Research on the Role of Bac Ai Pumped Storage Hydropower in the Operation of Vietnam's Power System in 2030 with a High Proportion of Renewable Energy

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Received: 27 June 2024 | Revised: 25 July 2024 | Accepted: 29 July 2024

 DOI: https://doi.org/10.48084/etasr.8238

ABSTRACT

Research on solutions to improve the regulation capacity of power systems is essential and urgent in the context of renewable energy sources being highly variable and constituting a significant proportion of

Vietnam's power system by 2030. Pumped storage hydropower plants serve as an excellent energy reserve and are widely used to provide peak energy demands for daily and nightly loads. In Vietnam, the Bac Ai hydropower storage project, currently under construction, is the first of its kind and is expected to play a significant role as a large-scale energy storage system. This comes at a time when renewable energy sources are growing rapidly, with many large-scale solar and wind power plants being invested and commissioned. This project will be crucial to addressing surplus and shortage issues in power system load, stabilizing the system, regulating frequency, and ensuring stable, safe, and reliable operation of the national power grid. However, to assess the necessity of this project within the Vietnamese power system, scientific evaluations are required regarding the impact of capacity scale, timing, and operational position of this project within the development scenarios of Vietnam's power system. This study investigates an optimization problem for the operation of the Vietnamese power system, considering the characteristics of generation sources and transmission lines using the PyPSA software. The aim is to calculate and identify the role of the Bac Ai pumped storage hydropower plant in Ninh Thuan province in the 2030 scenario of Vietnam's power system, which includes a high proportion of renewable energy sources.

Keywords-Power System (PS); Pumped Storage Hydropower (PSH); Renewable Energy (RE); Wind Power (WP); Solar Power (SP); peak shaving; power system optimization; Power Development Plan VIII (PDPVIII)

I. INTRODUCTION

Pumped Storage Hydropower (PSH) has been studied and applied worldwide since the 1960s. PSH currently represents more than 94% of global energy storage capacity and more than 96% of energy stored in grid-scale applications. The countries with the largest installed capacity are China (50,940 MW), Japan (21,817 MW), and the United States (16,744 MW) [1, 2]. Research focuses primarily on evaluating and analyzing PSH technologies, including their development, operation, and technical challenges. The literature provides a comprehensive view of the current status of PSH in different regions, such as Europe, China, India, and the United States, while also comparing it with other energy storage systems [3-12]. In Vietnam, many studies have focused on the management and optimization of water resources in Vietnam's hydroelectric system [13-18]. However, Vietnam has begun to study and implement PSH projects only in recent years [19-21]. The first PSH plant in Vietnam is the Bac Ai PSH in Ninh Thuan province, with a capacity of 1,200 MW [21]. This project started construction in early 2020 and is being developed by the Vietnam Electricity Group (EVN), with an expected operational date in 2030.

According to the Power Development Plan for the period 2021-2030, with a vision to 2050 (PDP VIII), by 2030, the total installed power capacity of Vietnam will reach 150,489 GW. Of this, coal-fired power will account for 20%, gas-fired power for 9.9%, LNG-fired power for 14.9%, hydropower and flexible sources for 19.7%, wind, solar, and other Renewable Energy (RE) sources for 30.3%, imported power for 3.3%, and PSH and other energy storage devices for 1.8%. By 2050, the total installed power capacity will nearly reach 573,129 GW, with thermal power sources at 15%, hydropower and flexible sources at 15.4%, wind, solar, and other RE sources at 65%, imported power at 2.3%, and PSH and other energy storage devices at 7.9%. The proportion of coal-fired power will decrease significantly from 29% in 2020 to 20% in 2030 and 0% by 2050 [22, 23].

The proportion of RE in Vietnam's Power System (PS) mix is expected to increase substantially from 30.3% in 2030 to 65.0% by 2050. This is a significant step toward a sustainable and low-emission PS, in line with the global trend toward developing clean energy. However, a large share of RE in PS will pose many economic and technical challenges to the safe operation of the power grid. This includes the issue of curtailing wind power and solar power due to excess electricity, especially during low-demand periods, such as midday on holidays. This not only wastes resources but also complicates frequency and voltage regulation operations, as the output of wind power and solar power sources fluctuates depending on weather and climate conditions. To address this issue, one of the crucial solutions is to develop PSH projects. PSH plays an essential role in balancing electricity supply and demand, especially during periods of significant fluctuations from RE sources. The characteristic of this type of plant is its reversible operation mode, using excess electricity from the system (from thermal power plants and RE) during low-demand hours to pump water into a reservoir for energy storage, acting as load-consuming during off-peak hours. During peak hours, when the system needs power, the PSH plant becomes a power station that supplies electricity to meet peak demand, similar to a conventional hydroelectric plant.

