\ 0 & \text{If } \Delta P_{ij} < 0 \end{cases} \quad (4)$$

where,

VOLL = cost of 1 MWh of electricity not supplied

VOLL = $10,000/MWh as proposed by MISO in the technical report [22].

$E_{ij}^{shed}$ = amount of electricity not supplied

Regret index [23]:

$$r_{ij} = a(i,j) - a_j^* \quad (5)$$

The optimal alternative is obtained by minimizing the maximum regret value:

$$\min_i(\max_j r_{ij})$$

The regret index reflects the cost penalty incurred when a planning option performs sub-optimally compared to the best option under a given scenario. Long-term dual objectives cannot be achieved by maximizing a single emissions scenario or forecast with minimal input assumptions. The focus is on avoiding ineffective long-term planning decisions. Therefore, the regret index is used to indicate the risk in planning decision-making. This index reflects the consequences of choosing a planning option that later requires costly adjustments or causes major disruptions. By minimizing the regret index across the set of scenarios presented, the proposed analytical framework aims to protect sustainability and emission-reduction goals from long-term uncertainty.

**Table 4.** Summary of calibration parameters for the Vietnamese power system

| Parameter | U.S. Reference Values/ Compiled Data | Calibrated Values for Vietnam | Vietnamese Reference Data Sources |
|---|---|---|---|
| $k_{VRE}$ | 0.20 ÷ 0.30 | Onshore wind power: 0.36; Offshore wind power: 0.54; Concentrated solar power with BESS, adjusted to a minimum of 10%. | [2, 16] |
| $k_{base}$ | 0.8 ÷ 0.85 | Decreases over time (flexible operation at low load levels). | [11] |
| VOLL $/MWh | 10,000 | Variations through sensitivity analysis combined with external Costs 3k/10k/20k. | [11] |
| PRM | 10-15% | Changes to ensure the reliability of the power supply and compliance with N-1 and N-2 criteria. | [2] |

### 3.5 Analysis methods and calculation process

3.5.1 Assumptions for specific input parameters of the mode

This study uses several input assumptions to reflect the planning data of Vietnam's power system. Load uncertainty is the primary source of uncertainty in the research and is modeled through three different scenarios: (1) S1 (low load): a 10% reduction compared to the baseline scenario; (2) S2 (baseline scenario): following the adjusted Power

Development Plan VIII; (3) S3 (high load): 10% increase compared to the baseline scenario. Each scenario is characterized by: Annual electricity consumption ($E_s$, $P_s^{peak}$).

In the study, 2030 was selected as the base year for convenience in simulating the adjusted Power Plan VIII data. Electricity generation: $E_s$ = 505.2 (TWh); $P_s^{peak}$ = 90.512 (GW). Required capacity accounts for the system reserve of 10 to 15%.

Assumptions regarding the capacity contribution factors of the power source groups:

- Dispatchable generation sources (coal, gas, regulated hydro power):

In the IEA's 2020 report, as the share of renewable energy increases, traditional baseload power plants will shift to flexible operation. Therefore, the IEA recommends calculating system costs with $k_{base}$ = 0.5 [7]. Additionally, according to the Vietnam Energy Outlook report, coal-fired power generation will decline after 2030. By 2040, the number of full-load operating hours will be approximately 2,300 hours $k_{base}$ = 0.26 [11]. The value of 0.5 is selected for the base-case scenario calculation.

- VRE sources (wind, solar):

Solar power: The capacity factor in Vietnam is typically around 20% [5, 16].

Wind power: Capacity factors range from 25% to 45%; offshore wind power can reach 55%. The adjustment for Vietnam averages approximately 35% [16].

Assuming the system is designed with 75% solar power and 25% wind power in the base case scenario, the $k_{VRE}$ factor is calculated as follows:

$$k_{VRE} = (75\% \times 0.2) + (25\% \times 0.35) = 0.23$$

Assumptions about system costs: Total system costs are determined to include: capital expenditure (CAPEX) - fixed by the source configuration of each option; operating expenditure (OPEX) - varying with load scenarios and dispatch structure; penalty costs due to power shortages; environmental costs; and stranded assets.

Also in the IEA's 2020 report, the baseline price set for power plants coming online in 2025 is \$30 per ton of $CO_2$. The IEA has established a baseline scenario involving a 50% reduction in project lifespans to assess risks [7]. Meanwhile, if Vietnam continues to build coal-fired power plants, by 2040 these plants will have been operational for only about 15 to 20 years, whereas the typical lifespan of a coal-fired power plant is 40 years. Therefore, the assumed unrecovered capital ratio is set at 50% [10].

