Modeling and Optimization of Hydropower Plant Operations in the Northern Vietnam Power System by 2030

Luong Ngoc Giap
Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Vietnam
luongngocgiap@istee.vast.vn (corresponding author)

Ngo Phuong Le
Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Vietnam
ngophuongle@istee.vast.vn

Nguyen Binh Khanh
Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Vietnam
nguyenbinhkhanh@istee.vast.vn

Bui Tien Trung
Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Vietnam
buitientrung@istee.vast.vn

Truong Nguyen Tuong An
Institute of Science and Technology for Energy and Environment, Vietnam Academy of Science and Technology, Vietnam
truongnguyentuongan@istee.vast.vn

Pham Ngoc Kien
Electric Power University, Vietnam
kienpn@epu.edu.vn

Received: 23 September 2024 | Revised: 19 October 2024 and 5 November 2024 | Accepted: 16 November 2024

ABSTRACT

The Northern Vietnam Power System (NVPS) has a long history, with over a century and a quarter of development. The NVPS has experienced a significant expansion in its total power generation capacity. In 1954, the total capacity was 31.5 MW. By the end of 2023, the total capacity of the NVPS reached 29,537 MW, with hydropower accounting for 9,764 MW, representing 33.06%. In 2023, the NVPS generated 90.380 billion kWh of electricity. Over the past decade, the annual growth rate of commercial electricity has averaged between 10% and 12%. Northern Vietnam is endowed with vast hydropower potential, particularly across its four major river basins: the theoretical maximum capacity of the Bang Giang-Ky Cung, Red River, Ma River, and Ca River basins is 20,598 MW. Hydropower plays a significant role in ensuring energy security due to its low production cost, capacity to rapidly meet peak demand, and status as a clean energy source. This study proposes an optimal operational model for hydropower plants in the NVPS for the period from 2025 to 2030. The results demonstrate that hydropower will continue to be crucial for meeting the growing energy demand while minimizing operational costs. Additionally, it

supports the integration of renewable energy sources into the power grid, thereby underscoring the strategic importance of hydropower in maintaining system stability and promoting sustainable development in the region.

Keywords-Northern Vietnam Power System (NVPS); Hydropower Stations (HPS); power system; Power System Optimization (PSO); Power Generation Optimization (PGO); hydropower optimization; Power System Optimization Model (PSOM); Power System Operation Problem (PSOP)

I. INTRODUCTION

The NVPS comprises power plants, transmission grids, and consumers that are interconnected to form a system which serves 28 provinces and cities in the northern region, spanning from Quang Ninh Province to Ha Tinh Province. The NVPS is connected to the National Power System (PS) via numerous 500 kV and 220 kV substations, including Hoa Binh, Nho Quan, Thuong Tin, and Ha Tinh. In terms of power sources, the advantages of hydroelectric and coal energy have facilitated the construction of numerous hydroelectric and coal-fired power plants since the country's liberation in 1975. These include the Hoa Binh Hydropower Plant (1,920 MW), the Son La Hydropower Plant (2,400 MW), the Lai Chau Hydropower Plant (1,200 MW), the Huoi Quang Hydropower Plant (520 MW), the Ban Chat Hydropower Plant (220 MW), the Cam Pha Thermal Power Plant (680 MW), the Hai Phong Thermal Power Plant (1,200 MW), and the Mong Duong Thermal Power Plant (3,280 MW), which collectively ensure a reliable electricity supply for the region's economic development. In the Northern region's PS, power sources and transmission lines play a pivotal role in facilitating the inter-regional connectivity of electricity, linking power plants and load centers, and supplying electricity to the Northern region of Vietnam. Additionally, they serve to support power for the Southern region and contribute to the National Grid [1-3]. In terms of the river system, Northern Vietnam is composed of four principal river basins: the Bằng Giang - Kỳ Cùng River Basin, the Red River Basin, the Mã River Basin, and the Cả River Basin. Northern Vietnam boasts the largest hydropower potential in the country, with an estimated theoretical capacity of 20,598 MW. Notable among these is the Sơn La Hydropower Plant, which has a capacity of 2,400 MW, and the Hòa Bình Hydropower Plant, which has a capacity of 1,920 MW. By 2016, the total installed capacity of hydropower plants in the North reached 8,037 MW, representing 51.8% of the total power sources in the Northern PS [4-8]. The demand for electricity in northern Vietnam in recent years has been documented by statistics, as shown in Table I.

TABLE I. FORECAST RESULTS OF COMMERCIAL ELECTRICITY AND PEAK CAPACITY IN NORTHERN VIETNAM [2]

2025		2030		2035		2040	
Atp (GWh)	*Pmax* (MW)	*Atp* (GWh)	*Pmax* (MW)	*Atp* (GWh)	*Pmax* (MW)	*Atp* (GWh)	*Pmax* (MW)
126,453	25,368	190,795	37,668	271,025	52,516	348,125	66,168

The process of electricity distribution in Vietnam is analogous to that observed in other countries. It commences with the generation of power, which is then transmitted through high-voltage lines to substations. Subsequently, the electricity is distributed to consumers via lower-voltage lines, thereby ensuring reliable access to electricity for various sectors. Approximately 40% of the country's total electricity demand is accounted for by the electricity demand in northern Vietnam. In practice, the northern region of Vietnam provides support to the southern region in terms of electricity supply during periods of high demand in the southern region. Given the region's natural advantages, hydropower plants play a significant role in the system. This gives rise to the practical issue of optimizing the operation of HPS in order to achieve the highest possible level of efficiency. In light of the growing proportion of renewable energy in Vietnam's power generation structure, which is projected to have significantly increased from 30.3% in 2030 to 65.0% by 2050, the optimal operation of hydropower plants assumes great importance in supporting the national PS. Hydropower, with its capacity for flexible adjustment and rapid response to peak demand, will assist in balancing the fluctuations of renewable energy sources, such as wind and solar power, which are susceptible to weather conditions and unable to provide uninterrupted power output.