To evaluate the role and necessity of PSH in terms of scale, timing, and location, it is essential to consider this power source in the context of optimizing the development and operation of the PS. This involves solving the problem of dispatching power and energy from various generation sources to meet consumption demands with the lowest total production and transmission costs. Studies in this field include:

- From 1993 to 1995, a group of scientists from the Institute of Energy Science investigated the optimal development of Vietnam's PS using a three-node model: the North, Central, and South regions. The 500kV Hoa Binh, 500kV Da Nang-Kon Tum, and 500kV Phu Lam substations were selected as the main nodes. This problem was solved using linear programming to determine the optimal structure of the PS with the lowest total production and transmission costs [24].
- From 2005 to 2012, building on previous research, a research group from the Institute of Energy Science improved the optimal development model of the PS, still based on linear programming, but with enhanced capabilities to handle larger datasets [25-33].

- In [34], optimization methods were studied to improve the operational efficiency of the power supply for smaller areas such as districts, towns, and cities.
- In [35], mixed-integer linear programming was used to develop an optimal power distribution software for the PS, although it did not fully consider transmission costs between regions.
- In [36], various models, such as EFOM-ENV, WASP, STRATEGIST, MARKAL, MESSAGE and LEAP, were compared to assess their advantages and disadvantages. LEAP was selected as the primary tool for the structure of RE sources in Vietnam's power development plan until 2030.
- In [37-39], a mathematical model was proposed, simulating Vietnam's PS from 2015 to 2030 and developing software to optimize the system's operation. This software calculated the optimal load curve based on the lowest total cost and CO_2 emissions but was not fully developed for specific sources such as PSH, WP, and SP.
- Other studies explored various methods. In [40], particle swarm optimization and the crow search algorithm were used to optimize generation costs and load shedding in the PS, ensuring operational constraints and significantly reducing total costs. In [41], binary particle swarm optimization and multi-objective functions were used to optimize feature selection, improving the effectiveness and accuracy of PS system stability classification. In [42], the coyote optimization algorithm was used to optimize the location and size of distributed generators in the electrical distribution system to minimize power losses.

To date, there has been no comprehensive study on the optimal development and operation of Vietnam's PS with the inclusion of PSH, a new source that serves both as a load and as a power source to address electricity surplus and shortage at certain times when the proportion of RE or thermal power sources is high in Vietnam's PS. Given the practical and scientific issues mentioned above, this study presents the results of applying the optimal development problem of the PS using the PyPSA open-source tool [43] to calculate and determine the timing, scale, and working location of the Bac Ai PSH plant in Vietnam's PS corresponding to development scenarios until 2030. This study focuses on building a PS simulation model with all characteristics of the generation sources, transmission lines, and software to determine the timing, scale, and working location of the PSH plants in Vietnam's PS according to the criterion of the lowest total system operating cost.

II. METHODOLOGY

Figure 1 shows the logic diagram of the research method. The blocks in Figure 1 are explained below.

- Building the PS data: Organize and construct data for generation, transmission, and load across six economic regions: (i) Northern Vietnam, (ii) North Central Vietnam, (iii) Central Vietnam, (iv) South Central Vietnam, (v) Central Highlands, and (vi) Southern Vietnam [23].
- Scenario Calculations: Scenarios with and without Bac Ai PSH, which is in Region 4 - South Central Vietnam.
- Calculating PS balance scenarios: Perform calculations using the PyPSA software.
- Comparing calculation results: Compare the results of the different scenarios based on three criteria: reducing thermal power generation, increasing the efficiency of RE utilization, and reducing PS production costs.
- Evaluating the Role of Bac Ai PSH: Assess the importance of Bac Ai PSH based on the three aforementioned criteria.

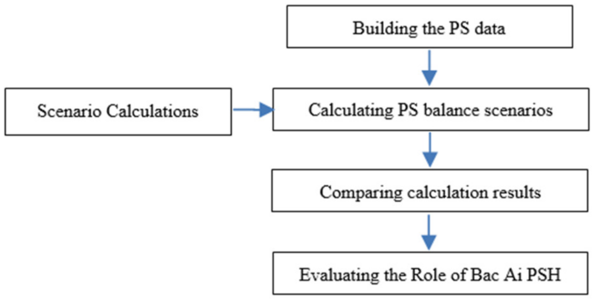


Fig. 1. The research method.

