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OPTIMIZATION OF RENEWABLE ENERGY SOURCES OPERATION IN VIETNAM'S ELECTRICITY MARKET

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In recent years, the rate of penetration of renewable energy sources (RES) into the Vietnamese power system continuously increased. Elaboration of the best grid codes to integrate renewable energy is one of the issues that must be solved in time. In order to prepare the most appropriate development plan, each country relied mainly on the cost curve marginal (Marginal Abatement cost - MAC) with optimal economic techniques to make the investment policy. In this study, the cost of electricity in the Vietnam power system is optimized by implementing a technical-economic optimization model solved hourly with 81 nodes, supported by a validated whether-converter renewable power generation data set and electricity demand data set. Numerical results indicate that these flexibility components can lead to a reduction in RES, allow a higher solar photovoltaics (PV) share with a factor of two and help meet electricity demand. From there, investors can make long-term investment orientation or short-term operation in conjunction with the small price determined in the competitive electricity market.

1. INTRODUCTION

Nowadays, the growth of renewable energy sources (RES) creates more opportunities for the countries in process of development for a sustainable power system with high reliability and also brings many challenges. With the level of high penetration of renewable energy sources created, the system is changing the inherent operating characteristics, facing many problems and having planning solutions, upgrading the grid to meet the amount of output power from these sources [1–3].

Some countries, including Vietnam, are still operating the power system in a centralized way, meaning that the electric power hold the most significant power sources of power generation, the entire transmission, operation, distribution, and electricity retailing business. Therefore, it is necessary to build a competitive electricity market in Vietnam, to improve power quality and cost system. Many studies on development issue of the future electricity system were performed: the modeling of grid integration of renewable energy and storage systems [4–6] combined nuclear and conventional plant, operating on hydrogen [7]; construction of the marginal cost curve to determine the direction of investment in the future [8]. The researches approach various other aspects, with new issues in the nowadays electricity market. However, no study has intuitively brought economic perspective - techniques that focus separately to analyze each aspect, and not all the elements joined together [9].

Some studies are made on the feasibility of integrating renewable energy into the electricity market to reduce CO_2. But the criteria for technical and economic optimization [10] and have also been implemented. These studies show that the most effective solution when developing renewable energy is when they are combined with storage.

However, the development of renewable energy, unique nature of peak shaving, and meeting energy needs depend on the specific characteristics of each country's applications. Accordingly, studies are needed based on regional characteristics, such as geographic potential, technology costs, and load demand.

In the situation of the retail competitive electric market is applied. In this study was conducted a modeling power system in Vietnam with the penetration of renewable energy by 2030, and the storage problem is also analyzed. The PyPSA framework is the basis of the Vietnamese power system model. It implements a partial equilibrium model by optimizing both short-term operation and long-term investment in the energy system. The implementation of the model is done as a linear problem using the linear equations of power flow [11,12]. Using the data provided by the Electricity corporation of Vietnam, the research results with long-term investment orientation along the marginal cost curve MAC are presented. The short-term operation in the electricity market with the price range at each bus is also analyzed. Besides, the continuous innovation of the system operation is guaranteed by the constraints in the model.

2. MODEL

In this study was modeled the Vietnam power system in perspective of 2030 when renewable energy sources will be integrated into the electricity system. The method of linear optimization total annual cost is expressed through equation (1):

$$\min_{G_{n,s},F_l,g_{n,s,t},f_{l,t}} \left(\sum_{n,s} c_{n,s} G_{n,s} + \sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} c_l F_l \right), \quad (1)$$

where nodes are labelled s, hours of the year by t and interconnectors by l, then total annual system cost consists of fixed annualised cost $c_{n,s}$ for generation and storage capacity $G_{n,s}$, fixed annualised cost c_l for transmission capacity F_l and variable costs $o_{n,s,t}$ for generation and storage dispatch $g_{n,s,t}$. Cost are not associated with the flow $f_{l,t}$ on interconnector l in hour t.

2.1 POWER BALANCE

In order to maintain the balance of power, equality between the power generated and the power consumed must be ensured at all times. The constraint for the power-balance on bus n is given by formula (2), as follows:

$$\sum_s g_{n,s,t} - d_{n,t} = \sum_l K_{nl} f_{l,t} \quad \leftrightarrow \quad \lambda_{n,t} \quad \forall n,t, \quad (2)$$

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where: $d_{n,t}$ – the load at the n bus at t time, K – the incident matrix of the system [12] $f_{l,t}$ – the transmission power through l line at t time.

The imbalance at node n between local power consumed and the power produced is regulated by the import and export of energy between interconnected transmission systems.