Identify three power source planning options (PA1-PA3). Option 1: rapid transition priority option, with VRE and baseload sources accounting for 70% and 30% of total installed capacity. Option 2: balanced transition option, with VRE and baseload sources accounting for 55% and 45% of total installed capacity, respectively. Option 3: energy security priority option, with VRE and baseload sources accounting for 40% and 60% of total installed capacity, respectively.

Scope and limitations of the assumptions in this study: The assumptions are considered to support the analysis of trade-offs when making decisions in highly uncertain situations. They also focus on the robustness of planning options. Therefore, the selected coefficients are representative and have been tested through scenario analysis and sensitivity analysis. Scenario analysis simulates the power system under uncertain conditions. For each scenario, planning options are evaluated independently to determine costs and the ability to meet technical requirements. The regret index is calculated as the difference between the effectiveness of an option and the optimal option in each scenario. The option with the smallest regret index is considered the most robust option.

3.5.2 Calculation steps

At each time point during the planning period, determine the power system's electricity demand and reliability requirements. The total available capacity is determined by the weighted sum of the capacities of baseload and VRE sources, reflecting each source type's actual contribution to meeting peak load and system reserve requirements.

Establish a system cost assessment problem with the objective function of minimizing total economic costs, including CAPEX, OPEX, and penalties for power shortages. In this case, the cost of power shortages is represented by the economic value of the unprovided power (Value of Lost Load – VOLL) multiplied by the amount of power cut. Then, three power source planning options (PA1-PA3) are determined. The uncertainty scenario set is constructed as S1-S3 to reflect the power system's long-term uncertainties. For each scenario, the system costs corresponding to each planning option are calculated. At the same time, the lowest possible cost in that scenario is determined. From there, the regret index is calculated as the difference between the cost of a planning option and the optimal cost in the same scenario. The criterion for minimizing the regret index is used to select the planning option, with the option that minimizes regret across the entire set of scenarios being optimal under high uncertainty. The results of the three options are summarized and compared through total system cost and regret index.

This research framework is designed to analyze and support decision-making without delving into detailed simulations or comparative scenario-evaluation frameworks for power system operation. Short-term fluctuations, such as load demand, power from renewable energy sources, and detailed constraints on the power grid's transmission capacity and energy storage, have not been studied or included as constraints. The research results emphasize the role of uncertainty in long-term planning with variable inputs, such as capacity and long-term costs, across different transition scenarios.

## 4. RESULTS AND DISCUSSION

### 4.1 Changes in system costs when load changes

The results (Table 5) of the system cost calculations for the three power generation planning scenarios (PA1, PA2, PA3) correspond to the load uncertainty scenarios S1, S2, and S3 (Figure 2). Load uncertainty refers to the variation in electricity consumption, ranging from 454.68 to 555.72 TWh, and the peak power requirement, including reserves, ranging from 93.68 to 114.50 GW. The total cost table clearly illustrates the trade-offs between the scenarios. In Scenario S1 (low load), PA1 with 70% VRE has the highest cost (671.38 billion USD) because over-investing in renewable energy when demand is low leads to curtailment and wasted CAPEX. Conversely, in Scenario S3 (high load), PA3 (40% VRE) reaches the highest cost (570.75 billion USD) due to fuel costs, environmental fees (\$30/ton $CO_2$), and stranded asset risks. PA2 (55% VRE) demonstrates a balance, achieving optimal costs in the Base S2 scenario (512.04 billion USD). This trend aligns with the economic theory of electricity. These results are consistent with deep-uncertainty decision-making theory, opportunity-cost theory, and external-cost theory.

**Table 5.** Cost calculation table based on various scenarios and corresponding options (Billion USD)

| | CAPEX | OPEX | Stranded Assets | Environmental Costs | Total Costs |
|---|---|---|---|---|---|
| Base Scenario S2 (Base Scenario): In accordance with the adjusted Power Development Plan VIII | | | | | |
| PA1 | 371.51 | 9.35 | 45.18 | 90.37 | 516.41 |
| PA2 | 315.38 | 12.76 | 59.97 | 123.93 | 512.04 |
| PA3 | 270.84 | 16.17 | 71.69 | 191.18 | 549.88 |
| Base Case S1 (Low-Load Scenario): 10% reduction compared to the base case | | | | | |
| PA1 | 533.25 | 8.41 | 64.86 | 64.86 | 671.38 |
| PA2 | 458.71 | 11.48 | 87.22 | 90.71 | 648.12 |
| PA3 | 398.14 | 14.55 | 105.39 | 118.04 | 636.12 |
| Base Scenario S3 (High-Load Scenario): 10% increase compared to the base scenario | | | | | |
| PA1 | 318.53 | 10.28 | 38.74 | 162.71 | 530.26 |
| PA2 | 263.09 | 14.03 | 50.02 | 214.77 | 541.91 |
| PA3 | 221.19 | 17.78 | 58.55 | 273.23 | 570.75 |