Figure 2 shows a simplified topology of the Vietnam electric grid. The optimization model for the PS is based on PyPSA [43].

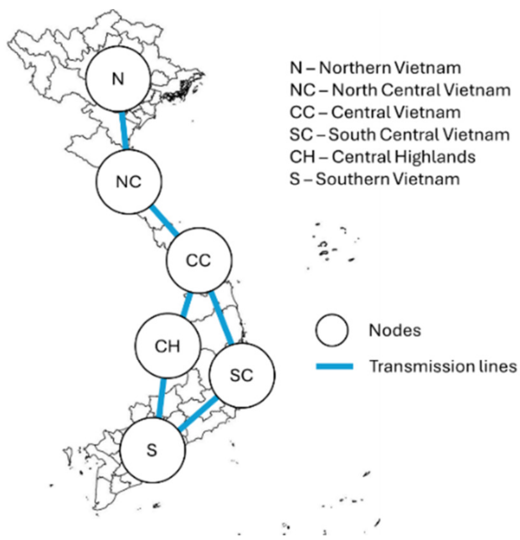


Fig. 2. Simplified topology of Vietnam power grid.

A. *Objective Function of the Optimization Problem*

The objective function of the problem aims to minimize the cost of operating the system during the day, including the total hourly operating cost of power plants, transmission costs of lines, and PSH, that is:

$$\min\left(\sum\nolimits_{n,m,t} O_{n,m,t}^{(G)} G_{n,m,t} + \sum\nolimits_{n,m,t} O_{n,m,t}^{(S)} S_{n,m,t} + \sum\nolimits_{l,t} O_{l,t}^{(L)} L_{l,t}\right) \quad (1)$$

where n is the index of the n^{th} node in the system, representing a region according to PDP VIII, m is the index of the m^{th} plant in node n, and is the index of the m^{th} stored hydropower in the n^{th} node, t is the time-of-day index (hour), l is the index of the l^{th} line, $O_{n,m,t}^{(G)}$ are the operating costs of the m^{th} power plant at node n at time t, $O_{n,m,t}^{(S)}$ is the operating cost of pumped storage hydropower plant s at node n at time t, $O_{l,t}^{(L)}$is the transmission cost of the l^{th} line at time t, $G_{n,m,t}$ is the generating capacity of plant m at node n and time t, $S_{n,m,t}$ is the generating capacity (>0) or storage (<0) of the m^{th} PSH at node n and time t, and $L_{l,t}$ is the transmission power of the l^{th} line at time t.

B. Constraints

The optimization must satisfy several constraints, which can be grouped into the following categories: power balance at nodes, minimum and maximum permissible generation capacity of power plants, energy storage, and maximum transmission capacity of power lines. The load demand $d_{n,t}$ at each node n at any given time t must be met by the generation sources, PSH at that node, or the power $L_{l,t}$ transmitted to that node via transmission line l. The fixed load demand at node n at time t is

$$\sum\nolimits_m G_{n,m,t} + \sum\nolimits_m S_{n,m,t} + \sum\nolimits_l \alpha_{l,n,t} L_{l,t} = d_{n,t} \ \ \forall n,t \ (2)$$

where $\alpha_{l,n,t}$ is the direction and power transmission efficiency of line l compared to node n, $-1 \le \alpha_{l,n,t} < 0$ if power l leaves node n, and $0 < \alpha_{l,n,t} \le 1$ if power l enters node n. This value can be defined depending on time t. The constraint on generating power of each power plant is:

$$g_{n,m,t}^{(min)} G_{n,m}^{(nom)} \le G_{n,m,t} \le g_{n,m,t}^{(max)} G_{n,m}^{(nom)} \ \ \forall n,m,t$$

where $g_{n,m,t}^{(\min)} \in [0,1]$ is the minimum generating power per unit of plant m at node n and time t, $g_{n,m,t}^{(\max)} \in [0,1]$ is the maximum generating power per unit of plant m at node n and time t, and $G_{n,m}^{(nom)}$ is the nominal power of plant m at node n.

For a regular power plant, $g_{n,m,t}^{(\min)}$ and $g_{n,m,t}^{(\max)}$ are constant over time. With a factory that allows full range of operation from 0% to 100% of nominal power, $g_{n,m,t}^{(\min)} = 0$ and $g_{n,m,t}^{(\max)} = 1$. For renewable energy plants, such as wind and solar, $g_{n,m,t}^{(\min)}$and $g_{n,m,t}^{(\max)}$ represent the available capacity depending on the weather. Also, $g_{n,m,t}^{(\min)}$ and $g_{n,m,t}^{(\max)}$ can be used to assume requirements for limited grid connection or mandatory grid connection of one or more power plants.