A number of studies have been conducted to investigate the optimal operation of hydropower sources within the context of the PS. From 1993 to 2012, a group of scientists from the Institute of Energy Science and collaborating units conducted a series of studies with the objective of solving the optimization problem of developing Vietnam's PS using a three-node model, comprising the North, Central, and South regions. The 500 kV Hoa Binh station, the 500 kV Da Nang - Kon Tum station, and the 500 kV Phu Lam station were selected as the primary nodes. This problem was solved using linear programming methods to determine the optimal structure of the PS with the lowest total production and transmission costs [5-17]. While these studies have built upon each other to refine the optimization model for the PS based on linear programming methods and improve the ability to solve the problem with larger datasets, they have modeled the entire Northern region as a single node, which is not suitable for the characteristics of the multi-node PS in Northern Vietnam. In order to address the issue of maximizing seasonal energy supply from cascading hydropower plants, authors in [18] proposed a multi-objective optimization method. Authors in [19] investigated the optimization of methods to enhance the operational efficiency of electricity supply for smaller areas, including districts, towns, and cities. Authors in [20] employed a mixed-integer linear programming model to develop a program for optimal power distribution in the electricity system. However, the model did not fully consider the transmission costs between different regions. Authors in [21] applied multi-objective optimization methods to investigate the optimization of reservoir operations. In order to assess the relative merits and shortcomings of the Energy Flow Optimization Model-Environment (EFOMENV), Water Quality Analysis Simulation Program (WASP) Strategist, Market and Allocation

(MARKAL), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), and Long-range Energy Alternatives Planning (LEAP) approaches, authors in [22] conducted a comparative analysis. Ultimately, the LEAP model was selected as the primary tool for a study proposing a structure for the integration of renewable energy sources into Vietnam's power development planning up to 2030. In a related development, authors in [23-26] devised a mathematical model simulating the Vietnam PS for the period 2015-2030 and developed a program to optimize the operation of the PS. The program calculates the optimal load curve based on the lowest total cost and CO_2 emissions. However, it has not yet been fully adapted for specific power sources, such as pumped storage hydropower, wind power, and solar power. Authors in [27] examined the significant contribution of the Bac Ai pumped-storage hydropower plant in optimizing the operation of the Vietnam PS, particularly in the context of integrating variable renewable energy sources. The research employed the open-source PS analysis method, namely Python for Power System Analysis (PyPSA), in an attempt to have determined the optimal operation of the Vietnam PS with the involvement of Bac Ai pumped storage hydropower by 2030. Nevertheless, this study treats the entire Northern PS as a single node within the seven nodes that comprise the national grid. Authors in [28], sought to optimize PS operation, with a particular focus on minimizing the costs associated with generation and load shedding. The proposed methods were demonstrated to result in a reduction in overall expenses while ensuring operational reliability. Authors in [29], investigated a multi-objective feature selection function that employed binary particle swarm optimization for PS stability classification. The approach they followed enhanced the efficiency and accuracy of the classification process, demonstrating significant improvements in stability assessment. Authors in [30], examined the optimal location and sizing of distributed generators within an electric distribution system using a novel metaheuristic algorithm. The findings indicated the possibility of reducing power losses and enhancing the overall performance of the distribution network. Authors in [31], concentrated on the reconfiguration of electric distribution systems incorporating distributed generators, employing a symbiotic organism's search algorithm. The objective of their work was to optimize network performance and enhance the integration of distributed energy resources. Authors in [32], put forth a congestion management approach founded upon a circulatory system optimization algorithm. The results displayed the efficacy of congestion alleviation within the PS, thereby contributing to enhanced operational efficiency. Authors in [33], introduced PyPSA, a robust open-source tool for modeling and analyzing PSs. This software facilitates a variety of analyses, including optimization, and fosters collaboration within the PS research community. Authors in [34], addressed the parallelization of the dual revised simplex method, which enhances computational efficiency for mathematical programming problems. Their work represents a substantial advancement in the resolution of large-scale optimization issues in PSs.

This study introduces a distinctive four-node model for the NVPS, which markedly diverges from the findings of previous studies. The model permits a more comprehensive examination of the interrelationships between energy sources and electricity demand in the region, thus facilitating the optimization of dispatching and energy management processes. The research addresses both practical and scientific issues by applying the open-source PyPSA tool to model the optimal operation of hydropower plants in the NVPS. In doing so, it considers generation characteristics and transmission losses while incorporating all sources in the system. In light of the growing demand for electricity, the study underscores the pivotal role of hydropower in guaranteeing energy security and maintaining price stability in the electricity market. By offering a detailed examination of the capacity structure, output, and production costs of hydropower over the 2025-2030 period, this research advances the comprehension of the NVPS and contributes to the sustainable development of Vietnam's energy sector.

II. METHODOLOGY

A. *Models for Optimal Operation of Hydropower Plants*

In order to address the operation of HPS within the electricity system of Northern Vietnam, a model of the Northern electricity system will be constructed to identify operational parameters with the aim of minimizing costs. In practice, to effectively solve the optimization problem of operating hydropower plants within the system, a multi-node network model of the electricity grid is constructed. In light of the aforementioned [4-6], the project constitutes a component of a comprehensive plan for the socio-economic development of the region, sector, and field. This approach offers the advantage of facilitating data collection regarding energy sources, infrastructure, and energy demand. The northern region will constitute of multiple sub-regions, each comprising a group of provinces and cities. Consequently, the entire area will be divided into N regions, each of which will be assigned to a specific node when a model for optimizing the PS is selected. Each region must possess the following essential attributes [4-5, 9-14]:

- A region must formed to encompass a geographically contiguous population. This issue pertains to the internal cohesion of the region.
- The transmission length of electricity is defined as the equivalent distance in the transportation of electrical energy between regions.
- The transmission infrastructure is concentrated at key points of transportation within the region.

