

Assessing Vietnam's CO₂ Emission Roadmap to 2030 Based on the Revised Power Development Plan VIII Using the PyPSA Model

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ABSTRACT

This study evaluated Vietnam's projected CO₂ emissions in 2030 under three Renewable Energy (RE) penetration scenarios- low (Case 1), medium (Case 2), and high (Case 3)- using the Python for Power System Analysis (PyPSA) model, an open-source high-resolution electricity system optimization tool. The modeled CO₂ emissions were 198.84, 191.15, and 183.65 million tons for Case 1, Case 2, and Case 3, respectively. These results were consistent with the PDP8-Rev baseline range while showing that higher RE deployment can reduce emissions by up to 15.19 million tons (about 7.6%) compared to the low-RE scenario, thereby enhancing Vietnam's alignment with its mid-term climate targets and approaching the conditional JETP pathway. The findings underlined the importance of accelerating RE investment, expanding energy storage, improving system flexibility, and strengthening regulatory mechanisms. Furthermore, this study demonstrated the value of transparent and reproducible modeling tools, such as PyPSA, in supporting evidence-based energy transition planning and policymaking.

Keywords-CO₂ emissions; renewable energy; PDP8-Rev; PyPSA; power system modeling

I. INTRODUCTION

According to the global climate commitments under the Paris Agreement, Vietnam will try to have achieved net-zero Greenhouse Gas (GHG) emissions by the end of 2050. The power sector, as the largest source of CO₂ emissions, plays a central role in this transition. The RE growth in Vietnam, particularly in solar and wind power, has emerged as a reliable solution, supported by policies and attractive feed-in tariffs [1-4]. Specifically, in 2025 the Vietnamese government issued Decision No. 768/QĐ-TTg, approving the Revised National Power Development Plan VIII (PDP8-Rev). The goal of this decision is to have enhanced the non-hydro RE by more than 40% of total installed capacity by 2030 [5]. At the same time, it establishes specific CO₂ emission targets for the power sector: 197-199 million tons by 2030, with a reduction pathway to no more than 170 million tons under the Just Energy Transition Partnership (JETP). These objectives highlight the need to evaluate whether these metrics can enable Vietnam to align its power sector development with both domestic and international climate goals.

The decarbonization of Vietnam's power system has been explored using modeling tools and policy assumptions [6-18]. For example, authors in [6] investigated green scenarios for power generation in Vietnam by 2030, focusing on emissions and costs under various RE targets. In [7], a simulation of a typical low-voltage distribution grid with single-phase and three-phase loads was conducted to evaluate the rooftop solar effects on power quality in urban networks. Additionally, authors in [8] analyzed hydrogen conversion for gas turbines to support net-zero goals, identifying technical feasibility but limited in system-wide implications. In [9], a modular, open-source framework for electricity system optimization - called PyPSA - was introduced, capable of handling multi-node, hourly simulations under technical and economic constraints. Authors in [10] examined decarbonization pathways for China's power system under neutrality targets, showing how the integrated modeling of generation, demand, and policy can inform realistic CO₂ reductions. Authors in [11] developed PyPSA-VN for Vietnam, allowing hourly, regional simulation. However, CO₂ emissions were not integrated at the time. The renewable integration potential in Vietnam was studied in [12] using optimization models, indicating cost reductions of up to 10% through transmission expansion.

While all these studies have relied on modeling tools for optimizing the national energy and power system, they focused on long-term approaches without capturing hourly system dynamics or the updated RE targets in the PDP8-Rev. So, this study tries to fill the specific gap by employing high-resolution temporal modeling using PyPSA, enabling a more accurate assessment of Vietnam's CO₂ emission trajectory to 2030.

II. METHODOLOGY

A. Model Framework

PyPSA has been widely applied in several studies for power system modeling and optimization, especially in Europe [9, 10] and in Vietnam [11]. Their simulation results were consistent

with those obtained from commercial tools, such as PLEXOS or DIgSILENT PowerFactory, especially when considering dispatch optimization, renewable integration analysis, and transmission constraint modeling.

To evaluate CO₂ emissions under Vietnam's power system in 2030, this study utilized the PyPSA model, a high-resolution, open-source electricity system modeling tool [19]. The objective was to simulate the least-cost dispatch of generation sources and estimate CO₂ emissions under various power system configurations derived from PDP8-Rev. The national power system was modeled as a multi-node network. Each node represented a region, characterized by hourly demand, installed generation capacity by technology, renewable profiles, and inter-regional transmission limits. These inputs were derived from PDP8 and revised PDP8 (PDP8-Rev). The topology of the simplified Vietnam power grid is depicted in Figure 1.