The charge/discharge power constraints of the PSH are similar to those of power plants:

$$s_{n,m,t}^{(min)} S_{n,m}^{(nom)} \le S_{n,m,t} \le s_{n,m,t}^{(max)} S_{n,m}^{(nom)} \ \ \forall n,m,t \quad (3)$$

where $s_{n,m,t}^{(\min)} \in [-1,1]$ is the minimum power per unit of energy storage m at node n and time t, $s_{n,m,t}^{(\max)} \in [0,1]$ is the maximum power per unit of energy storage m at node n and time t, and $S_{n,m}^{(nom)}$ is the nominal capacity of energy storage m at node n.

The energy storage from a power plant, denoted as $s_{n,m,t}^{(\min)}$, can be negative, because the energy storage power can be negative (when charging) and positive (when discharging). The state of charge of energy storage $E_{n,m,t}$ of the m^{th} PSH at node n and time t is:

$$E_{n,m,t} = E_{n,m,t-1} + \eta_{n,m}^{(c)} S_{n,m,t}^{(c)} - \eta_{n,m}^{(dc)} S_{n,m,t}^{(dc)} + S_{n,m,t}^{(inflow)} - S_{n,m,t}^{(spillage)} \quad (4)$$

$E_{n,m,t}$ must be determined and limited by the nominal stored energy $E_{n,m}^{(nom)}$:

$$e_{n,m,t}^{(min)} E_{n,m}^{(nom)} \le E_{n,m,t} \le e_{n,m,t}^{(max)} E_{n,m}^{(nom)} \quad (5)$$

where n denotes the n^{th} node, m is the m^{th} energy storage in the n^{th} node, $E_{n,m,t-1}$ is the state of charge at the previous time $(t-1)$, $\eta_{n,m}^{(c)}$ is the charging efficiency, $S_{n,m,t}^{(c)}$ is the charging power, $\eta_{n,m}^{(dc)}$ is the discharge efficiency, $S_{n,m,t}^{(dc)}$ is the discharge power, $S_{n,m,t}^{(inflow)}$ is the natural inflow capacity (e.g. rain, natural flow), $S_{n,m,t}^{(spillage)}$ is the natural spillage power (e.g. evaporation), $e_{n,m,t}^{(\min)} \in [0,1]$is the minimum state of charge of energy storage per unit, and $e_{n,m,t}^{(\max)} \in [0,1]$ is the maximum state of charge of energy storage per unit.

The transmission power $L_{l,t}$ of the lines are constrained according to line capacity $L_l^{(nom)}$:

$$f_l^{(min)} L_l^{(nom)} \le L_{l,t} \le f_l^{(max)} L_l^{(nom)} \quad (6)$$

where l is the l^{th} line, $f_l^{(\min)} \in [0;1]$ is the minimum transmission power per unit, $f_l^{(\max)} \in [0;1]$is the maximum transmission power per unit, and $L_l^{(nom)}$ is the nominal transmission capacity of the line.

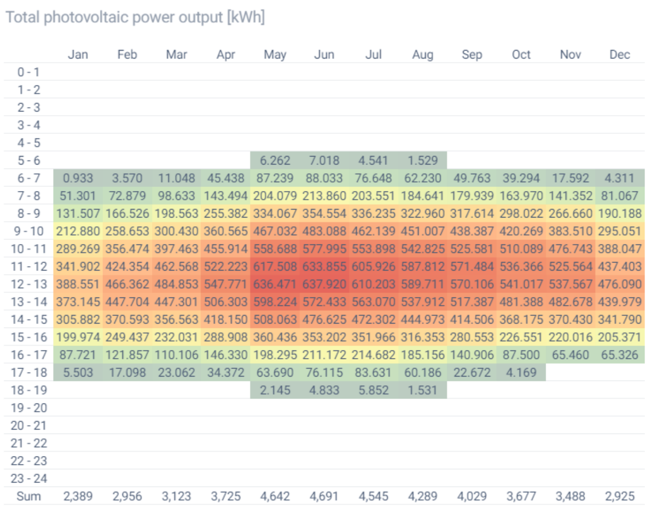
C. Data

The data used are based on data published in PDP VIII [23]. The nodes of the power system are defined according to the six economic regions. The lines connecting the nodes are built based on data on transmission lines according to PDP VIII, with the following modeling method:

- Skip if the line goes from province A to province B of the same region (node).
- The line going between the two regions 1 and 2 has:
  - Nominal transmission capacity equal to the total nominal transmission capacity of all lines going from a province in region 1 to a province in region 2.
  - Line length equal to the longest length among all lines going from a province in region 1 to a province in region 2.