Two models exist for the selection of nodes (regions) in northern Vietnam. [1, 2, 15-26]:

- Model 1: 3-Node Model. The Northern region is subdivided into three areas, comprising 28 provinces and cities, as described in Figure 1. The Northern Midland and Mountain Area constitutes Region 1. The following provinces are included in the region: Ha Giang, Cao Bang, Bac Kan, Lao Cai, Lai Chau, Yen Bai, Tuyen Quang, Dien Bien, Son La, Phu Tho, Lang Son, Thai Nguyen, and Bac Giang. Region 2 includes the Northern Coastal Area and the Hanoi Region. Additionally, the following provinces are situated in the region: Ha Noi, Hoa Binh, Hung Yen, Hai Duong, Hai Phong, Quang Ninh, and Nam Dinh. Region 3 is the North Central Region, including the two provinces of Nghe An and Thanh Hoa

- Model 2: 4-Node Model. The Northern region, comprising 28 provinces, is subdivided into four distinct areas, as presented in Figure 2. Region 1, Northwest Area, is composed of the following provinces: The provinces of Lai Chau, Lao Cai, Yen Bai, Son La, and Hoa Binh comprise the northern region. Region 2, the Northeast Area, comprises of the following provinces: The remaining provinces are Ha Giang, Cao Bang, Bac Kan, Tuyen Quang, Lang Son, Thai Nguyen, Phu Tho, Bac Giang, and Quang Ninh. Region 3, the Red River Delta, encompasses the provinces of Bac Ninh, Ha Nam, Ha Noi, Hai Duong, Hai Phong, Hung Yen, Nam Dinh, Ninh Binh, Thai Binh, and Vinh Phuc. Region 4, the North Central Area, comprises the following provinces: The remaining regions are Nghe An and Thanh Hoa.

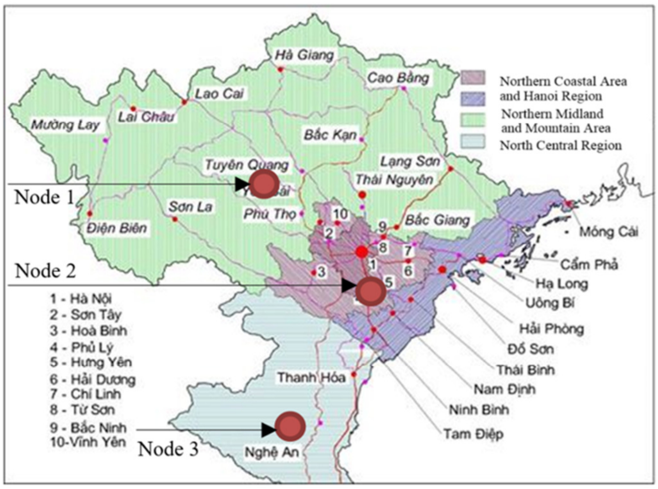

Fig. 1. 3-Node Model for Selecting Nodes (Regions) in Northern Vietnam.

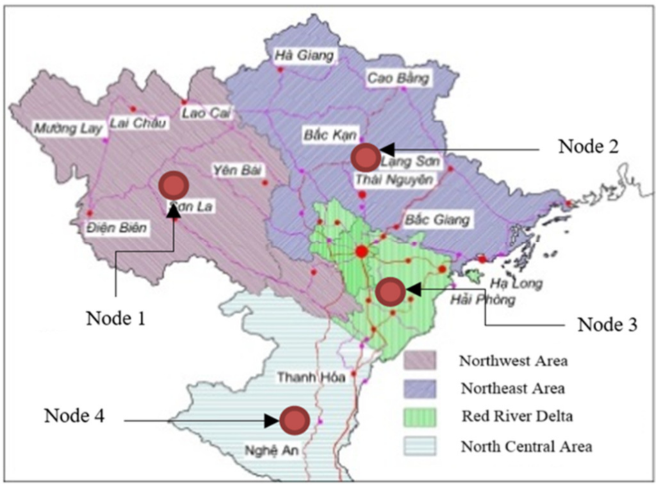

Fig. 2. 4-Node Model for Selecting Nodes (Regions) in Northern Vietnam.

In consideration of the presented evidence, it can be concluded that:

- The PS is a multi-node network that facilitates the distribution of electricity to meet various demands. The aforementioned regions of the northern area are regarded as load centers, which function as nodes within the system.
- The interconnection between nodes represents the distance between logically connected nodes, thereby forming a model of a system that is linked by various sources, nodes, and grids. These interconnections are subject to a complex set of relationships and constraints, including but not limited to capacity, energy generation, load, losses, generation limits, and fuel consumption constraints.
- Based on this, a model is established, and a solution method is selected to identify a combination of optimal results suitable for the optimal operational conditions of the hydropower plants in the Northern PS.
- This paper employs the 4-node model (Model 2) to simulate the Northern PS for the purpose of calculating the optimal operation of hydropower plants in the region.

The objective function of the problem is to identify the optimal strategy for minimizing the operational costs of the system over a given day. This is achieved by considering the total hourly operational costs of each power plant and the transmission costs associated with the lines:

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

where n is the index of the *n*-th node in the system, representing a region according to the Power Plan VIII (for the northern region, it is divided into 4 nodes, each other region is represented by one node) [2], m is the index of the *m*-th power plant in node *n*, and also indicates the index of the pumped-storage hydroelectric plant *m* in node *n*, *t* is the time index within the day (hours), *l* is the index of the *l*-th transmission line, $O_{n,m,t}^{(G)}$ is the operating cost of power plant *m* at node n, at time *t*, $O_{n,m,t}^{(S)}$ is the operating cost of a pumped storage hydroelectric plant at node *n,* at time *t*, $O_{l,t}^{(L)}$ is the transmission cost of line *l* at time *t*, $G_{n,m,t}$ is the generation capacity of plant *m* at node *n,* at time *t*, $S_{n,m,t}$ is the generation capacity (positive value) or charging capacity (negative value) of pumped storage hydropower plant *m* at node *n,* at time *t,* and $L_{l,t}$ is the transmission capacity of line *l* at time *t*.