Note: CAPEX = capital expenditure; OPEX = operating expenditure

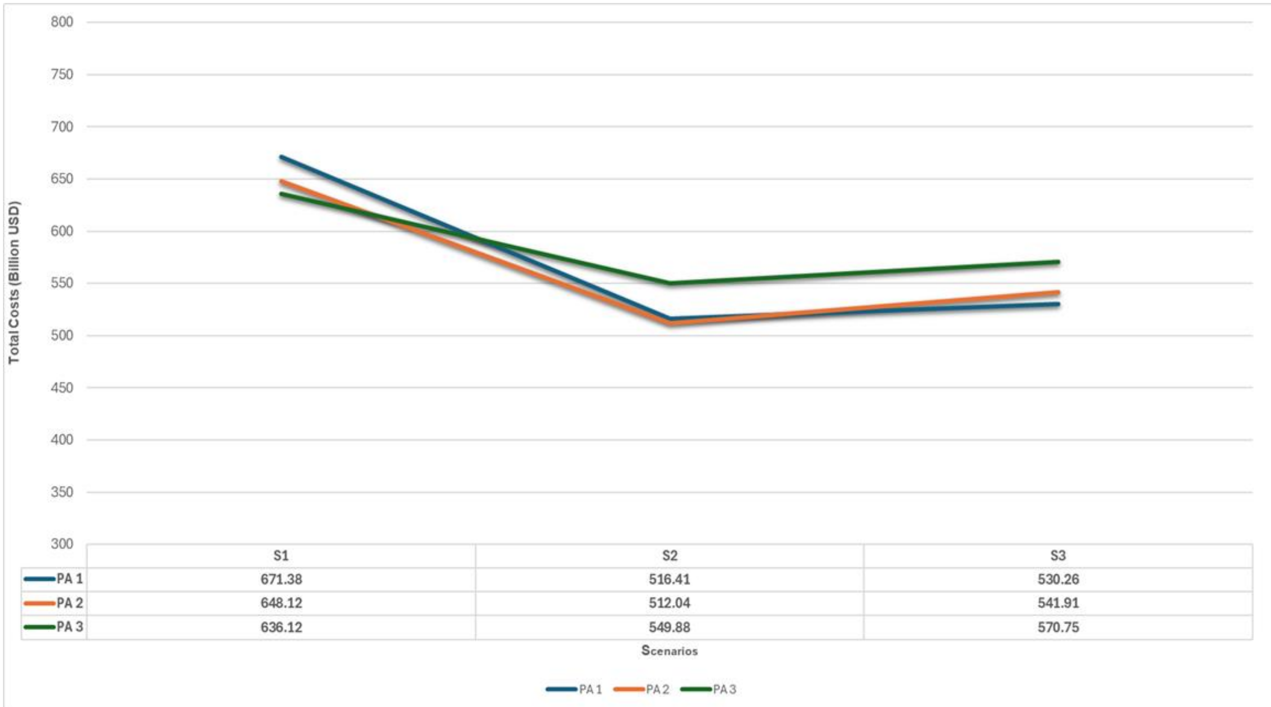


**Figure 2.** Cost diagram according to scenarios corresponding to each option

Given the specific characteristics of Vietnam's power system, the solar power factor is typically around 20%. The power factor for offshore wind power ranges from 25% to 45%, with a peak of only 55%. Therefore, the kVRE factor is selected to lie between 0.21 and 0.24.

As $k_{VRE}$ increases from 0.21 to 0.24, renewable energy becomes more efficient at generating electricity, reducing pressure on the power system (Table 6). The total system cost decreases across all three scenarios. Specifically, in PA1 (70% VRE), the total system cost decreases at the fastest rate (from 540.3 to 505.24 Billion USD). However, the initial investment cost burden is too high, making PA1 more expensive than PA2. In PA3 (40% VRE), the total system cost decreases slowly (from 561.01 to 544.50 Billion USD), but it remains the most expensive scenario because, in the baseline case, PA3 is constrained by fossil fuels, taxes, and high fuel costs. Scenario 2 with 55% VRE remains the optimal option within the range of 0.21-0.24. Therefore, this can be seen as the economic equilibrium point.