According to PDP VIII, power plants (coal, gas, wind, and solar) are added to each node of the network. For coal-fired power plants, the capacity constraint is between 20% and 100%. For gas-fired power plants, it is between 0% and 100%. For RE sources, there is a time-dependent capacity constraint, which is $g_{n,m,t}^{(\min)} = 0$, and $g_{n,m,t}^{(\max)}$ must follow the technical potential characteristics of each type of source in each region (node).

For solar power sources, the solar potential is determined through the Global Solar Atlas [44]. 1 MW is used as a base value to calculate hourly and monthly electricity production. The electricity production of any large-scale project of any capacity is calculated by multiplying this base value by the installed capacity of that project. The implementation method is as follows: (i) For each region n (node n), select a representative point on the Global Solar Atlas to simulate a 1250 kWp project (corresponding to an AC power of 1 MW), (ii) Simulate and obtain a data table of hourly and monthly energy values (for example, Figure 3 shows for the Northern region). Since the division is by hour, this value is also the available capacity of solar power per hour and month needed $g_{n,m,t}^{(\max)}$. Here, all plants m of node n have the same available capacity value $g_{n,m,t}^{(\max)}$ at the same time t.


Total photovoltaic power output [kWh]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6					6.262	7.018	4.541	1.529				
6 - 7	0.933	3.570	11.048	45.438	87.239	88.033	76.648	62.230	49.763	39.294	17.592	4.311
7 - 8	51.301	72.879	98.633	143.494	204.079	213.860	203.551	184.641	179.939	163.970	141.352	81.067
8 - 9	131.507	166.526	198.563	255.382	334.067	354.554	336.235	322.960	317.614	298.022	266.660	190.188
9 - 10	212.880	258.653	300.430	360.565	467.032	483.088	462.139	451.007	438.387	420.269	383.510	295.051
10 - 11	289.269	356.474	397.463	455.914	558.688	577.995	553.898	542.825	525.581	510.089	476.743	388.047
11 - 12	341.902	424.354	462.568	522.223	617.508	633.855	605.926	587.812	571.484	536.366	525.564	437.403
12 - 13	388.551	466.362	484.853	547.771	636.471	637.920	610.203	589.711	570.106	541.017	537.567	476.090
13 - 14	373.145	447.704	447.301	506.303	598.224	572.433	563.070	537.912	517.387	481.388	482.678	439.979
14 - 15	305.882	370.593	356.563	418.150	508.063	476.625	472.302	444.973	414.506	368.175	370.430	341.790
15 - 16	199.974	249.437	232.031	288.908	360.436	353.202	351.966	316.353	280.553	226.551	220.016	205.371
16 - 17	87.721	121.857	110.106	146.330	198.295	211.172	214.682	185.156	140.906	87.500	65.460	65.326
17 - 18	5.503	17.098	23.062	34.372	63.690	76.115	83.631	60.186	22.672	4.169		
18 - 19					2.145	4.833	5.852	1.531				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	2,389	2,956	3,123	3,725	4,642	4,691	4,545	4,289	4,029	3,677	3,488	2,925

Fig. 3. Hourly and monthly energy generation of a 1MW solar power project at a representative location in the Northern region.

For wind power, in the simulation model considered for a typical day, it can be assumed that the wind does not change significantly, and the values are set as $g_{n,m,t}^{(\min)} = 0$ and $g_{n,m,t}^{(\max)} = 0{,}7$. The Bac Ai PSH, located in the South Central region (node) of Vietnam, has the following parameters [21-23]: rated power: 1,200 MW, pumping efficiency: 87,76%, generation efficiency: 86%, pumping hours: 8, and generation hours: 6. The load is constructed based on a typical daily load pattern. The structure of the PS, investment and operational costs, and electricity purchase and sale prices were also taken from PDP VIII [22, 23, 46, 47].

III. RESULTS

Vietnam's PS has developed robustly with a diverse array of power sources. Main sources include hydropower, thermal power, solar power, wind power, and other RE sources. The primary transmission lines are the 220 kV and 500 kV systems, which ensure the transmission of electric energy from power plants to substations and ultimately to consumers. This network is developed and managed to meet the increasing load demand, especially in regions with high economic growth rates. Different regions in the country have varying distributions of power sources and loads, with areas such as the South and Central regions having higher solar and wind power capacities, while the North has more thermal and hydroelectric sources.