B. Constraints

The optimization process must satisfy a number of constraints, which can be grouped into the following categories: power balance at the node, minimum and maximum allowable generation capacity of the power plants, and maximum transmission capacity of the lines [4-6, 33-34]. It is essential that the load demand $d_{n,t}$ at each node (*n*), at each time point (*t*) is met by the generation sources, pumped storage hydropower at that node, or the transmission capacity $L_{l,t}$ delivered to that node via line lll. The fixed load demand at node n at time t is given by:

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

where $\alpha_{l,n,t}$ is the direction and efficiency of the power transmission of line l relative to node n, $-1 \le \alpha_{l,n,t} < 0$ if the power l is leaving node n, and $0 < \alpha_{l,n,t} \le 1$ if the power l is entering node n. This value may be defined based on the time t. The power generation constraints for each power plant are:

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

where $g_{n,m,t}^{(\min)} \in [0;1]$ is the minimum generation capacity in per unit (pu) of power plant m, at node n, at time t, $g_{n,m,t}^{(\max)} \in [0;1]$ is the maximum generation capacity in pu of power plant m, at node n, at time t, $G_{n,m}^{(nom)}$ is the rated capacity of power plant m, at node n. For a conventional power plant, $g_{n,m,t}^{(\min)}$ and $g_{n,m,t}^{(\max)}$ is a constant over time. For a power plant that allows operation across the entire range from 0% to 100% of its rated capacity, then $g_{n,m,t}^{(\min)} = 0$ 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 weather conditions. Additionally, the values $g_{n,m,t}^{(\min)}$ and $g_{n,m,t}^{(\max)}$ can be used to assume the requirements for grid connection limitations or mandatory grid connection for one or more power plants. Constraints on the limits for increasing/decreasing the output power of the power plant are:

$$-rd_{n,m} G_{n,m}^{(nom)} \le G_{n,m,t} - G_{n,m,t-1} \le ru_{n,m} G_{n,m}^{(nom)} \quad (4)$$

where $rd_{n,m}$ is the limit on decreasing the output power of plant m at node n and $ru_{n,m}$ is the limit on increasing the output power of plant m at node n. The constraint on transmission power $L_{l,t}$ according to the capacity of the transmission line $L_l^{(nom)}$ is:

$$f_l^{(min)} L_l^{(nom)} \le L_{l,t} \le f_l^{(max)} L_l^{(nom)} \quad (5)$$

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

C. Optimal Operation Model Solution Method

The optimal operation model of hydropower plants within the PS necessitates the determination of a set of optimal variables, with the objective of achieving the maximum value of the objective function while simultaneously satisfying all related constraints. A multitude of methods have been developed for the resolution of control problems that require a significantly large number of calculations. The selection of an appropriate method for solving such problems is contingent upon the form of the objective function, the constraints, the number of optimal variables, and the characteristics of the optimization problem itself [4-14]. The rationale for solving the optimal operation model of the Northern PS of Vietnam can be analytically examined [4-27]. The electricity generation structure of the Northern PS of Vietnam encompasses hydropower, coal-fired thermal PS power, and electricity derived from other energy sources. Nevertheless, it is anticipated that coal-fired thermal power and hydropower will continue to represent the dominant sources of electricity generation until 2030. From this characteristic, it can be observed:

- In the case of hydropower, the model must demonstrate the superiority and high efficiency of hydropower's ability to meet peak demand based on the given electricity output and generation capacity under various hydrological conditions, such as: the impact of uneven energy generation and the significant difference between the dry and wet seasons on the PS structure, the influence of considerable discrepancies in electricity generation capacity between average and drought years on the necessity for supplementary thermal power reserves, and the impact of fluctuations in available capacity (P_{kd}) on the configuration of the power supply system on an annual basis.
- In addition, the model must exhibit the capacity to leverage the advantages of the model when addressing the non-linear relationship between fuel consumption and the operational time and location of thermal power sources within the PS. It is insufficient to employ a simplified PS model that uses a typical annual power and energy balance method in order to adequately reflect these characteristics. In lieu of this, a bespoke model must be developed that permits a more comprehensive depiction of the power and energy balance corresponding to N nodes, which are supplied by a variety of sources within the system.

1) Description of the Transmission Network

It is assumed that the transmission system has the same unit cost, and therefore it is only necessary to describe the distance and total transport capacity of the lines between the nodes. The node load graph of the system is transformed into an integral load graph by arranging the load graph from the highest to the lowest over a typical 24-hour load profile. This enables the use of linear programming for the comprehensive and accurate modeling of the optimal operational model for the Vietnamese electricity system during the 2025-2030 period, as outlined in the 8th Power Plan. This solution is highly advantageous and effectively captures the requirements set forth by the optimization methodology for the Vietnamese electricity system, which is characterized by several key features. Firstly, the system is interconnected by 500 kV and 220 kV transmission lines. Secondly, it has the capability to develop large hydroelectric sources, which constitute a significant share of the system. Thirdly, it must consider the operational modes of thermal power plants. In order to achieve this, a detailed account of the alterations made to the objective function is provided in order to facilitate optimization. In the case of the Vietnamese electricity system, the optimal operation model can encompass hundreds of thousands of optimization variables, along with their associated constraints. The system in question requires a significant number of calculations, and thus necessitates the selection of an appropriate method for solving it. This selection must take into account the form of the objective function, the constraints, the number of optimization variables, and the characteristics of the optimal operation model.

The goal of this study is to determine the values of a set of optimization variables that will achieve the maximum value of the objective function while satisfying all related constraints. A plethora of methodologies has been devised to address optimal control modeling problems. The system, along with the transmission capacity between load regions, is based on the fluctuations of typical day-night load profiles, which characterize monthly or seasonal variations (dry and rainy) throughout the year across the country. The objective is to demonstrate that the recently constructed linear model is fully capable of detailing and satisfying the specific requirements of the electricity system. Subsequently, the model can be used to conduct a comprehensive evaluation of the sustainable and economic operations of power sources, both in the present and in the future. Furthermore, the outcomes of the model will elucidate the fuel consumption of thermal power plants and their disparate mobilization methodologies throughout the year. At this juncture, the solutions generated by the model will inform the formulation of a robust and highly effective strategy for sectors, such as hydropower, coal, oil, and gas for electricity generation. Regarding the transmission system, it is essential to demonstrate enhancements and the capacity to regulate the efficacy of power and energy transmission across diverse seasons through the utilization of 500 kV and 220 kV transmission lines.

2) *Description of Load*

The load of the electricity system is represented at various nodes, where it is possible to observe the fluctuations in demand. Each node is associated with a specific geographical region and contains data that can be used to construct a representative daily load profile. Accordingly, the electricity system in Northern Vietnam will be delineated through the load values at N nodes that are compatible with the natural and climatic conditions of Vietnam.

