

Article

Energy Transition in Vietnam: A Strategic Analysis and Forecast

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Abstract: Energy landscapes in Asia and other regions are currently undergoing a transformation aimed at increasing the share of clean energy sources. This article analyzes and forecasts the electricity demand in Vietnam, examining existing constraints that necessitate the shift from coal to renewable energy sources. The rapid economic growth in Vietnam is driving a substantial surge in electricity demand, projected to reach 124 thousand MW by 2030 according to the National Electricity Plan, positioning Vietnam second in Southeast Asia. This surge poses a significant challenge to national energy security, given the impracticality of effective coal mining in the country and the imperative to develop renewable energy sources. Anticipating the changes in Vietnam's energy mix by 2050, this study foresees a substantial reduction in dependence on coal production. Government investment and green energy investment funds such as JETP are strategically directed towards renewable energy sources, including solar, wind, biomass, hydrogen energy, and efficient energy storage technologies. Consequently, this research substantiates the viability of an energy transition from coal to green energy in Vietnam. The article presents an assessment of the rate of replacing coal with renewable energy sources, taking into consideration various scenarios for economic development, energy consumption growth, and the utilization of renewable energy sources.

Keywords: environmental management; resource efficiency; energy transition; renewable energy sources; sustainable development; energy sector; forecast; government support; sustainable development goals; trilemma; SDGs



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1. Introduction

Relevance of the research topic. Currently, there is a growing need to implement sustainable development goals within national economies and energy sectors [1]. This implementation aims to uphold the principles of the energy trilemma [2] while simultaneously achieving high rates of economic growth in the national economies of developing countries. As a consequence, it is necessary to explore and justify solutions for selecting and diversifying energy generation sources.

Energy-related sustainable development goals include [3]:

- Affordable and Clean Energy (SD 7): Ensuring access to affordable, reliable, sustainable, and modern energy for all.
- Decent work and economic growth (SD 8): Promoting sustainable, inclusive, and sustainable economic growth, full and productive employment, and decent work for all.
- Industry, Innovation, and Infrastructure (SD 9): Building sustainable infrastructure, promoting inclusive and sustainable industrialization, and stimulating innovation.
- Sustainable Cities and Communities (SD 11): Making cities and human settlements inclusive, safe, resilient, and sustainable.
- Responsible Consumption and Production (SD 12): Ensuring sustainable consumption and production patterns.

- Climate Action (SD 13): Taking urgent action to combat climate change and its impacts by regulating emissions and promoting the development of renewable energy.
- Life Below the Sea (SD 14): Conserving and sustainably using oceans, seas, and marine resources for sustainable development.
- Life on Land (SD 15): Protecting, restoring, and promoting the sustainable use of terrestrial ecosystems, sustainable forest management, combat desertification, and halting and reversing land degradation and biodiversity loss.

The World Energy Trilemma Index is a comparative ranking of the energy systems of 127 countries, assessing their performance along three dimensions: energy security, energy equity, and environmental sustainability [2,3]:

- Energy security measures a country's ability to *reliably* meet *current and future energy demand*, withstand systemic shocks, and recover quickly from them with minimal supply disruptions. This dimension covers the efficiency of management of internal and external energy sources, as well as the reliability and sustainability of energy infrastructure.
- Energy equity assesses a country's ability to provide *universal access* to reliable, affordable, and abundant energy for residential and commercial use. This dimension covers *basic access to electricity, clean fuels*, and cooking technologies, access to prosperous levels of energy consumption, and affordability of electricity, gas, and fuels.
- Environmental sustainability of energy systems represents the transition of a country's energy system to *mitigate and prevent potential environmental damage and the effects of climate change*. This measurement focuses on productivity and efficiency in generation, transmission and distribution, decarbonization, and air quality.

According to the World Energy System Index for the period 2018–2022, Vietnam held the following positions: 83rd place (2018), 91st place (2019), 65th place (2020), 61st place (2021), and 55th place (2022). Despite fluctuations, the overall trend is positive, indicating significant improvement in Vietnam's energy system performance over five years. Nevertheless, the lower position in the ranking signals shortcomings in government regulation of the energy sector, an unbalanced national energy mix, the potential for improvement, and inefficiencies in the energy system. This underscores the need to develop technologies for the extraction and processing of fossil fuels (coal and hydrocarbon resources) and renewable energy sources, as well as advancements in energy generation, storage, transmission, and enhanced government regulation in the energy sector.

Energy security is determined by the amount of energy needed by industry and households, considering the projected growth rates of the national economy. Energy equity is determined by the cost of energy and the ability of companies and the population to purchase it. Environmental sustainability is associated with the neutralization of environmental damage. Therefore, an urgent problem is to ensure the technologically and economically sound diversification of energy sources. This diversification is determined by the current and future needs for energy sources, the availability and accessibility of various energy sources, the development of scientific and technological progress, and R&D in the field of extraction and processing of fossil energy sources. It also considers the use of renewable energy sources in energy production, opportunities to achieve sustainable development goals, and the implementation of the energy trilemma [2].

Among fossil energy sources, the most important is coal, which is found and has relatively large reserves in many countries of the world, including Vietnam. According to [3], coal will continue to play a crucial role in the global energy sector. Large reserves are not exploited or planned to be extracted in Vietnam [4], as the coal is of relatively low quality compared to the coal grades available on the global market. The share of imported coal is increasing, and dependence on the global coal market is growing. Oil is currently not used as an energy source; gas is imported.

Considering the shortage of fossil energy sources and modern global trends (the transition to green energy, which helps reduce greenhouse gas emissions into the environment), it is necessary to diversify the energy sources used by Vietnam's energy system. Coal gen-

eration produces the highest carbon dioxide emissions compared to other sources, which requires the introduction of “clean coal” technologies and the reduction or abandonment of coal generation. On the other hand, the insufficient quantity and quality of Vietnamese coal and difficult mining and geological conditions [4,5] stimulate the priority use of other (renewable) energy sources. It should be noted that the economic growth rate in Vietnam is approximately 6–7% per year, which requires solving the problem of a corresponding increase in energy needs.

As a financing mechanism, Just Energy Transition Partnerships (JETP) [6] can be used. In such a partnership, wealthy nations fund a coal-dependent developing nation to support the country’s own path to phase out coal and transition towards clean energy while addressing the social consequences. JETPs aim to bridge the gap between developed and developing nations in moving towards clean energy. South Africa, Indonesia, and Vietnam are the first three countries to receive funding. This research also helps managers and the Vietnamese government have a deeper theoretical foundation for planning action strategies and serves as the basis for choosing green energy sources to be prioritized for more feasible investment.

The purpose of the study is to substantiate the possibilities of transitioning to green energy in the context of Vietnam, considering both the rate of economic growth, the scarcity of fossil energy resources, the SDGs, and the energy trilemma domain.

The goals set in the study are as follows:

- Identify the factors contributing to the gradual replacement of fossil energy with renewable energy sources;
- Economically justify the directions for the development of the energy sector in Vietnam, considering energy source diversification and the transition to renewable energy sources.