**Table 6.** Sensitivity analysis by $k_{VRE}$ for Scenario S2 (Billion USD)

| | S2 | | | |
|---|---|---|---|---|
| $k_{VRE}$ | 0.21 | 0.22 | 0.23 | 0.24 |
| PA1 | 540.30 | 528.08 | 516.40 | 505.24 |
| PA2 | 528.16 | 519.96 | 512.03 | 504.34 |
| PA3 | 561.01 | 555.39 | 549.89 | 544.50 |

## 4.2 Cost sensitivity and robustness of options to load change

Across the load scenarios considered, the active power capacity consistently falls below the reserve margin. However, the results (Table 7) show significant differences in the sensitivity of system costs to load uncertainty between options 1, 2, and 3.

**Table 7.** Regret index of options when load changes

| | Regret | | | Regret Index | Evaluation |
|---|---|---|---|---|---|
| | S1 | S2 | S3 | | |
| PA1 | 35.26 | 4.37 | 0 | 35.26 | Less robust, with a risk of capital wastage. Sensitive to low-load scenarios (S1). |
| PA2 | 12.00 | 0 | 11.65 | 12.00 | Most robust and achieves economic balance. |
| PA3 | 0 | 37.84 | 40.49 | 40.49 | Less sustainable due to high risks of carbon taxes and stranded assets. |

This is the result of a comparative scenario evaluation framework, which, rather than seeking the lowest-cost option under a single future scenario, supports large-scale investment decision-making under conditions of deep uncertainty.

The regret value of PA1 (70% VRE) is $35.26 billion in Scenario S1 (low demand). This figure reflects the costs associated with system integration and investment in renewable energy systems. When electricity demand is low, the system cannot fully consume the electricity generated by wind and solar power, leading to curtailment of renewable energy production. When capital is tied up in renewable energy systems, assets are underutilized, creating an opportunity cost of up to 35.26 billion USD.

In PA3 (40% VRE), the highest regret value across the entire matrix is 40.49 billion USD. This value reflects the consequences of internalizing external costs through carbon pricing. When strong environmental and climate policies are implemented, coal-fired power plants are forced to close early or operate at low load levels, turning these assets into stranded assets with difficult-to-recover investments.

In the S2 scenario, PA2 with 55% VRE achieves an optimal state. In both low- and high-load scenarios, PA2 still performs best, limiting regret to 12.00 billion USD for S1 and 11.65 billion USD for S3. PA2 represents the economic equilibrium point, where a 55% VRE share is sufficient to mitigate the risk of carbon tax penalties similar to PA3 while avoiding the wasteful overinvestment seen in PA1.

### 4.3 Discussion

Short- and medium-term load uncertainties are reflected not only in power deficits but also in operating costs incurred by mobilizing marginal generation sources during peak load periods. Therefore, evaluating and selecting planning scenarios based solely on the objective of minimizing costs and ensuring sufficient capacity is insufficient. From a decision-making perspective, the balanced transition option (PA2) is more comprehensive and robust. This option avoids the high costs of the renewable energy priority option and the risks associated with a long-term, difficult-to-change baseload structure. It emphasizes the importance of accounting for load uncertainty in system cost assessments. Conversely, resilient planning options typically have a more balanced mix of baseload and VRE sources. This choice does not achieve the lowest cost in any scenario but minimizes avoidable risks across the entire set of scenarios presented.

In terms of policy, the results show that Vietnam's adjusted Power Plan VIII has demonstrated flexibility in its scenario-based planning approach. However, criteria for assessing resilience, calculating regret indices, and similar metrics should be added to select scenarios appropriate to the current energy transition context, where the share of VRE is increasing.

Other international research emphasizes that technology affects VRE deployment forecasting in planning, as well as on electricity prices and energy demand [24]. Some studies propose comparative-scenario evaluation frameworks to address the challenge of expanding power sources and grids in integrated power systems by using the k-medoids method to reduce the number of calculation scenarios [25]. Sustainable assessment has recently been studied, focusing on designing solutions to address uncertainty in modern power systems over time, while accounting for short-term operating conditions and system security [26]. Unlike previous international studies, this study proposes an assessment framework based on the regret index. This framework aims to support risk-minimizing decision-making in national planning, towards the Net Zero goal, in line with Vietnam's power system development. In this context, power system planning is gradually shifting from cost assessment to a more sustainable approach as VRE sources increasingly dominate the power system. Although environmental and social aspects are not yet included in the regret index calculations, this study emphasizes mitigating decision-making risks in long-term scenarios. This is an essential contribution to Vietnam's energy transition planning strategy.