3) *Description of Power Sources*

Each power source within the system will contribute to the fulfillment of the load profile across all system nodes. For each node, a day-night load profile will be constructed, along with the requisite adjustments to variables and related constraints of the linear programming model when transitioning the problem to cover the integrated load profile, as previously analyzed. It is evident that the scientific content of the modeling method using linear programming is fully capable of addressing all the stringent requirements of the electricity development problem in Vietnam. Furthermore, the proposed solutions serve as specific guidelines on how to detail the objective function indices and constraints when using the linear model to solve the problem. This will be highly beneficial for those utilizing this model to tackle the optimal operation problem of the electricity system.

4) *Solution Method*

The issue is represented through the employment of linear programming, deploying the open-source software PyPSA [33] for its formulation and the HiGHS solver [34] for its resolution. HiGHS is a high-performance solver for large-scale sparse linear optimization problems of the following form:

$$\min_x \frac{1}{2} x^T Q x + c^T x \tag{6}$$

where x is the vector of decision variables to be optimized, Q is a positive definite symmetric matrix representing the quadratic part of the objective function, c is the vector of linear coefficients, A and b are the matrix and vector representing the inequality constraints, E and d are the matrix and vector representing the equality constraints. With linear constraints, the model includes: $Ax \leq b$ and $Ex = d$. HiGHS is capable of solving a variety of mathematical optimization problems, including Linear Programming (LP), convex Quadratic Programming (QP), and Mixed-Integer Programming (MIP).

III. RESULTS AND DISCUSSIONS

A. *Calculation Cases*

By 2025, the data on power generation sources, transmission, loads, and fuel and electricity prices will have been updated in accordance with the provisions set forth in Power Plan VIII and the related documents [1–3], as shown in Figure 3. The power capacity and electricity generation costs, along with the base load of Northern region in 2025, are presented in Table II and Figure 4, respectively.

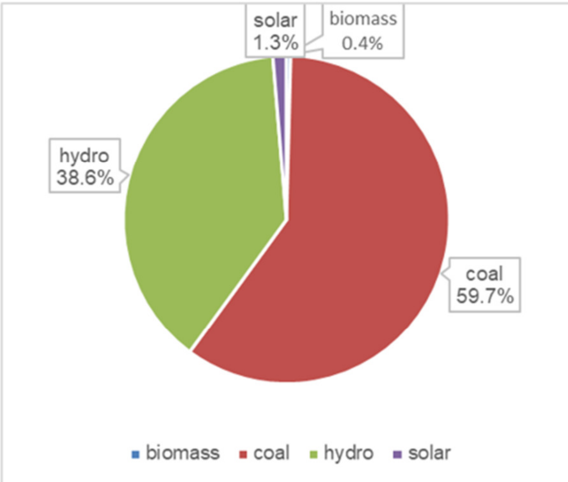

Fig. 3. Power Generation Capacity Structure for Northern Vietnam in 2025 (%).

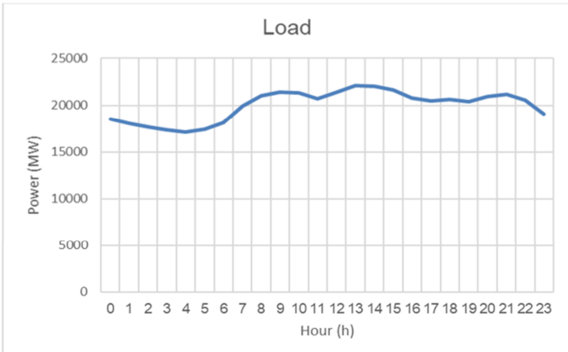

Fig. 4. Typical Daily Load Curve for Northern Vietnam in 2025 (MW).

TABLE II. POWER CAPACITY AND ELECTRICITY GENERATION COSTS OF NORTHERN VIETNAM HYDROPOWER COMPARED TO NORTHERN PS AND NATIONAL PS IN 2025

2025	Installed Capacity (MW)	Energy Generated (MWh)	Cost (USD)
National	99,499	1,297,000	74,574,921
Northern	23,914	479,807	28,652,718
Northern Hydropower	9,219.6	200,445	8,937,545

In Case 2, data on power generation sources, transmission, loads, and fuel and electricity prices are updated according to the provisions set forth in Power Plan VIII and related documents [1-3], as evidenced in Figure 5. The base load of Northern region in 2030, and the power capacity and electricity generation costs, are portrayed in Figure 6 and Table III, respectively.

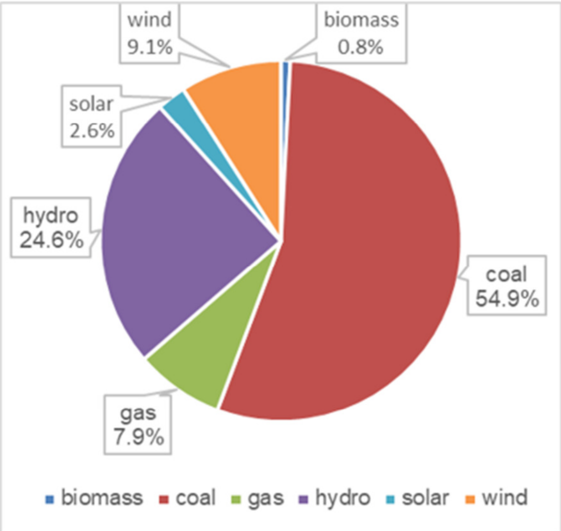

Fig. 5. Installed Power Capacity Structure of Northern Vietnam in 2030 (%).

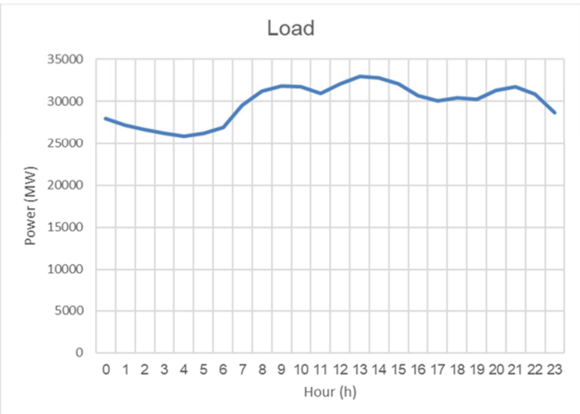

Fig. 6. Typical Daily Load Curve for Northern Vietnam in 2030 (MW).