2. Materials and Methods

The analysis of statistical data and government planning documents in this study involves summarizing the latest reports from the Vietnam Electricity (EVN), coal businesses, and the General Statistical Office of Vietnam. Additionally, it encompasses examining documents within the national regulation system pertaining to renewable energy sources.

The research methodology includes the following components:

- The authors developed GDP forecasts until 2050 based on the State Plan for Economic and Social Development for the 5-year period from 2021 to 2025 (<https://thutuong.chinhphu.vn/chuong-trinh-hanh-dong-cua-chinh-phu-thuc-hien-ke-hoach-phat-trien-kt-xh-5-nam-2021-2025-10939679.htm>, accessed on 20 January 2024). Analytical studies were conducted for four scenarios, with a preference for the “growing well” scenario. Based on this scenario, the study assessed forecasted energy consumption until 2050 across three options (low, medium, and high).
- An analysis was conducted on Vietnam’s energy mix in 2023, including the examination of power plant capacities and the volume of energy production from fossil sources (coal, gas, oil) and renewable sources (hydropower, solar energy, wind energy, biomass energy).
- The study analyzed indicators of the country’s energy system in alignment with the energy trilemma (energy security, energy equity, and environmental sustainability).
- Forecasts were generated for the volume of energy consumption and the structure of energy supply from various sources, with a particular focus on renewable energy sources.
- Recommendations were formulated for Vietnam’s sustainable energy development plan for the period 2023–2050, considering the growth of green energy and the reduction of the share of fossil sources.

The Structure of the Article Includes the Following Parts

The first part contains a literature review where the authors provide comments on scientific articles related to feasibility studies and the efficiency of various energy sources within Vietnam's energy system, including coal, hydropower, renewable energy, wind, solar, and biomass. The authors draw conclusions about the multiplicity of energy sources and advocate for their diversification.

The second part focuses on forecasting Vietnam's electricity consumption due to economic development for the period 2023–2050.

The third part analyzes the current state of Vietnam's electricity sector, categorizing sources into two main groups: fossil energy and renewable energy sources.

The fourth part presents an assessment of energy governance in Vietnam, evaluating it against the trilemma indicators of energy security, energy equity, and environmental sustainability.

The fifth part delves into an analysis and forecast of the restructuring of Vietnam's electricity supply for the period 2023–2050. This includes a comparison of the costs of generating electricity from various sources and projected changes in capacity and electricity supply in Vietnam.

The sixth part concentrates on proposing action plans for applying Vietnamese energy sustainable development strategies to the energy transition.

The seventh part is the conclusion; the study summarizes its results and draws conclusions based on the conducted analysis.

3. Literature Review

Researchers analyzed the main problems of Vietnam's energy industry. There are studies on the energy transition mechanism (a project supported by Carbon Trust, Asia Group Advisors, and Climate Smart Ventures [3]), the use of fossil fuels in the past and the present (Nevskaya M.A. et al. [4], Nguyen Q.N. et al. [5]), and renewable energy for the future (Nguyen X.P. et al. [7], Nguyen K.Q. [8], Gerard Sassges and Alan D. Ziegler [9]).

Energy transition mechanism.

The project supported by the Carbon Trust, Asia Group Advisors, and Climate Smart Ventures [3] is devoted to a technical and economic analysis of the Energy Transition Mechanism (ETM) in Vietnam. Its content provides an overview of the electricity system, the electricity market, coal-fired power plants, and renewable energy development. The project assessed country-level factors, such as the rate of decommissioning coal-fired power plants. However, the research information is limited, and much of the data are outdated.

Fossil energy—past and present.

In the article by Nevskaya M.A. et al. [4], the authors proved that the complex mining and geological conditions will not allow the Vietnamese economy to provide enough coal for electricity generation, taking into account the required growth rates. In addition, the environmental consequences of burning coal in thermal power plants and green energy conditions determine the need to reduce the share of coal in the energy mix.

The article by Nguyen Q.N. et al. [5] provides a comprehensive review of the Vietnamese coal industry, examining current coal mining conditions and highlighting key points of the 2030 Coal Industry Development Plan. The plan projects coal production to be 51–54 million tons by 2025 and 55–57 million tons by 2030, with underground coal mining's share expected to decline to 11% by 2030.

Renewable energy—the energy of the future.

The article by Nguyen X.P. et al. [7] explores venues for growth in Vietnam's renewable energy sector until 2050. The Development Strategy of Renewable Energy of Vietnam by 2030 with a vision to 2050 determined the main directions for the development of the fuel and energy sector of Vietnam, including many important regulations. It recognizes Vietnam's renewable energy sector as crucial for sustainable socio-economic development, emphasizing the need for economic reforms incorporating green energy technologies.

The article by Nguyen K.Q. [8] demonstrates that Vietnam holds promising wind energy potential, with available land suitable for wind energy development. Despite the environmental, economic, and social benefits associated with wind energy, its exploitation in Vietnam remains limited, primarily due to a lack of strong political will and an effective framework for sustainable development in renewable energy. Therefore, the highest priority lies in establishing renewable energy development goals and implementing necessary measures to achieve them. Two main instruments are proposed: the introduction of feed-in tariffs and the provision of investment incentives.

In the article “Past, Present, and the Unsustainable Future of Hydropower in Vietnam”, written by Gerard Sassges and Alan D. Ziegler [9], the authors clarify the remarkable development of hydropower in recent times. It is noteworthy that Vietnam’s hydropower industry ranks second only to China and Japan in Asia. The development history and operational patterns of 720 hydropower projects in Vietnam are analyzed from both positive and negative environmental perspectives.

In the article by Cuong T.T. et al. [10], studies were conducted on the possibility of producing electricity from rice straw in Vietnam. This represents renewable energy from Vietnam’s largest source of surplus biomass, along with other sources such as sugarcane bagasse, coffee bean shells, agricultural waste, and wood mulch. The study reveals that the current power generation capacity from rice straw is 2565 MW, with 24 out of 63 provinces having a capacity potential exceeding 30 MW. The study also analyzes limitations and obstacles and proposes corrective measures for the development of the domestic biomass energy industry.

Despite theoretical research on existing problems in Vietnam’s energy industry, there is currently insufficient research on an integrated and flexible approach to planning and forecasting the energy transition from coal to solar, wind, biomass, and other environmentally friendly energy sources until 2050, considering the rate of economic growth.

4. Electricity Consumption in Vietnam: Forecasts

4.1. In Accordance with the Plan [11], the GDP Growth Rate for the Period 2023–2025 Is Planned at 6.5–7%

It is predicted that from 2023 to 2050, Vietnam will experience economic growth. According to [12], four scenarios can occur:

- “Growing well”: growth until 2050 at different rates, including 6.5% in the period 2023–2025, 5.9% in the period 2025–2030, 5.1% in the period 2030–2040, and 3.96% in the period 2040–2050.
- “Low growth”: growth until 2050 at a lower rate, including 3.5% in the period 2023–2025, 3% in the period 2025–2030, 2.5% in the period 2030–2040, and 2% in the period 2040–2050;
- “Not growing”: no changes in GDP in the period 2023–2050;
- “Decrease”: economic decline by 2% in the period 2023–2025, 2.5% in the period 2025–2030, 3% in the period 2030–2040, and 3.5% in the period 2040–2050.
- These forecasts are examined based on two main groups of factors [13]:
- The first group is economic factors that directly affect the growth process, including capital, labor, natural resources, and technology;
- The second group is non-economic factors that indirectly contribute to the process of economic growth, including socio-cultural factors, socio-political institutions, ethnic characteristics, religion, and community participation.