A. Input Data and Calculation Results for Scenarios

To determine the role of the Bac Ai PSH in Vietnam's PS, calculations were made for two scenarios: one with the participation of Bac Ai PSH and one without it. The calculation year is 2030, when Bac Ai PSH is expected to be operational. The calculations are based on a typical summer day in June 2030, which has the highest load demand and the highest RE (solar) capacity. During this time, the available capacity of traditional peak-shaving hydropower sources is only 60-70% due to the dry season, while the available capacity of thermal power and other sources remains unchanged.

1) Scenario 1: Without Bac Ai PSH

- Year of calculation: 2030
- Load data: typical working day load profile countrywide with peak load in June 2030 (Figure 4) [22, 23].
- Electricity generation data: according to the 2030 power generation development plan in PDP VIII (Figure 5, Table I) [22, 23].
- Substation and transmission line data (220kV and 500kV): according to the 2030 grid development plan in PDP VIII [22, 23].

TABLE I. SET CAPACITY OF POWER SOURCES (MW)

Biomass	Coal	Gas	Hydro	Oil	Solar	Wind
1,126	85,940	40,432	30,106	1,952	23,030	14,383

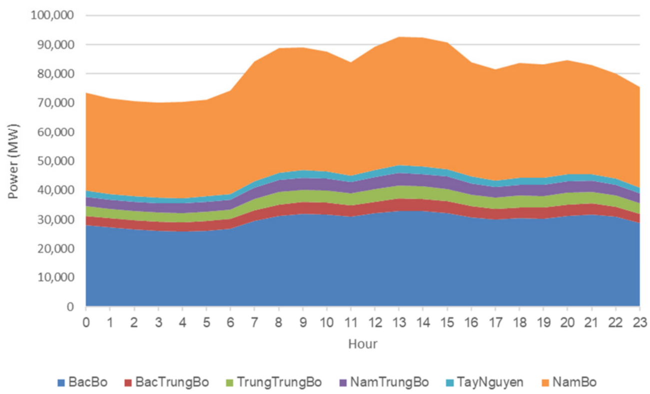


Fig. 4. Load curve for the entire country on a typical summer workday with the highest load capacity in June 2030.

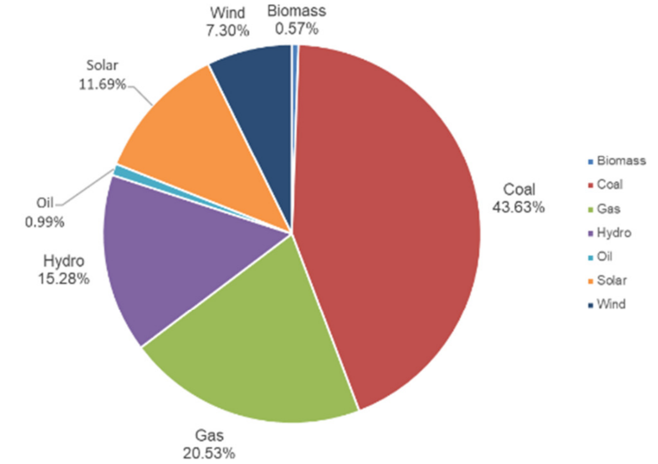


Fig. 5. Electricity generation structure in 2030 without Bac Ai PSH.

2) *Scenario 2: With the Participation of Bac Ai PSH*

- Calculation year: 2030
- Load data: National typical load curve for the highest load working day in the summer of June 2030 (Figure 4) [22, 23]
- Electricity generation data: according to the 2030 power generation development plan in PDP VIII (Figure 5, Table II) [22,23]
- Substation and transmission line data (220kV and 500kV): according to the 2030 grid development plan in PDP VIII [22, 23].