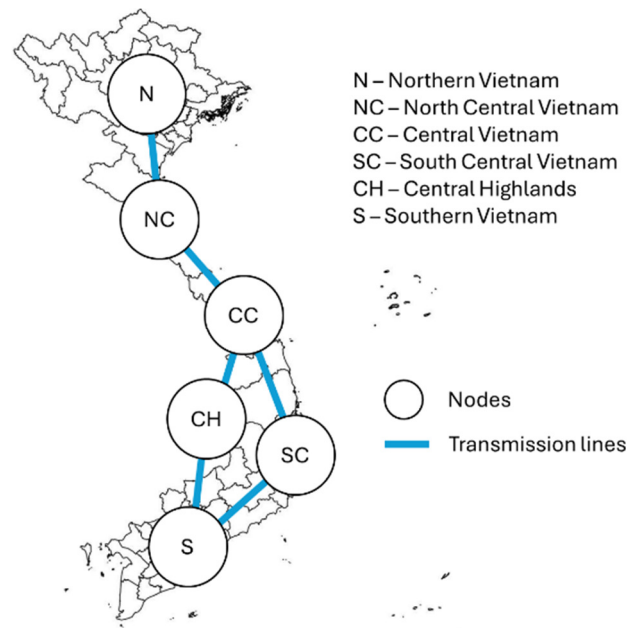


Fig. 1. The topology of simplified Vietnam power grid.

The model minimized the total operating costs while satisfying technical and environmental constraints, such as:

- Power balance at each node and hour
- Generator capacity and availability limits
- Transmission capacity constraints

The objective function of the problem was minimizing the cost of operating the system during the day, including the total hourly operating cost of power plants, transmission costs of lines, and Pumped Storage Hydropower (PSH) [8, 9, 13]:

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

The operating cost term $O_{n,m,t}^{(G)}$ included the fuel cost and variable Operation and Maintenance (O&M) cost of each unit. Start-up and shutdown costs of thermal units were represented through standard cost adders implicitly embedded in $O_{n,m,t}^{(G)}$. This formulation is consistent with common applications of PyPSA in dispatch optimization in which:

- n is the index of the n -th node in the system, representing a region according to PDP VIII (Northern region, North Central region, Central region, South Central region, Central Highlands, Southern region),
- m is the index of the m -th plant in node n , as well as 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
- $O_{n,m,t}^{(G)}$ represents 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 PSH plants 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 , at time t
- $S_{n,m,t}$ represents the generating capacity (> 0) or storage (< 0) of m -th PSH, at node n , at time t
- $L_{l,t}$ is the transmission power of the l -th line, at time t

To make sure that the current model reflected the operation of power system, a few basic constrains were set.

- The fixed load demand at node n at time t was:

$$\sum_m G_{n,m,t} + \sum_m S_{n,m,t} + \sum_l \alpha_{l,n,t} L_{l,t} = d_{n,t} \quad \forall n, t \quad (2)$$

where $\alpha_{l,n,t}$ is the direction and power transmission efficiency of line l compared to node n . If power flow l leaves node n then $-1 \leq \alpha_{l,n,t} < 0$, whereas if power flow l enters node, then $0 < \alpha_{l,n,t} \leq 1$. This value can be defined depending on time t .

- Constraint on generating power of each power plant:

$$g_{n,m,t}^{(\min)} G_{n,m}^{(\text{nom})} \leq G_{n,m,t} \leq g_{n,m,t}^{(\max)} G_{n,m}^{(\text{nom})} \quad \forall n, m, t \quad (3)$$

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

For regular power plants, $g_{n,m,t}^{(\min)}$ and $g_{n,m,t}^{(\max)}$ are constant over time, with a powerhouse that allows full range of operation from 0% to 100% of nominal power, then $g_{n,m,t}^{(\min)} = 0$ and $g_{n,m,t}^{(\max)} = 1$. For RE 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, value $g_{n,m,t}^{(\min)}$ 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 transmission power $L_{l,t}$ of the lines was constrained according to line capacity $L_l^{(\text{nom})}$:

$$f_l^{(\min)} L_l^{(\text{nom})} \leq L_{l,t} \leq f_l^{(\max)} L_l^{(\text{nom})} \quad (4)$$