Based on the current state of the factors that were assessed [7], the authors predict that the realization of the “growing well” scenario is the most likely.

Vietnam’s GDP has grown steadily over the years and, with its development advantages, contributed to trade progress in previous years. Taking into account the expected growth rates under the “growing well” scenario, the projected values of Vietnam’s GDP will be 488 USD billion in 2025, 649 USD billion in 2030, and 1575 USD billion in 2050 (Figure 1).

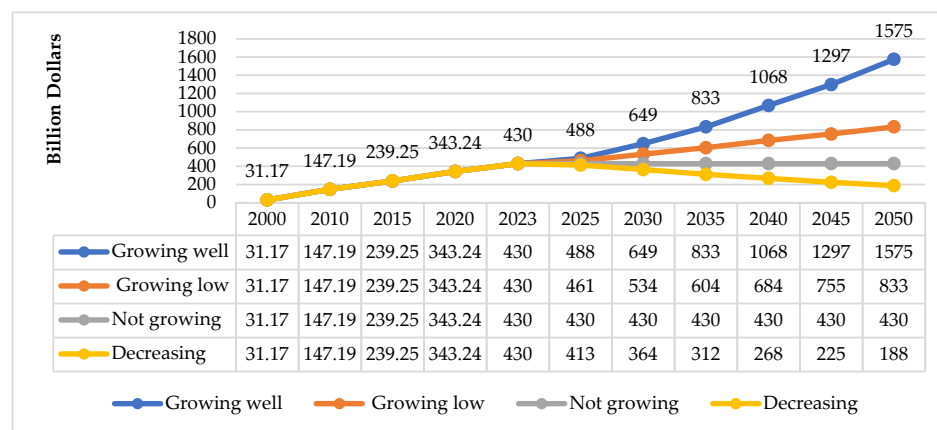


Figure 1. Actual (until 2023) and forecast (according to the authors' estimates) Vietnam's GDP. Compiled by the authors based on data on Vietnam's GDP [1,12].

At the end of 2023, Vietnam's GDP grew by 5.05%, and inflation was at 3.25%, remaining at a low level. Consumer price growth in 2023 is already below the 10-year average inflation rate of 3.8%. The unemployment rate fell, contributing to increased consumer spending. Economic growth in the well-being of the population has led to an increase in demand for household electrical appliances [4].

The actual GDP values are presented in the graph and in the table of indicators. Forecasted GDP values are presented for four scenarios.

Economic development scenarios require manufacturing industries to operate effectively, in which the contribution of the electricity industry is very important. If the demand for electricity is not met, the economy cannot develop, so the electricity industry and economic development are closely linked and interrelated.

4.2. Electricity Consumption Forecasts under the "Growing Well" GDP Scenario

Analysis data indicate that the demand for electricity generated by power plants increases in proportion to the level of people's well-being. On average, Vietnam's electricity demand increased by 11% during the 10-year period before the COVID-19 pandemic [1].

According to actual data, the demand for electricity in Vietnam in 2023 amounted to 80.56 thousand MW [1]. The electricity consumption forecast was calculated with the growth rates specified when forecasting GDP under the "growing well" scenario (Figure 2). The latter assumes that the demand for electricity production capacity fluctuates within three specific ranges: "lowest" (−10%), "most similar," and "highest" (+10%).

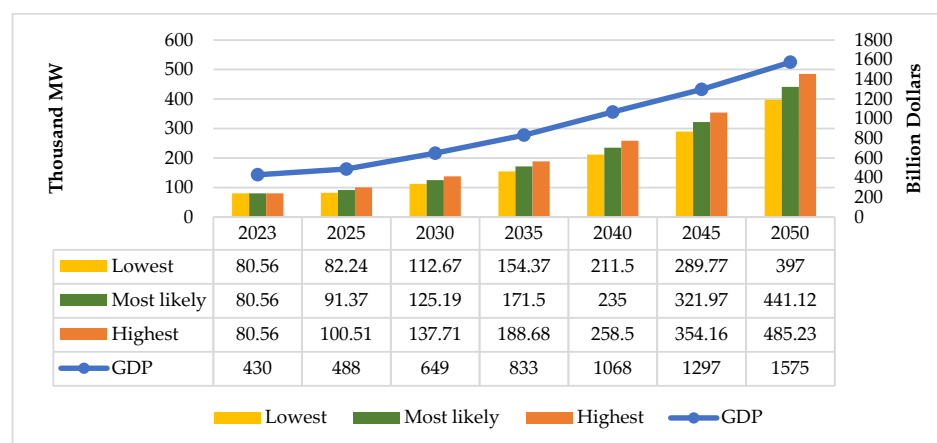


Figure 2. Electricity consumption forecasts corresponding to GDP growth in the period 2023–2050, according to three scenarios. Plotted by the authors based on the "National Electric Power System of Vietnam", "Economy of Vietnam" [1,14], and the accepted assumptions.

The increase in demand for electricity generation is associated with the optimization of the use of electricity production capacity at existing power plants or the construction of additional power plants [15–17]. The “Most likely” is the case scenario that the authors will use for further use in research due to the level of feasibility that is most suitable for economic development.

5. The Energy Mix, Fossil Energy, and Green Energy in Vietnam: An Analysis of the Current State

5.1. Electricity Production in Vietnam for 2023

In 2023, the total volume of electricity amounted to 280,629 thousand MWh, including that produced by coal power plants supplying the national energy system (129,577 thousand MWh, or 43%) and that produced by hydropower plants (80,904 thousand MWh, or about 29%) [11]. Figure 3 shows the energy sources used in Vietnam and the volumes of energy generation.

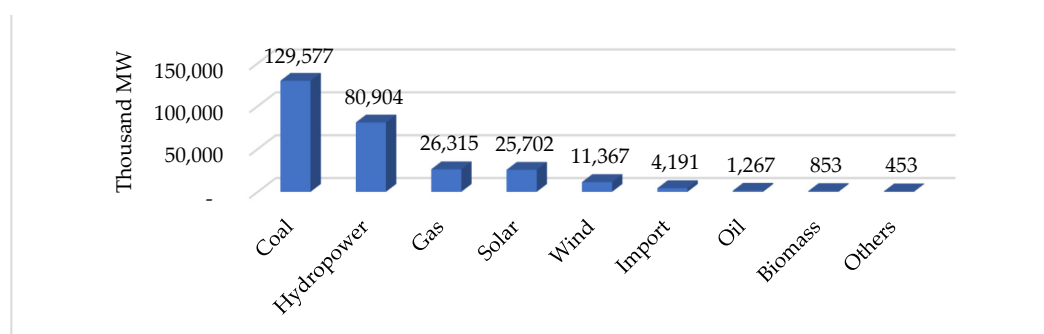


Figure 3. Electricity production by source in Vietnam in 2023. Compiled by the authors based on the “Report on the annual results of electricity production” [14].