TABLE II. APPLIED CAPACITY OF POWER SOURCES (MW)

Biomass	Coal	Gas	Hydro	Oil	Solar	Wind	PSH
1,126	85,940	40,432	30,106	1,952	23,030	14,383	1,200

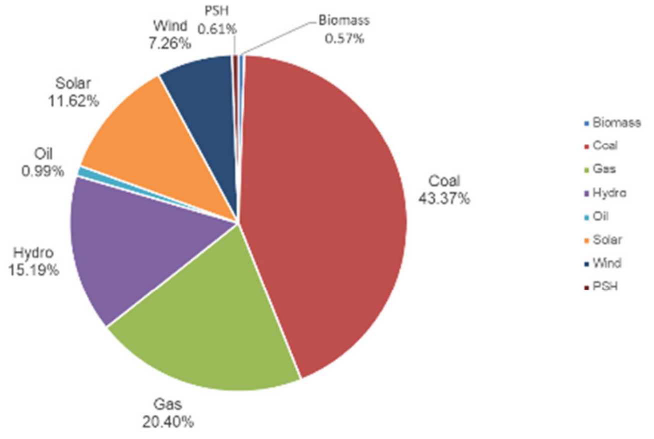


Fig. 6. Power source structure in 2030 with Bac Ai PSH.

B. *Calculation Results for Scenario 1*

TABLE III. CALCULATION RESULTS OF POWER RESOURCES IN COVERING LOAD CURVE (MW)

Biomass	Coal	Gas	Hydro	Oil	Solar	Wind
1,126	27,240	27,346	22,555	1,952	13,566	10,068

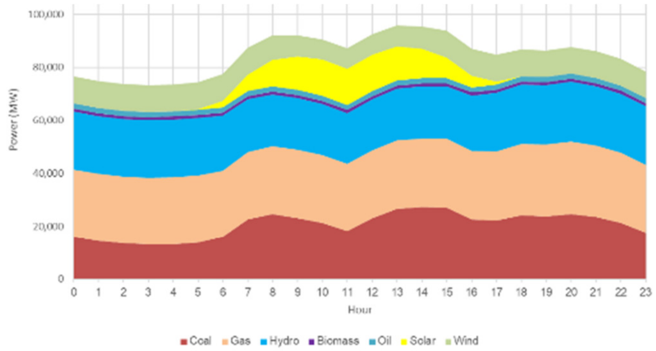


Fig. 7. Results on a typical daily load curve in June 2030 (Scenario 1).

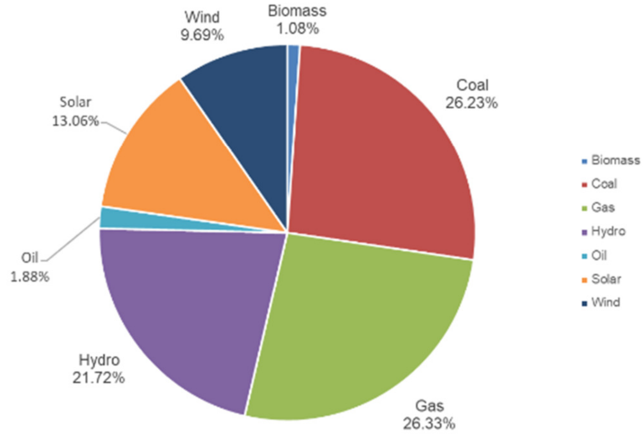


Fig. 8. The ratio of participating sources covering the typical daily load curve in June 2030 (Scenario 1).

The operating cost of the PS in a day without the participation of the Bac Ai PSH is 100,219,007 USD.

C. *Calculation Results for Scenario 2:*

TABLE IV. CALCULATION RESULTS OF MOBILIZED POWER RESOURCES IN COVERING LOAD CURVE (MW)

Biomass	Coal	Gas	Hydro	Oil	Solar	Wind	PSH
1,126	27,240	26,358	22,555	1,952	14,766	10,068	988

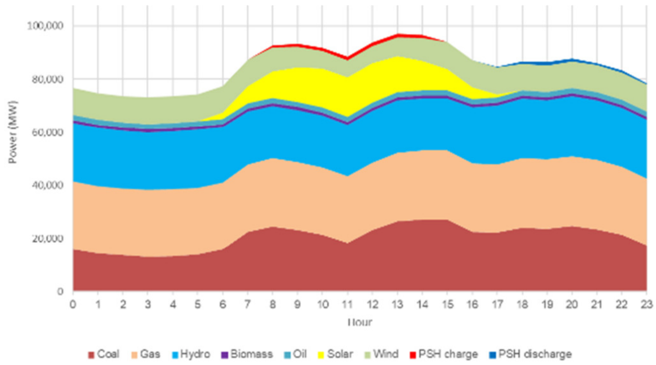


Fig. 9. Results on a typical daily load curve in June 2030 (Scenario 2).