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

It is important to note that several simple assumptions were adopted in this study. First, electricity demand was modeled as static and aggregated by month at the provincial level, then assigned to six regional nodes according to PDP8 and PDP8-Rev. Secondly, while inter-regional transmission constraints were represented, the internal transmission grid was simplified, and detailed intra-regional bottlenecks were not modeled. Third, system losses were incorporated implicitly in the dispatch optimization but not separately reported. These assumptions, while consistent with similar studies [8-10, 13], represent limitations that should be addressed in future research to enhance accuracy and reproducibility.

B. Input Assumptions

This study employed input data solely from the official PDP8-Rev (Table I). The plan outlined the Vietnam's power system development targets toward 2030 under three RE penetration scenarios. The input assumptions included installed generation capacity by technology, projected electricity demand, fuel prices, GHG emission factors, and RE profiles. Notably, fossil fuel-based sources (coal, gas, oil), hydropower, and load demand remained constant across scenarios, while the shares of solar PV and wind varied significantly depending on national and international commitments (e.g., JETP).

TABLE I. INPUT ASSUMPTIONS UNDER PDP8-REV SCENARIOS

Power source	Case 1: Low RE	Case 2: Medium RE	Case 3: High RE
Biomass	1,523 MW	1,523 MW	1,523 MW
Coal	31,055 MW	31,055 MW	31,055 MW
Gas	35,000 MW	35,000 MW	35,000 MW
Hydro	33,500 MW	33,500 MW	33,500 MW
PSH	1200 MW	1200 MW	1200 MW
Oil	1,952 MW	1,952 MW	1,952 MW
Solar PV	46,459 MW	60,000 MW	73,416 MW
Wind (onshore + offshore)	32,066 MW	46,000 MW	55,061 MW
Total wind+solar	~78.5 GW	~92.5 GW	~107.5 GW
Electricity demand	567 TWh	567 TWh	567 TWh

C. Estimation of Greenhouse Gas Emissions

The amount of CO₂ emissions from Vietnam's power system was calculated based on the total electricity output from each source and the corresponding CO₂ emission factor. This method helped assessing the environmental impact of the power system and proposing solutions to reduce these emissions.

The total amount of CO₂ emissions of Vietnam's power system is determined by:

$$CO_{2total} = \sum_i (E_i \times EF_i) \quad (5)$$

where CO_{2total} is the total CO₂ emissions (tons), E_i is the electricity output of source i (MWh), EF_i represents the CO₂ emission factor of source i (tons of CO₂/MWh), and I is the type of power source (coal, gas, oil, hydropower, renewable energy, nuclear, etc.).

The CO₂ emission factors used in this study were adopted from the World Nuclear Association's comprehensive life-cycle assessment of GHGs emissions across various power generation technologies [15]. Given the absence of officially published emission factors specific to each power source in Vietnam, the medium values from the international dataset were applied as a representative estimate for each technology type. The emission factors for each generation technology are summarized in Table II.

TABLE II. GHG EMISSION FACTOR OF POWER GENERATION TYPES

Source Type	Medium	Low	High
	Tons CO ₂ eq/MWh		
Coal	888	756	1310
Oil	733	547	935
Gas	499	362	891
Solar	85	13	731
Wind	26	6	124
Biomass	45	10	101
Hydro	26	2	237

In the simulation, the Medium values were adopted as central estimates, since Vietnam-specific technology-based emission factors are not officially available. This choice avoided systematic under- or over-estimation and is in line with common practice in international studies.

III. RESULT AND DISCUSSION

A. CO₂ Emissions Results

1) Total Emissions by Scenario

Under the Revised PDP8, three scenarios corresponding to different RE penetration levels were simulated. The total CO₂ emissions from Vietnam's power system in 2030 were projected at approximately 198.84 million tons in the Low RE scenario (Case 1), 191.15 million tons in the Medium RE scenario (Case 2), and 183.65 million tons in the High RE scenario (Case 3). A potential reduction of up to 15.19 million tons or 7.6% is observed when comparing Case 3 to Case 1. These results demonstrated the significant emission reduction potential associated with higher RE integration.