Coal-fired and hydropower plants are the two largest sources of electricity in Vietnam. Other energy sources providing electricity currently account for a small share, but their growth rates are increasing rapidly in line with the needs of the economy and the need to diversify the energy sector.

5.2. Fossil Energy

(1) Coal

Coal accounted for the largest share of the country’s energy mix and was actively supported by the government during the period of economic growth (2005–2020) [18]. Coal-fired power plants are concentrated in areas near coal mines. There are currently 38 coal-fired power plants in operation, with a capacity of approximately 25 GW. Most of the capacity of existing coal-fired power plants is owned by state-owned corporations, such as Vietnam Electricity; or EVN (57%), Vietnam National Petroleum Group, or Petrolimex (11%); and Vietnam Coal and Mineral Industries Group or Vinacomin (7%) [19]. Coal-fired power plants in Vietnam are classified based on two main factors: combustion technology and steam parameters [20].

According to the Vietnam Energy Statistics Report for 2023, approximately 63% of the total amount of coal consumed in the electricity sector fuels coal-fired power plants, while almost 35% is utilized in industrial production (including iron and steel production, cement, mining, paper production, and the chemical industry) [21].

After being a coal-exporting country for decades, Vietnam has become a net importer of coal since 2015 [22]. Coal imports are continuously rising to meet the demand for new coal-fired power plants commissioned in recent years [23]. In 2022, Vietnam imported a record 54.8 million tons, surpassing the total domestic coal production of 11.5 million tons. The reason behind this surge is the significant reduction in coal prices after 2020, coupled

with a heightened demand for suitable quality coal for thermal power plants, reaching unprecedented levels.

Coal is primarily imported from Indonesia, Australia, Russia, China, Malaysia, South Africa, and Canada (Figure 4). Among these sources, Indonesia holds the top position [24]. Currently, domestic demand is on the rise, particularly for thermal power plants, while mining production remains significantly lower, exacerbating the challenge of coal imports [25].

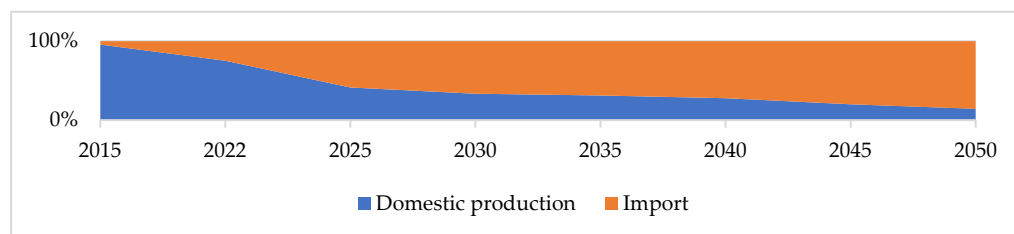


Figure 4. Coal supplies for electricity generation in Vietnam, 2016–2050. Compiled by the authors based on an analysis of high-voltage direct current in Vietnam [26].

The State Administration will cease controlling prices and production in Vietnam’s coal industry from 2030. Starting in 2030, enterprises will dynamically adjust their coal production and trading plans to meet market demands. Coal quality standards will undergo changes, requiring higher quality coal to align with market needs. New types of high-quality coal will entail higher costs [21,27]

By committing to achieving carbon neutrality by 2050, EVN decided to stop developing new coal power projects and reduce its dependence on this energy source. Vietnam has six coal power plants transitioning to liquefied gas, namely Bac Lieu, Dung Quat 1–2, Gan Dau, Long Son Petrochemical Thermal Power Plant, Phu Yen, and Son My 1–6.

(2) Natural gas

Natural gas plays a crucial role as one of the alternative fuels in the transition process, being more environmentally friendly and a suitable option until the full establishment of infrastructure, technology, and financial mechanisms for renewable energy. Additionally, natural gas may continue to be a long-term supplementary fuel source in the future [28].

While a complete transition to 100% renewable energy is unlikely in the near future, combining the combustion of natural gas and hydrogen could be one of the greenest, cleanest, and most economical moves for the electric power industry [29]. When operated on low or zero-emission fuels like hydrogen, modern gas turbines with carbon capture and sequestration technology [30] produce electricity with extremely low or no carbon emissions, regardless of whether it is a heavy-duty turbine operation or a high-power gas-derived turbine [31]. It was predicted that by 2023, gas turbine modifications of the LM2500 would have achieved over 6 million operating hours on hydrogen-containing fuel mixtures with a hydrogen content of up to 95%. Hydrogen has the potential to decarbonize emission-intensive industries such as electricity, heat generation, and transport, with notable examples in Japan, Australia, and South Korea. Simultaneously, GE gas turbines demonstrated the ability to run on hydrogen, creating numerous opportunities for utilities to reduce emissions [11].

In 2021, natural gas production reached 10.6 billion m³, marking a 1% increase, and the volume of liquefied petroleum gas reached 437.6 thousand tons, representing an 18.5% increase from the same period in 2020. However, by 2023, Vietnam’s natural gas fields are expected to be depleted, necessitating the importation of tens of billions of cubic meters of gas [26].

(3) Oil

In 2023, according to the Vietnam Oil and Gas Group (PVN), Vietnam’s oil reserves were projected to increase by 16.97 million tons, with oil production reaching 10.84 million tons, marking a 24% surplus compared to the annual plan [32]. Additionally, in the same

year, Vietnam exported 2.7 million tons of crude oil and imported 10.2 million tons to supply Vietnam's two largest refineries, Nghi Son and Dung Quat. Kuwait stands as Vietnam's primary crude oil supply market, constituting nearly 90% of the total. Despite the considerable oil production, the mastery of oil refining technology remains lacking. Consequently, oil-fired thermal power plants in Vietnam face numerous limitations. They generated only 1267 thousand MWh in 2023. Due to various challenges, issues, and environmental impacts, this sector is not considered the future development direction for Vietnam's energy industry.

Overall, Vietnam has accumulated substantial experience and technology in the development and utilization of fossil energy. Fossil energy sources offer advantages in the thermal energy infrastructure in Vietnam [33]. Boiler systems, power plants, and transmission systems have been designed for efficient operation and use [34]. Fossil energy, widely employed for decades, continues to provide stable electricity [35]. Presently, power plants utilizing fossil energy produce a significant amount of electricity, primarily meeting Vietnam's current electricity needs.

Although fossil energy plays an important role in Vietnam's electricity supply today, the transition to renewable energy sources is influenced by the following factors:

- The use of fossil energy results in CO₂ emissions, which contribute to climate change and environmental pollution. This creates international pressure on Vietnam to reduce its dependence on fossil energy.
- The price of fossil energy may change depending on market factors and the situation in the world. This may cause price uncertainty and affect the stability of the energy sector.
- Depletion of high-quality fossil energy sources and infrastructure limitations hindering their exploitation. This emphasizes the increasing significance of importing coal, oil, and gas for electricity production.