TABLE III. POWER CAPACITY AND ELECTRICITY GENERATION COSTS OF NORTHERN VIETNAM HYDROPOWER COMPARED TO NORTHERN PS AND NATIONAL PS IN 2030

2030	Installed Capacity (MW)	Energy Generated (MWh)	Cost (USD)
National	190,483	1,960,952	111,381,970
Northern	47,215	596,742	35,542,212
Northern Hydropower	11,635	211,556	9,590,308

B. Calculation Results

Figure 7 shows the peak load coverage for Northern Vietnam in the year 2025 (Case 1), indicating a peak power output of 8,482 MW and a corresponding energy output of 42,410 MWh. The associated production cost for this peak coverage is calculated to be USD 2,067,613, as illustrated in Table IV.

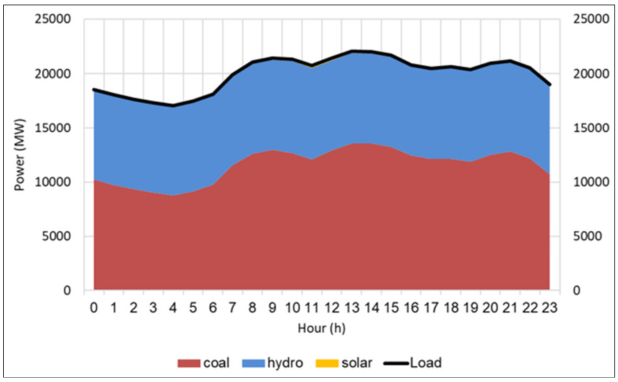

Fig. 7. Peak Load Coverage Results for Northern Vietnam in 2025 (MW).

TABLE IV. PEAK HOUR POWER OUTPUT AND PRODUCTION COSTS OF HYDROPOWER IN NORTHERN VIETNAM IN 2025

2025	Peak Power Output (MW)	Energy Output (MWh)	Cost (USD)
Hydropower Peak Coverage	8,482	42,410	2,067,613

Similarly, for the year 2030 (Case 2), Figure 8 presents the peak load coverage results for the Northern Region, with a peak power output of 10,704 MW. The energy output for this period reaches 53,521 MWh, with a production cost of USD 2,720,376, as detailed in Table V. These figures provide a comprehensive overview of the expanding role and associated costs of hydropower in the region, reflecting the growth of the system and the considerable contribution of hydropower in meeting peak load requirements over time.

TABLE V. PEAK HOUR POWER CAPACITY AND ELECTRICITY GENERATION COSTS OF NORTHERN REGION HYDROPOWER IN 2030

2030	Peak Power Output (MW)	Energy Output (MWh)	Cost (USD)
Hydropower Peak Coverage	10,704	53,521	2,720,376

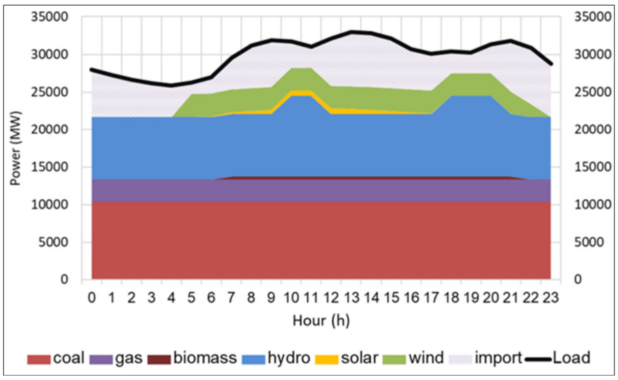

Fig. 8. Peak Load Coverage Results of the Northern Region in 2030 (MW).

IV. DISCUSSIONS

A comprehensive analysis of the Northern Vietnam power load profiles for 2025 and 2030, along with the associated calculation results, has revealed the significant role that hydropower will play in the PS, not only in the North but also on a nationwide scale. The most important findings can be summarized as:

- The load coverage results for 2025 show that hydropower is a vital contributor to meeting electricity demand during peak hours. With a peak capacity of 8,482 MW and an annual electricity production of 42,410 MWh, hydropower constitutes a significant portion of the energy mix in northern Vietnam. This emphasizes the adaptable nature of hydropower, particularly during periods of elevated electricity consumption.
- In 2025, the installed capacity of hydropower in Northern Vietnam was 9,219.6 MW, representing 38.55% of the total installed capacity in the region, which was 23,914 MW. This considerable proportion serves to reinforce the role of hydropower as the primary energy supplier for the region, therefore enhancing energy security in Northern Vietnam.
- The cost of electricity production for Northern Vietnam's hydropower in 2025 is estimated at USD 8,937,545, representing a significant portion of the total electricity production cost in Northern Vietnam, which is USD 28,652,718. This indicates that the production cost of hydropower constitutes only 31.18% of the total cost. With a production cost per kWh of 4.45 cents, which is lower than the Northern system's average (5.97 cents) and the national average (5.75 cents), hydropower is found to be economically efficient.
- The cost of electricity production during peak hours for hydropower is USD 2,067,613, which is significantly lower than that of other energy sources, particularly those based on fossil fuels. This highlights the fact that hydropower not only serves to stabilize the electricity supply, but also helps reduce electricity prices during peak hours, hence playing a vital role in ensuring the stable operation of the PS.
- The load coverage results for 2030 indicate a notable surge in electricity demand in Northern Vietnam. Notwithstanding this expanding demand, hydropower persists as the predominant energy source, with a peak capacity of 10,704 MW and a generation of 53,521 MWh during peak hours. The expansion of hydropower capacity serves to illustrate that this energy source not only fulfills the region's basic electricity needs, but also meets the demands of its robust economic growth.
- By 2030, the installed capacity of hydropower in Northern Vietnam will have reached 11,635 MW, accounting for 24.64% of the region's total installed capacity, which is 47,215 MW. Although this ratio has experienced a slight decline in comparison to 2025, due to the emergence of alternative energy sources, hydropower continues to play a critical role in the PS of Northern Vietnam. This is attributed to its consistent electricity generation and relatively low operational costs.
- The cost of electricity production from Northern Vietnam's hydropower in 2030 is estimated at USD 9,590,308, representing 10.11% of the total electricity production cost for Northern Vietnam (USD 35,542,212). Despite a decline in this percentage compared to 2025, hydropower remains a cost-effective energy source, alleviating financial strain on the PS and consumers.
- Furthermore, the electricity production cost during peak hours for hydropower in 2030 is USD 2,720,376, which is lower than that of many other energy sources. This suggests that the operation of hydropower plants remains a vital contributor to the reduction of electricity costs during periods of high demand.