2) Emission Composition by Technology

The breakdown of CO₂ emissions by technology under each scenario is presented in Table III. As expected, coal and gas remained the dominant contributors to total emissions. In Case 1, coal-fired generation emitted 105.32 Mt CO₂, followed by gas (69.30 Mt) and oil (12.53 Mt). In Case 3, these values dropped to 96.50 Mt, 64.40 Mt, and 11.90 Mt, respectively.

The emissions from renewable sources remained negligible across all scenarios.

TABLE III. EMISSIONS BY TECHNOLOGY IN 2030 UNDER PDP8-REV SCENARIOS

Technology	Emissions (Mt CO ₂ /year) - Case 1	Case 2	Case 3
Coal	105.32	100.25	96.50
Gas	69.30	66.50	64.40
Oil	12.53	11.97	11.90
Biomass	0.44	0.44	0.44
Hydro	5.83	5.93	6.05
Solar PV	3.33	3.33	3.33
Wind	2.09	2.33	2.33
Total	198.84	191.15	183.65

This shift underscored the mitigation potential of scaling up RE and phasing down fossil fuel generation, especially coal.

B. Discussion

The simulation results based on the Revised PDP8 indicated that Vietnam's power sector CO₂ emissions in 2030 could decline from 198.84 million tons (Low RE-Case 1) to 183.65 million tons (High RE-Case 3), representing an absolute reduction of 15.19 million tons (7.6%). These findings confirmed that increasing the use of RE, particularly solar and wind, is vital for the decarbonization of the Vietnamese power system.

Compared to the official PDP8-Rev projection of 197 - 199 million tons of CO₂ by 2030 (with an aspirational target of ≤ 170 million tons under the JETP), the simulated results aligned with the baseline range but they were far from the conditional JETP pathway. This comparison highlighted that while expanding RE capacity is unavoidable, several measures should be considered, such as accelerated grid reinforcement, advanced storage deployment, and enhanced system flexibility.

The reduction of GHGs emissions is, thus, dependent on the timely implementation of planned RE projects and parallel investments in infrastructure. Challenges, including regional transmission bottlenecks, renewable curtailment, and variability of generation, need to be addressed through comprehensive policy frameworks. To enhance the effectiveness of high-RE scenarios, planning mechanisms should incorporate flexibility options, such as Battery Energy Storage Systems (BESS), Demand-Side Management (DSM), and expanded interregional connections.

Although the installed PSH capacity was constant at 1,200 MW across all scenarios, its operational role varied significantly with higher RE penetration. The simulation demonstrated that PSH typically pumped during midday solar surpluses and generated during evening peaks, thereby mitigating renewable curtailment, reducing thermal ramping requirements, and enhancing system security under transmission constraints.

C. Policy Implications

The modeling results highlighted some policy directions to support Vietnam's energy transition under the Revised PDP8 roadmap:

- Increase the deployment of solar PV and wind power through streamlined permitting processes, competitive auctions, and prioritized connection to upgraded regional grids.
- Enhance transmission infrastructure to reduce regional bottlenecks and support inter-provincial power exchange, particularly from high-RE potential areas.
- Invest in grid-scale energy storage systems (such as BESS and pumped storage) to address variability and enable peak shaving and load shifting.
- Promote flexible demand-side measures, including smart grid applications, time-of-use pricing, and industrial demand response programs.
- Gradually retire inefficient coal-fired plants and implement stricter approval processes for new fossil-based capacity, in line with Vietnam's net-zero target.
- Strengthen coordination between national and local planning bodies to ensure timely implementation of approved capacity and infrastructure investments.

IV. CONCLUSION

This study examined Vietnam's projected CO₂ emissions from the power sector in 2030 under three scenarios using the open-source Python for Power System Analysis (PyPSA) model and updated assumptions from the Revised Power Development Plan VIII (PDP8-Rev). The results highlighted that under the Low RE scenario, the total CO₂ emissions reached nearly 199 million tons, while under the High RE scenario, the emissions could be reduced to around 183.65 million tons - a difference of approximately 15 million tons or 7.6%. Despite this mitigation potential, several challenges should be considered to fulfill this plan, including grid congestion, variability of renewable resources, delays in energy storage deployment, and misalignment between planning and implementation.

Future research should expand the PyPSA model to incorporate sector-coupled emissions, such as transportation and industry, and assess system reliability and social-economic benefits under high-RE transition pathways. This will ensure a more comprehensive approach to achieving Vietnam's net-zero target by 2050.

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