Consequently, fossil energy sources (coal, gas, oil) are gradually losing priority in the government's agenda for providing electricity due to the growing development of renewable energy sources in Vietnam. Investments in technological research and development within the renewable energy industry create opportunities for Vietnam to establish a clean and sustainable electricity supply in the future.

5.3. Renewable Energy

(1) Hydropower

Hydropower plants contribute 29% to the total energy production in Vietnam, with a capacity of approximately 22,544 MW. The distribution of hydropower capacity is as follows: 60% in the North, 27% in the Central region, and 13% in the Southern region [1]. By 2023, a total of 374 hydropower projects were operational.

Given Vietnam's geographical location in a tropical climate zone characterized by high temperatures, humidity, abundant rainfall (around 1800–2000 mm annually), and a dense river system consisting of more than 3450 rivers, the country possesses substantial hydropower resources [36]. The topography varies from more than 3100 m in elevation to sea level [37], creating a significant potential energy source due to topographical differences [14].

According to global hydropower experiences, Vietnam's potential hydropower capacity in the future could range between 30,000 MW and 38,000 MW, with electricity production reaching 100 to 110 million MWh [38].

(2) Solar energy

Vietnam boasts significant solar energy potential due to its proximity to the equator and the presence of arid and sunny areas, especially in the south-central provinces. Solar radiation intensity ranges from 897 to 2108 kWh/m²/year, equivalent to 2.46 to 5.77 kWh/m²/day. The highest radiation intensity is concentrated in the Central Highlands and southern provinces like Dak Lak, Gia Lai, Nha Trang, Ninh Thuan, Binh Thuan, Tay Ninh, and Binh Phuoc [39].

The Vietnam Energy Development Plan VIII [11] aims to increase the share of solar energy in renewable sources to 25% within eight years. This initiative also intends to reduce reliance on imported coal energy, thereby providing greater opportunities for the country's solar energy market.

Vietnam has made important strides in the use of solar energy by 2023, but efforts are still needed to increase the optimization of the use of this renewable energy source.

(3) Wind energy

Wind power in Vietnam belongs to the emerging energy group [40]. Although the construction of wind farms began only in 2012 with the Tuy Phong Wind Farm (now called Binh Thanh), more than 28 projects with installed capacities ranging from 20 to 400 MW were expected to be operational in 2023 [41].

Due to Vietnam's geographical features, which include over 3000 km of coastline and a tropical monsoon climate, the country has been extensively studied and recognized as having substantial wind energy potential in the region. In more than 39% of Vietnam, the average annual wind speed exceeds 6 m/s at an altitude of 65 m, and in over 8% of the country, the average annual wind speed exceeds 6 m/s [42]. The technical potential of onshore wind power, approximately 42 GW, is suitable for large-scale wind power projects [8].

Offshore wind potential surpasses onshore wind potential (Table 1) due to the extensive coastal zone, higher wind speeds, and more persistent conditions offshore. Offshore wind projects face fewer constraints related to land use issues and infrastructure. The technical potential of offshore projects in Vietnam, assessed using global wind maps at 100 m and within 200 km of the coast, along with GEBCO seabed data [43], indicates a total technical potential of 475 GW, including 261 GW in fixed towers and 214 GW in floating towers [44].

Table 1. Wind energy potential in Vietnam.

Region	Onshore Wind Potential (GW)	Offshore Wind Potential (GW)
Northeastern	4.6	64.5
Northwestern	2.8	-
Red River Delta	1.5	66.7
North Central	0.3	113
South Central	16.8	78.8
Highlands	12.5	-
Southeastern	3.3	27.1
Mekong Delta	0.2	259.7
Total	42	609.8

The above is compiled by the authors based on materials from "Wind Energy Development in Vietnam" [44].

Many energy companies and international investors participated in wind energy projects in Vietnam. International cooperation helps improve the quality of technologies and ensures the sustainability of projects.

Despite positive progress, infrastructure challenges remain, including the development of transmission networks to connect areas with high wind resources to energy consumption centers.

The Vietnamese government applied incentive and preference policies, such as tax cuts and financial support, to encourage investment in wind energy resources.

(4) Biomass

Vietnam initiated the utilization of biomass energy in 2010, yet it has not reached the required level. Currently, biomass is mainly used to produce electricity, heat for households,

businesses and manufacturing plants, and biofuels such as ethanol and biodiesel. According to the Ministry of Industry and Trade, Vietnam has 16 biomass power plants with a total installed capacity of 350 MW [11].

Vietnam has great potential for biomass energy development, with a total potential of up to 50 million tons of oil equivalent (TOE). The main sources of biomass include wood and forestry by-products, as well as agricultural waste. Wood is the main source of biomass in Vietnam, accounting for about 40% of the total potential, equivalent to 20 million tons of fuel equivalent. Wood is used to produce electricity, heat, and biofuels. Agricultural waste (straw, sugarcane bagasse, and manure) accounts for about 30% of the total potential, equivalent to 15 million tons of fuel equivalent. Agricultural waste is used to produce electricity, heat, and fertilizers. Municipal waste (domestic and industrial waste) accounts for about 30% of the total potential, equivalent to 15 million tons of fuel equivalent. Municipal waste is used to produce electricity, heat, and fertilizers.

However, biomass energy production in Vietnam still faces some challenges [10], including:

- Investment costs for biomass energy projects are relatively high. This is because biomass resources are often scattered and difficult to collect and transport. In addition, biomass energy production technologies are still relatively new and undeveloped, resulting in high investment costs.
- Infrastructure for biomass energy production in Vietnam is limited. This is because biomass power plants, biofuel processing plants, and biomass energy distribution systems have not yet developed in sync.
- Policies to support biomass energy development in Vietnam are still incomplete. This is attributed to biomass energy being a relatively new energy source in Vietnam, with insufficient focus on investment and development.

As of now, the Phu Tho Thermal Power Plant is the sole thermal power plant in Vietnam, utilizing waste instead of coal [7].

Vietnam holds vast potential in renewable energy sources like hydropower, solar energy, wind energy, and biomass. The country's abundant rivers, sunlight, strong winds, and extensive agricultural system provide abundant resources for the development of renewable energy.

6. An Analysis of the State of the Energy Sector in Vietnam Based on the Energy Trilemma Indicators

6.1. Key Indicators of the Energy Trilemma in the Vietnamese Energy Sector

Table 2 presents indicators that balance Vietnam's energy security, equity, and environment, as assessed by the World Energy Council.

Table 2. A framework for assessing the Vietnam Energy Trilemma provided by the World Energy Council to 2022.

	2019	2020	2021	2022
1. Energy security	21	19	18	19
2. Energy equality	17	22	20	20
3. Environmental sustainability	15	18	16	18
Total	53	59	54	57
Rank in the world	91	65	61	55

Compiled by the authors based on the "World Energy Trilemma Index" [2].