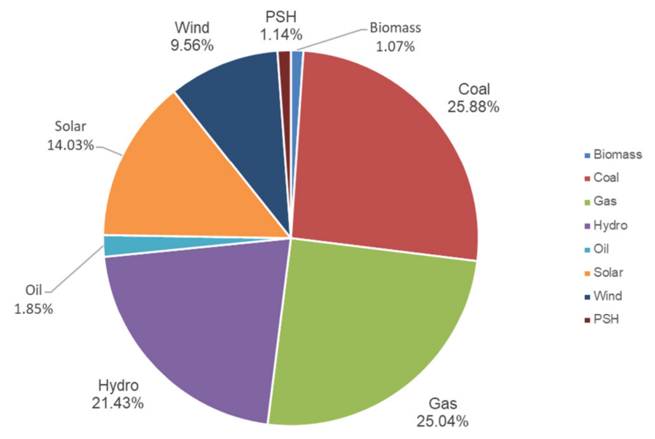


Fig. 10. The ratio of participating sources covering the typical daily load curve in June 2030 (Scenario 2).

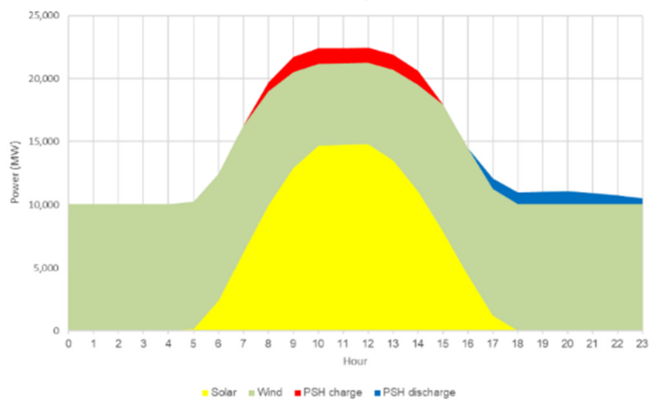


Fig. 11. Overlaying results on a typical daily load curve in June 2030 (only showing RE sources (wind, solar) and Bac Ai PSH.

The operating cost of the power system during the day with the participation of Bac Ai PSH is 99,904,008 USD. Bac Ai PSH will work at peak load with the optimal capacity of 988 MW entering the system, reaching 82.33% of the set capacity of 1,200 MW.

IV. DISCUSSION

Based on the optimized calculations for the development of Vietnam's electricity system in 2030 under scenarios without (Scenario 1) and with the participation of the Bac Ai PSH (Scenario 2), the following conclusions can be drawn:

- The participation of the Bac Ai PSH reduces the system's dependency on gas-fired thermal power from 27,346 MW to 26,358 MW (approximately 3.75%). This underscores its role as a flexible power source, albeit with higher peak electricity costs.
- The participation of the Bac Ai PSH increases the efficiency of utilizing the most RE sources, especially solar power, with mobilized capacity increasing from 13,566 MW to 14,766 MW (8.85% increase).
- In the scenario where the Bac Ai PSH participates, the electricity production costs of the system are optimized, decreasing from 100,219,007 USD per day to 99,904,008 USD per day, corresponding to a reduction of approximately 315,000 USD per day.

Therefore, the operational involvement of the Bac Ai PSH in 2030 is crucial, especially with a high proportion of RE sources in the system. It enhances the efficiency of RE utilization, rationalizes the deployment of thermal power sources, and contributes to reducing the total electricity production costs for the entire system.

V. CONCLUSION

This study evaluated the critical role of the Bac Ai PSH in optimizing the operation of Vietnam's power system, particularly when integrating large proportions of unstable RE sources. This evaluation was performed using PyPSA for optimal power system operations. The computational results highlighted the increasing installation capacities and robust development of RE sources, such as wind and solar power, in Vietnam's 2030 scenario. The results emphasize the necessity of building the Bac Ai PSH with a capacity of 1,200 MW, operational from 2030 onward, to ensure the stability, efficiency, and flexibility of the electricity system. Furthermore, this study underscored the importance of developing energy storage infrastructure, such as PSH, to enhance the efficiency and stability of the power system, particularly with the integration of RE sources. This also contributes to Vietnam's sustainable development goals and environmental protection efforts for the future. However, the results were based on calculations for a typical peak load day in the summer of 2030. For comprehensive scientific grounds in developing the Bac Ai PSH, further research and calculations are necessary for the period from 2030 to 2050, considering seasonal and annual load scenarios. These studies can focus on optimizing models for the development and operation of the power system to assess the roles and impacts of other PSH plants within Vietnam.

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