## 5. CONCLUSION AND POLICY IMPLICATIONS

### 5.1 Conclusion

In the context of an electricity system with a high proportion of VRE, and a commitment to reducing greenhouse gas emissions to achieve the Net Zero target by 2050, the paper analyzed the challenge of planning Vietnam's electricity system under increasingly uncertain conditions. The study highlights the limitations of traditional planning. It emphasizes the need to evaluate options in different scenarios while considering the capacity-contributing factors for each group of power generation sources. The results show that options have different costs depending on electricity demand. The results demonstrate a balance between short-term electricity system costs, stability under uncertain conditions, and energy transition objectives. Specifically, options prioritizing baseload sources have lower system costs and are less sensitive to load changes. In contrast, options prioritizing renewable energy are more expensive. Thus, the planning problem does not aim to find an absolute robust solution in the short term. Instead, stability is chosen to minimize risk and achieve acceptable long-term efficiency. In Vietnam, the research results are highly consistent with the national power system planning direction, which adopts a cautious approach to energy transition. Applying this approach can improve the reliability, feasibility, and sustainability of national power plans amid a rapid energy transition driven by environmental commitments. Prioritizing baseload sources offers advantages in terms of cost and short-term electricity supply security, but also carries risks related to technological advancements and difficulties in achieving long-term emission reduction targets. Conversely, rapid transition options to renewable energy are better aligned with Net Zero goals but entail trade-offs in costs and load uncertainty management. In this context, a balanced approach is preferred that simultaneously addresses security, cost, and environmental objectives.

The results are consistent with the analyses of the International Energy Agency [27]. In the short term, the plan's energy mix will prioritize baseload sources as the mainstay for providing stable capacity and reducing electricity system costs. A rapid transition to renewable energy will increase costs if there are no supporting solutions, such as storage or regulation, during peak-load periods. Therefore, to minimize risks in decisions under load uncertainty, the proposed balanced option is the most sustainable.

The study analyzes the trade-offs and robustness of national power-source planning options. Several assumptions were incorporated into the calculations to simplify the planning problem. The paper analyzes load uncertainty, while other uncertainties (fuel prices, grid development speed, climate change, carbon policies, etc.) are assumed to be fixed to avoid overlap. As the study focuses only on short-term costs, long-term impacts, such as emissions and risks associated with technology transition, have not been included in the calculations. These limitations present opportunities for future research directions, such as: integrating detailed uncertainty calculation models to assess the sustainability of options corresponding to different scenarios; extending the scope of uncertainty to carbon policy and climate change; and incorporating environmental and energy indicators with the pillars of distributive justice, procedural justice, and recognition justice to more comprehensively evaluate trade-offs in the energy transition process.

### 5.2 Policy implications

The results and analyses above show that planning based solely on minimizing total system costs will create significant trade-offs between costs and sustainability among uncertain long-term scenarios. This also reduces flexibility in the power generation mix. The calculation results in this research indicate that Option 2 (PA2) – the balanced option – is a suitable choice for Vietnam's current context, with costs that are not too high and a low regret index across the set of scenarios. This option helps minimize risks in planning scenarios and facilitates comparisons between planning options in the context of the energy transition using the regret index. The process of adjusting planning to account for uncertainty factors will enhance the reliability and adaptability of Vietnam's long-term power system development strategy. Therefore, this study proposes the following four key policy implications:

Firstly, institutionalize specific national power system plans for each scenario, integrating sustainability indicators into the development and selection of these plans.

Secondly, standardize input data (load capacity, fuel costs, availability factors, etc.) at the national level. This is a prerequisite for a complete assessment of trade-offs among costs, reliability, and emissions.

Thirdly, the plan must include regulations and policies that ensure coordination between power generation planning and power grid planning. This will help avoid increased investment costs in power generation, thereby reducing the effectiveness of sustainable solutions.

Finally, developing market mechanisms that encourage flexibility in the power system (e.g., peak sources, storage sources, load adjustment) will help reduce regret indices in various scenarios. At the same time, it will enhance the power system's long-term adaptability.

Sustainable power system planning is the foundation for Vietnam to achieve its long-term goals of energy security, economic development, and environmental protection.

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