6.2. The Main Factors Determining the Values of the Energy Trilemma Indicators in Vietnam

- Energy security

Today, in the context of high and continuous economic growth, energy security is considered the basis of Vietnam's economic development policy. Priority was given to rapid

and sustainable energy development and strides were made in protecting the ecological environment, ensuring national defense and security, and realizing social progress and justice as a key regular objective throughout the process of industrialization and modernization of the country.

National energy development aligns with the principles of a socialist market economy and conforms to trends in international integration [45]. Presently, Vietnam is rapidly building a synchronized, competitive, and transparent energy market, diversifying ownership forms and business methods. Using market prices for all types of energy, encouraging and creating favorable conditions for the participation of all sectors of the economy, especially the private sector, in energy development is planned. The country is committed to eliminating all forms of subsidies, monopolies, unfair competition, and opacity within the energy sector [43].

– Energy equity

The Vietnamese government encourages private investment by introducing transparent governance and pricing mechanisms, as well as through strategic public investment in basic infrastructure. There has been a sustainable transition to a low-carbon economy and a climate-resilient trajectory [46].

The energy transition is characterized by fairness and inclusivity, ensuring that workers, communities, and those affected benefit from new economic opportunities. The process involves job creation, reskilling initiatives, capacity-building, and fortifying the social safety net [47].

– Sustainable environment

Vietnam's commitment to limit the global temperature increase to 1.5 °C above pre-industrial levels, in accordance with the Paris Agreement on climate change, is reflected in strategic decisions and their ongoing implementation. The nation adopts innovative, equitable, and sustainable approaches to decarbonize economies, achieving an inclusive energy transition between countries while meeting climate goals [44]. Vietnam emphasizes that its energy transition must uphold justice and the rights of all citizens.

Beyond climate goals, a just energy transition is also a catalyst for achieving the sustainable development Goals (SDGs). The transformation of energy systems has created new jobs and increased access to clean and modern energy [3].

6.3. *The Main Problems of the Vietnamese Energy Sector in the Energy Trilemma Domain*

Energy security is sometimes compromised, and power shortages occur periodically, especially in rural and mountainous areas of Vietnam in summer at peak hours (from 11 to 13 p.m. and from 18 to 20 p.m.). The inadequacy of electricity quality affects the functionality of household appliances such as televisions, refrigerators, and air conditioners.

Energy equity is not uniformly guaranteed for all citizens, particularly in rural areas. As of 31 December 2023, 99.26% of households in rural areas had access to electricity, leaving approximately 0.74% without electricity.

As for the quality of the environment, Vietnam has been experiencing growth in CO₂ emissions: 285.9 million tons in 2019, 251.1 million tons in 2020, 266.1 million tons in 2021, 381.1 million tons in 2022, and 384.911 million tons in 2023 [1,3]. This means that Vietnam must invest in finance, technology, capacity building, and energy transition. A suitable roadmap must be implemented that takes into account Vietnam's current conditions and circumstances.

The government proposed several directions to improve the performance in the energy trilemma domain:

1. Energy-saving measures, such as turning off billboards and dimming lighting during peak hours, encouraging the use of energy-saving devices, and turning off electricity when not in use;
2. Energy efficiency measures, such as energy-efficient air conditioners and other equipment;

3. Using six electricity tariffs depending on the level of energy consumption (0–50, 51–100, 101–200, 201–300, 301–400, and over 400 kWh): 0.0695, 0.7126, 0.08276, 0.10421, 0.11646, and 0.12028 USD/kWh.

However, the growing electricity demand makes the government build new power plants using various energy sources. This has an impact on the economic, environmental, and social components of energy sustainability.

7. Forecast for the Restructuring of Vietnam’s Electricity Supply 2023–2050

To create forecast energy mixes, the authors used the following data:

- Specific costs for the production of electricity from various sources;
- Information on energy efficiency and CO₂ emissions at power plants of various types;
- Forecasts of energy consumption in Vietnam until 2050 by options;
- Plans regarding the decommissioning of power plants running on fossil fuels and the commissioning of new power plants using renewable energy sources.

A comparison of the cost and production of electricity from different energy sources in Vietnam is presented in Table 3.

Table 3. Estimated costs of producing 1 kWh of electricity from various energy sources in Vietnam in 2023 [compiled by the authors].

Energy Source Type	Coal	Coal Import	Gas Turbines	Hydropower	Solar	Wind	Biomass
Cost of raw materials for electricity production (USD/kWh)	0.0554	0.0593	0.027	0	0	0	0
Total cost of electricity production (USD/kWh)	0.0865	0.0974	0.071	0.068	0.0611	0.05	0.101

For coal, gas, hydro, and wind, the authors used the National Electric Power Development Plan [11], which includes the costs of construction, insurance, maintenance, and transportation to generate 1 kWh of electricity.

For other renewable sources (solar and biomass), data based on the Vietnam Renewable Energy Policy [7] and costs in several countries (Korea, Indonesia, China, Malaysia, and Thailand) [3] were used as these Asian countries share similar characteristics to Vietnam in terms of economic and social aspects.

The cost of energy resources (coal and gas) is determined by the authors as follows. One ton of 5a.1 TCVN lump coal produces 2419 kWh of electricity [14]. The TCVN coal price set by the government in 2023 was USD 134. Thus, the cost of raw materials (coal) used to produce 1 kWh of electricity is USD 0.0554. Imported coal (mainly Australian anthracite, as well as South African coal and sub-bituminous coal) had an average price of USD 146 per ton in 2023 and generated an average of 2460 kWh [11] due to higher quality. However, imported coal incurs import tax costs (10%), as well as transportation costs and risks due to market fluctuations compared to domestic coal, resulting in higher prices and overall power generation costs [4].

According to the contract for the import of natural gas from gas turbine power plants of the Vietnam National Electric System Dispatch Center, the gas price in 2023 was 2974 USD/million BTU [14]. The cost of raw materials (natural gas) to produce 1 kWh of electricity was USD 0.027.

The authors found the total costs of wind energy production by dividing the total costs of building a power plant (205 USD million for a 100 MW power plant), maintenance costs (USD 80,000 per year), and insurance premiums for total power generation. The project cost is approximately USD 821,523 per year for the cost of a 100 MW wind power plant. The total cost of producing 1 kWh of electricity from wind is 0.05 USD/kWh, and the total cost of producing 1 kWh of electricity from hydropower plants is USD 0.068 [11].

An analysis of the costs shows that producing 1 kWh of electricity using wind energy is the cheapest at 0.05 USD/kWh. The second cheapest sources for electricity production are solar energy (0.0611 USD/kWh) and hydropower (0.068 USD/kWh). Natural gas and coal energy have average costs, while biomass is currently the highest-cost energy source due to power plants having insufficient capacity. From an economic, social, and environmental perspective, this indicates that expanding the use of green energy is quite feasible, and numerous new projects are expected to be built and commissioned in the period 2025–2030.