A. *Comparative Evaluation*

A comparison of Case 1 (2025) with Case 2 (2030) reveals an increase of 26.2% in hydropower's peak capacity (from 8,482 MW in 2025 to 10,704 MW in 2030), indicative of its expanding role in meeting peak load demand. Similarly, the energy output during peak hours demonstrates a 26.2% increase, from 42,410 MWh to 53,521 MWh, which evinces hydropower's capacity to adapt to rising electricity needs. However, the proportion of hydropower installed capacity in the Northern region declines from 38.55% to 24.64% over the five-year period, reflecting a diversification of the energy mix with the rise of other energy sources. Nevertheless, hydropower continues to constitute a significant proportion of the energy supply. In terms of cost-efficiency, the cost per MWh remains competitive between the two cases. The economic advantage of hydropower is evident in its low production costs during peak hours. By 2030, the cost will have been USD 2,720,376, which is significantly lower than that of other energy sources. This reinforces the critical role of hydropower in reducing peak-hour electricity costs and stabilizing the PS.

B. *Infrastructure Investment*

It is recommended that governments and industry stakeholders prioritize investment in the modernization and expansion of hydropower infrastructure:

- Support for Hydropower in the Context of the Energy Transition: It is recommended that policymakers implement incentives to facilitate the development of hybrid systems, which combine hydropower with other renewable energy technologies to optimize energy storage and distribution.

- Cost-Reduction Strategies: While hydropower remains cost-efficient, especially during peak hours, further cost-reduction measures should be investigated.
- Regulatory Support and Policy Frameworks: It is imperative that comprehensive policies be developed to facilitate the rapid deployment of hydropower projects.
- Environmental and Social Considerations: Although hydropower is a renewable resource, it is essential to exercise caution regarding its environmental and social implications, particularly with respect to water management and resettlement concerns.

V. CONCLUSIONS

The Northern Vietnam Power System (PS) has undergone substantial growth over the past 120 years, with hydropower representing a crucial component of the electricity supply for 28 provinces. The proposed optimal operation model for hydropower plants is designed to enhance the efficiency with which clean energy is produced and to reduce the costs associated with its operation. By 2025, Northern Vietnam's hydropower will have met peak loads with a capacity of 8,482 MW and an energy output of 42,410 MWh, at a cost of USD 2,067,613. It is projected that this capacity will have risen to 10,704 MW and 53,521 MWh by 2030, with costs of USD 2,720,376. Notwithstanding a slight decline in the proportion of hydropower from 38.55% in 2025 to 24.64% in 2030, the latter continues to be a crucial element in ensuring cost-effectiveness and grid resilience, particularly during periods of peak demand. The representation of the PS as a multi-node grid facilitates more effective dispatching and power management, reflecting constraints in generation capacity and electricity demand. Given the abundance of hydropower potential and the ongoing development of renewable energy sources, Northern Vietnam is well-positioned to establish a sustainable PS that will serve as a vital foundation for socio-economic growth.

Although production costs may have been slightly increased by 2030, hydropower will remain a competitive source of energy. A strategic combination of hydropower, solar, and wind energy will enhance the reliability of the energy supply, with hydropower serving as the primary source. It is recommended that future energy policies prioritize the integration of these sources, the modernization of infrastructure, and the development of hybrid systems to ensure the operational efficiency and long-term stability of the energy sector. In order to maximize the contributions of hydropower, it is essential that investment be made in the modernization of infrastructure and the adoption of advanced technologies. It is recommended that policymakers give priority to research aimed at optimizing hydropower operations and establishing flexible regulations that promote hybrid systems. It is imperative that the government, industry stakeholders, and local communities collaborate to guarantee that hydropower will continue to play a significant role in the energy landscape of Northern Vietnam.

ACKNOWLEDGEMENT

"The authors gratefully acknowledge the support of the selective foundational research project, titled 'Research on the Role of Bac Ai Pumped Storage Hydropower in the Operation of Vietnam's Power System in 2030-2045,' Code: CSCL31.01/24-24. This work was supported by the Institute of Science and Technology for Energy and Environment (ISTEE) under the Vietnam Academy of Science and Technology (VAST), with funding provided by VAST through the same project code."

REFERENCES

[1] *Prime Minister, Decision No.500/QD-TTG on approving Vietnam's electricity development plan for the period 2021 - 2030, vision to 2050. 2023.*

[2] *National electricity development plan for the period 2021-2030, vision to 2050 (PDP VIII).* Institute of Energy, 2023.

[3] *Summary report on operation of the National Power System in 2023, (A0, EVN).* National Load Dispatch Centre, 2023.

[4] *Master plan for development of Vietnam's energy system until 2010.* National Center for Natural Science and Technology, 2010.

[5] N. T. Kiet, "Overview research and development orientation of Vietnam's energy system," Institute of Energy Sciences, Scientific Research, 2008.

[6] N. H. Mai, "Building a scientific basis for the methodology for establishing the overall energy balance until 2005," National Center for Natural Science and Technology, Hanoi, Vietnam, Science KC-3-02, 1993.

[7] V. H. Hai, *et al.*, "Discussing the selection of installed capacity in hydropower investment projects in Vietnam today", *Water Resources*, no. 4, 2006.

[8] V. H. Hai; N. T. Kiet, "Improving the efficiency of exploitation and use of hydropower resources in Vietnam's energy system", Ministry-level project 2005-2006.