Energy efficiency is assessed by a number of indicators, including the coefficient of utilization of installed capacity of power plants. It is the most important characteristic of the operating efficiency of electricity generation. It is calculated as the ratio of the arithmetic mean power to the installed power of the electrical installation for a certain period [45]. Average capacity factors for different kinds of energy sources are as follows: coal—63.8%; gas turbines—42.5%; oil—7.8%; hydro—39.8%; solar generation—33%; wind generation—45%; biomass—27.47% [42,48]. These values were used for further calculations [24]. The current power supply capacity of energy sources in Vietnam, types of power plants, and volumes of energy generation are presented in Table 4 based on [1].

Table 4. Electricity capacity supplied by power plants in Vietnam in 2023.

Energy Source Type	Power (MW)	Very Large Power Plants (>1000 MW)	Large Power Plants (>400 MW)	Medium Power Plants	Small Power Plants (<50 MW)
1. Coal	26,744	9	16	12	1
2. Gas turbines	7169	2	8	1	
3. Oil	1127				2
4. Import					
5. Others					
6. Renewable energy	42,709	3	7	121	420
a. Hydropower	22,878	3	2	36	333
b. Solar	16,353		4	67	62
c. Wind generator	5799		1	16	11
Biomass	483			2	14
Total	80,555	14	31	134	423

Compiled by the authors based on “General Statistics Office of Vietnam” [1].

Coal-fired and hydropower plants currently account for the majority of the energy supply to Vietnam’s power grid, but most research reports believe that the development prospects for coal and hydropower are poor [5,9,12].

In accordance with the Plan [11], six coal-fired power plants will be built from 2023 to 2030 with a total capacity of 5660 MW: Long Phu 1, An Khanh–Bac Giang, Na Duong 2, Vu Ang 2, Quang Trach 1, and Van Phong 1. After 2030, Vietnam is not planning to build additional coal power plants, shifting its focus towards investments in renewable energy sources.

In terms of hydropower, all rivers in Vietnam are exploited, with a significant total of about 375 hydropower stations operating at different scales. Vietnam’s hydropower industry is well-developed and ranks third in Asia after China and Japan [9].

In the period 2023–2030, the total installed capacity is projected to increase from 80,555 to 125,190 thousand MWh (see Figure 2). Addressing the energy deficit during this period is crucial, taking into consideration the requirements of the Energy Trilemma, as outlined in Table 5.

Table 5. Forecast for the growth of total production capacity and electricity generation in Vietnam in 2023–2030. [compiled by the authors].

Source	Power (MW)		Quantity of Electricity Supplied (Thousand MWh)	
	2023	2030	2023	2030
1. Coal	26,744	30,970	129,577	150,052
2. Gas	7169	11,140	26,315	40,891
3. Oil	1127		1267	
4. Hydropower	22,878	30,770	80,904	108,813
5. Sun	16,353	44,400	25,702	69,783
6. Wind	5799	46,620	11,367	91,382
7. Biomass	483	26,640	853	47,047
8. Other		6200	453	21,598
Total	80,555	125,190	280,629	529,568

The government is giving priority to solar, wind, biomass, and other green energy sources, with many new power plants using clean energy being built [14]. New renewable energy projects, including combined energy storage programs such as hydropower storage or hydrogen thermal energy, are given high priority by the government. A total of 133 solar power plants were projected to be built from 2017 to 2023, although not all of the plans were realized. Concurrently, an efficient exploitation and utilization strategy for fossil energy sources, coupled with imports, is deemed necessary. This involves gradually diminishing the share of coal thermal energy, giving precedence to the development of the natural gas sector, and advancing LNG energy sources, including imports. The energy transition will be executed by closely monitoring global technological advancements and trends in economical and efficient energy storage technologies [7].

Vietnam's energy sector will undergo major changes between 2023 and 2050. Vietnam will not build new coal-fired power plants after 2030 to ensure it reduces carbon emissions and meets commitments made at COP 26 (2021 United Nations Climate Change Conference). Some existing coal-fired power plants still employ outdated technologies that do not meet conversion requirements, resulting in a significant decrease in production capacity.

Green energy sources are being actively promoted by the government and will account for a significant share. Fossil fuels will gradually be replaced with solar energy, wind energy, biomass, and hydrogen combustion technologies. The share of electrical capacity from renewable energy sources (including hydropower) will reach about 61.41% (776.88 thousand MW) by 2030, aiming for a renewable energy share of over 47%, in line with the commitments outlined in the Political Declaration establishing the Just Energy Transition Partnership (JETP) with Vietnam. International partners are fully committed to practical implementation, targeting a renewable energy share exceeding 65% by 2050. Figure 5 illustrates the structure of electricity generation capacity in Vietnam by source, encompassing renewable energy sources and fossil resources.

To implement significant structural changes in Vietnam's energy sector, strategic plans and programs must be developed and implemented.

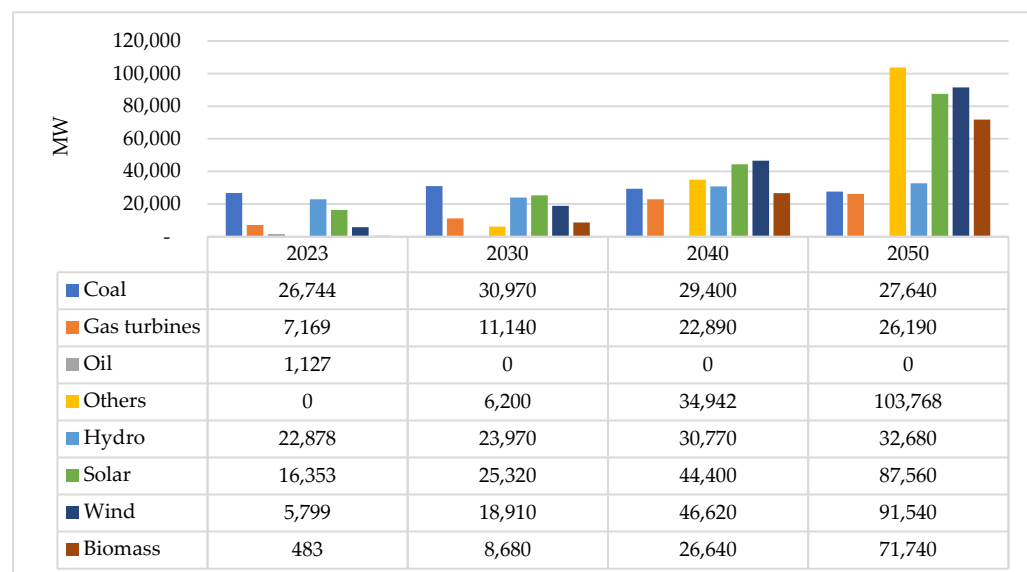


Figure 5. Electricity production capacity in Vietnam in 2023, 2030, 2040, and 2050 [compiled by the authors].

8. Strategic Plan for Transition to Renewable Energy Sources

Vietnam's Energy Ministry predicts that the country is likely to face an electricity shortage as the development of new power plants lags behind the country's rapidly growing energy consumption. The government allowed Vietnamese companies to have 100% foreign ownership in the energy sector. Therefore, Vietnam is focusing on renewable energy sources to meet future electricity demand [7]. The government hopes to become an electricity exporter in the next eight years.