[9] N. H. Mai and L. T. Tu, "Solving the problem of optimizing power system development using linear planning method (analysis of some power system modeling solutions)," in *1st International Conference SED*, Užice, Serbia, Sep. 2008.

[10] N. H. Mai and L. T. Tu, "Analysis of two methods of recovering capital for energy projects when taking into account the factor of foreign loans," in *1st International Conference SED*, Užice, Serbia, Sep. 2008.

[11] L. N. Giap and V. H. Hai, "Improving the efficiency of exploiting the Song Da hydropower cascade in Vietnam's electricity system," *Jurnal of Science and Technology Construction*, vol. 10, Sep. 2011.

[12] L. T. Tu, "Reducing the amount of calculation in the optimal model for developing Vietnam's power system taking into account the characteristics of power sources and main transmission lines," in *International Science Conference on Green Energy and Development*, Hanoi, Vietnam, 2012.

[13] L. T. Tu, "Automation of data processing and transmission in the program Optimizing the development of Vietnam's power system, taking into account the characteristics of power sources and main transmission lines," in *International Science Conference on Green Energy and Development*, Hanoi, Vietnam, 2012.

[14] L. T. Tu, "Overview analysis of cost components in calculating the supply and demand balance of Vietnam's energy system using linear programming method," in *International Science Conference on Green Energy and Development*, Hanoi, Vietnam, 2012.

[15] N. T. Bang, H. D. Dung, N. T. Kiet, and V. H. Hai, "Hydropower and flow regulation," *Construction Publishing House*, 2012.

[16] N. T. Bang, N. T. Kiet, and P. D. Cuong, "Irrigation planning," *Construction Publishing House*, 2013.

[17] Bui Huy Phung, "Optimal calculation method for sustainable development of energy systems," *Science and Technology Publishing*, 2011.

[18] N. T. Bang, "Multi-objective optimization of irrigation-hydropower systems to exploit integrated water resources," Ph.D. dissertation, Department of Engineering and Technology, Vietnam National University, Hanoi, Vietnam, 2002.

[19] T. V. Tinh, "Research on optimization methods to improve the efficiency of regional power supply operations," Ph.D. dissertation, Hanoi University of Science and Technology, Hanoi, Vietnam, 2002.

[20] N. D. Cuong, "Topic on optimal operation of the power system considering factors limiting capacity exchange of regions," Ph.D. dissertation, Hanoi University of Science and Technology, Hanoi, Vietnam, 2002..

[21] L. Hung, "Optimizing multi-purpose reservoir operation," Ph.D. dissertation, University of Da Nang, Da Nang, Vietnam, 2011.

[22] P. T. T. Mai, "Research on developing power sources from Renewable Energy in Vietnam's power source planning," Ph.D. dissertation, Hanoi University of Science and Technology, Hanoi, Vietnam, 2017.

[23] N. V. Dung, "Optimizing the operating mode of hydroelectric plants in the Vietnamese power system," Ph.D. dissertation, Hanoi University of Civil Engineering, Hanoi, Vietnam, 2018.

[24] L. N. Giap and T. T. Vinh, "Improving the efficiency of exploiting the Da River hydropower cascade on the basis of inter-reservoir regulation," in *International Scientific Conference on Energy and Green Growth in the ASEAN region 2014*, Hanoi, Vietnam, 2014, pp. 75–83.

[25] L. N. Giap, V. H. Hai, N. V. Dung, N. B. Khanh, T. T. Vinh, and L. T. Tu, "Models and methods of calculating the optimal development and optimal operation of Vietnam's power system," *IOSR Journal of Engineering*, vol. 8, no. 6, pp. 01–07, Jun. 2018.

[26] L. N. Giap, V. H. Hai, N. V. Dung, N. B. Khanh, T. T. Vinh, and L. T. Tu, "Building software for optimal calculation of electricity system and results of optimal calculation and operation of Vietnam's electricity system," *IOSR Journal of Engineering*, vol. 8, no. 9, pp. 01–10, Sep. 2018.

[27] L. N. Giap *et al.*, "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," *Engineering, Technology & Applied Science Research*, vol. 14, no. 5, pp. 16565–16572, Oct. 2024, https://doi.org/10.48084/etasr.8238.

[28] T. N. Le, H. M. V. Nguyen, T. T. Hoang, and N. A. Nguyen, "Optimizing the Power System Operation Problem towards minimizing Generation and Damage Costs due to Load Shedding," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11643–11648, Oct. 2023, https://doi.org/10.48084/etasr.6221.

[29] N. A. Nguyen, T. N. Le, and H. M. V. Nguyen, "Multi-Goal Feature Selection Function in Binary Particle Swarm Optimization for Power System Stability Classification," *Engineering, Technology & Applied Science Research*, vol. 13, no. 2, pp. 10535–10540, Apr. 2023, https://doi.org/10.48084/etasr.5799.

[30] T. N. Ton, T. T. Nguyen, A. V. Truong, and T. P. Vu, "Optimal Location and Size of Distributed Generators in an Electric Distribution System based on a Novel Metaheuristic Algorithm," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5325–5329, Feb. 2020, https://doi.org/10.48084/etasr.3372.

[31] T. L. Duong and T. T. Nguyen, "Network Reconfiguration for an Electric Distribution System with Distributed Generators based on Symbiotic Organisms Search," *Engineering, Technology & Applied Science Research*, vol. 9, no. 6, pp. 4925–4932, Dec. 2019, https://doi.org/10.48084/etasr.3166.

[32] G. T. Tang, N. D. H. Bui, and D. T. Long, "Congestion Management using the Circulatory System Based Optimization Algorithm," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14361–14366, Jun. 2024, https://doi.org/10.48084/etasr.7204.

[33] T. Brown, J. Hörsch, and D. Schlachtberger, "PyPSA: Python for Power System Analysis," *Journal of Open Research Software*, vol. 6, no. 1 Nov. 2024, Art. no. 4, https://doi.org/10.5334/jors.188.

[34] Q. Huangfu and J. A. J. Hall, "Parallelizing the dual revised simplex method," *Mathematical Programming Computation*, vol. 10, no. 1, pp. 119–142, Mar. 2018, https://doi.org/10.1007/s12532-017-0130-5.