The solar photovoltaic segment is likely to have the largest market share due to the declining cost of solar modules and the versatility of these systems to produce electricity and heat. According to the IRENA renewable energy statistics [40] for 2023, the installed capacity of solar PV systems in Vietnam reached 15,815 MW in 2023. The Ministry of Industry and Trade (MOIT) [11] has an additional plan to increase the installed capacity of solar PV systems. In May 2023, the Vietnamese government launched a 135 USD million energy strategy aimed at outfitting half of the country's residential rooftops with photovoltaic (PV) systems using a real metering system. In addition, the country was planning to commission the 50 MW Phong Hoa solar photovoltaic park by STEAG Solar Energy Solutions and Thai Dat Construction by the end of 2023 [24].

The increase in wind energy capacity is associated with the implementation of many large projects. The government has set targets and policies to encourage wind energy investment to meet energy needs and reduce greenhouse gas emissions.

For the rapid development of renewable energy technologies, Vietnam is fostering independent equipment production:

- Solar panels for 60% of the market are produced by eight companies in Vietnam: First Solar in Cu Chi, HT Solar in Hai Phong, IREX Solar in Vung Tau, Vina Solar in Lao Cai, IC Energy in Quang Nam, Trina Solar in Bac Giang, JA Solar in Bac Giang, and Canadian Solar in Haiphong [49].
- Wind turbines for 18–22% of the market are produced in Vietnam, including the General Electric wind turbine plant in Hai Phong [40].
- Biomass processing currently relies 100% on imports from countries such as China, Japan, America, Australia, and Germany. However, more than seven projects for the production of local equipment are expected to be implemented in Vietnam from 2023 to 2030 [8].

Renewable energy is associated with the following advantages and opportunities:

- Renewable energy does not generate CO₂ emissions and does not pollute the environment like fossil energy. Using renewable energy helps minimize environmental impact and helps reduce climate change.
- Renewable energy sources have low material and operating costs once the system is built. This helps ensure stable tariffs and reduces dependence on imported fuels.
- Investments in hydropower, solar, wind, and biomass technologies and infrastructure will create opportunities for growth in the renewable energy industry, create jobs, and promote economic development.
- The use of renewable energy sources helps to diversify energy supplies, reduces dependence on fossil energy, and increases the stability of the energy system.
- Vietnam is one of the first countries in the world to receive the JETP fund, announced in December 2022 after a lengthy negotiation process. This partnership will support Vietnam with finance, technology, and capacity building. It will also support improving the country's policies and regulations to increase private investment in renewable energy. The initial fund for the next three to five years is USD 15.5 billion. Vietnam is expected to announce the JETP Resource Mobilization Plan (JETP-RMP) in early 2024 [6].

However, there are many problems associated with renewable energy projects, including large initial investments, intermittency and instability of solar and wind energy sources, and the imperative need to develop efficient energy storage and management capabilities.

Based on a strategic analysis of the state, problems, and opportunities in the energy sector, coupled with forecasts of economic development and energy demand in Vietnam, the authors propose a strategic plan for the sustainable development of the national energy sector guided by the following principles:

1. Promoting energy conservation. The government should progressively shift from voluntary incentives to mandatory ones, setting energy-saving targets for each industry with reward and penalty mechanisms. Utilizing advanced science and technology, modern technologies, and promoting the development of mechanical engineering can achieve this goal.
2. Develop renewable energy and energy storage technologies. Increasing reliance on alternative and renewable energy sources such as hydropower, wind energy, solar energy, biomass energy, and geothermal energy helps reduce traditional energy consumption and mitigate environmental impacts.
3. Promoting the search and exploration of energy resources along with environmental protection. The energy system must be green, clean, economical, and efficient.
4. Introduce a pricing policy for electricity in accordance with the market mechanism. Aligning pricing policies with market mechanisms and improving wholesale and retail prices for electricity is necessary to create financial resources for reinvestment in the energy sector.
5. Strengthen coordination between ministries and other bodies, fostering a shift in thinking and awareness in the field of energy production and use to ensure energy security.

9. Discussion and Conclusions

The transition from fossil energy to renewable energy is an inevitable trend worldwide [3], and Vietnam is no exception [7]. The energy mix is determined by the requirements of energy sustainability [2]:

Energy security depends on the depletion of fossil energy resources, high levels of imports, rising prices for fossil energy sources, and the possibility of efficient use of renewable energy sources.

Energy equity is determined by the availability of electricity and depends on the costs of energy production and government subsidies.

Environmental sustainability is primarily determined by meeting decarbonization commitments and the sustainable development goals (SDGs), i.e., achieved by reducing greenhouse gas emissions.

Therefore, for an effective energy transition, the following must be taken into account.

Renewable energy projects are rated more favorably from an economic and environmental point of view than fossil energy projects. Renewable energy sources are projected to make up the majority of Vietnam's energy mix during the period 2023–2050, especially wind power, solar power, hydropower, biomass, and new hybrid green energy sources in the future.

Renewable energy technology projects need to be invested in simultaneously, in combination with energy storage technologies. New technologies are attracting attention due to their efficiency and low environmental impact (hydrogen thermal energy storage and hydroelectric energy storage), providing an environmentally friendly alternative to coal.

Electricity generation should not use only green sources instead of fossil fuels. Economic factors should be judiciously considered, promoting diversified solutions. Research into enhancing clean and environmentally friendly coal, exploring chemical modifications, and evolving mining and processing methods through clean coal technologies can be part of this strategy.

National energy regulation measures are aimed at creating a balanced structure of Vietnam's energy mix, ensuring maximum energy efficiency, minimal costs, and a reduced load on the environment. The Vietnamese government is investing in expanding the exploitation of renewable energy sources to fill the gap created by phasing out the use of coal. Renewable energy sources have enormous potential, and there will be a major shift towards improving the energy sector between 2023 and 2050.

The direction of further research on this topic is to economically evaluate the prospects for sustainable development using the potential of fossil and renewable energy in many political, social, technological, environmental, and legal fields in Vietnam.

In our opinion, in further research, it is necessary to substantiate in more detail the scenarios for the development of the Vietnamese economy, taking into account the influence of factors and perhaps more widely applied forecasting tools, which will increase the reliability of estimates. Undoubtedly, more attention should be paid to risks, their identification, and assessment in relation to renewable energy sources—for example, the in-house production of equipment for wind farms and solar power plants, batteries, new materials, and other risks and prospects.

Ensuring sustainable growth and economic development in the energy sector mandates a simultaneous focus on environmental activities. Collaborating with international organizations and enterprises is crucial to developing environmentally friendly and safe technologies for electricity production. Seeking long-term energy sources and utilizing economic resources from the JETP fund are avenues to enhance Vietnam's energy security.

Limitations of the research: The research is constrained by its reliance on materials from government planning until 2025 in Vietnam's energy sector, resulting in limited information for forecasting. The available data sources, comprising open data and background research information, introduce potential errors in the research forecast estimates.

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