2.2 GENERATORS

Equation (3) states the limitation of the power generation capacity $G_{n,s}$ produced power plants:

$$0 \le g_{n,s,t} \le G_{n,s} \qquad \forall n,s,t\,. \tag{3}$$

Maximum energy production per hour per unit of the renewable energy generator depending on weather conditions, is given as a value $\partial_{n,s,t}$ per unit of its capacity:

$$0 \le g_{n,s,t} \le \partial_{n,s,t} G_{n,s} \qquad \forall n,s,t\,. \tag{4}$$

It is important to keep in mind that excess energy can always be reduced. This can be done, for example, in the case of wind turbines (WT) by controlling the pitch angle or in the case of PV systems by disconnecting them. It is also possible to delay the dispatch of the natural inflow to a certain extent, but this can be done by means of reservoir hydropower plants, using the storage reservoir.

But even the installed capacity is subject to optimization, and the potential given by the location is the one that establishes the maximum limit $G_{n,s}^{\max}$, expressed through:

$$0 \le G_{n,s} \le G_{n,s}^{\max} \quad \forall n,s\,. \tag{5}$$

The optimization problem aims at determining the capacity and the $G_{n,s}$ and the final dispatch $g_{n,s,t}$ of each generator. They are determined so as to respect the physical constraints at the same time, but also to minimize the total costs summed up in equation (1) of the objective function.

2.3 STORAGE OPERATION

Equation (6) expresses the concordance that must exist between the state-of-charge $soc_{n,s,t}$ of all storage units and the charging and discharging in each hour. Also, as shown in equation (7), it must be less than the energy capacity.

$$\begin{aligned} soc_{n,s,t} &= soc_{n,s,\mathrm{t}-1} + \eta_1 g_{n,s,t,\mathrm{charge}} - \eta_2^{-1} g_{n,s,t,\mathrm{discharge}} \\ &+ g_{n,s,t,\mathrm{inflow}} - g_{n,s,t,\mathrm{spillage}} \end{aligned}\,, \tag{6}$$

$$0 \le soc_{n,s,t} \le h_{s,\max} \cdot G_{n,s} \quad \forall n,s,t\,. \tag{7}$$

Losses during loading and unloading are determined by the efficiencies η_1 and η_2. These losses cause the storage systems to be charged when a surplus of energy occurs in the system. Also, the storage systems will be discharged when the generators will not be able to produce enough compared with the consumed energy, and the import possibility cannot be satisfied.

The energy capacity $E_{n,s} = h_{s,max} \cdot G_{n,s}$ limits the state-of-charge. In the energy capacity equation, $h_{s,max}$ represents the fixed time in which the storage unit can be fully loaded or discharged at maximum power. It is assumed that the state of charge is cyclic, so it is equal in the first and last hour of simulation: $soc_{n,s,t=0} = soc_{n,s,t=T}$.

The three various energy storage systems are restricted: lithium-ion battery, reservoir hydro and hydrogen storage [13]. The former store electricity as chemical energy. Batteries can have a capacity of 100 W or less and a few megawatts and can also have different sizes. The batteries $h_{battery,max}$ is considered to be at 6 hours, the charge/discharge efficiency is considered to be 0.9/0.9 which leads to a round-trip efficiency of 0.81 [14]. On the other hand, the efficiency of hydrogen storage is lower, which is assumed to be at 0.75 (electrolyte)/0.59 (fuel cell), overall 0.435 for a storage process [15]; $h_{H2,max}$ is assumed to be one week, i.e., 168 hours. Hydrogen is predicted to be the next type of clean energy developed in the future [16].

2.4 INTER-CONNECTING WITH THE TRANSMISSION SYSTEM

The model of transmission power lines that establish the connection between consumption areas is simplified, being considered as a transport model with controllable dispatch (a coupled source and sink), constrained by energy conservation at each node.

The maximum power flow on such transmission lines is limited by the capacity of the line due to thermal limits and is determined according to equation:

$$\left| f_{l,t} \right| \le F_l, \forall l\,. \tag{8}$$

The capacities of the line Fl can be extended by the model, but if it is cost effective. To meet n – 1 safety requirements, a secure margin of 33 % of installed capacity may be used [17].

2.5 CO_2 EMISSION CONSTRAINTS

According to equation (9), a CAP_{CO2} capacity also limits CO_2 emissions, In the equation are used the specific emissions (CO_2-tonne-per-MWh) of generator fuel type, marked with s and the efficiency of the generator, marked with η_s:

$$\sum_{n,s,t} \frac{1}{\eta_s} g_{n,s,t} \cdot e_s \le CAP_{CO2}\,. \tag{9}$$

For various simulations the defined limit is modified so as to meet the emission reduction target. The comparison is made with the current annual level of CO_2 in the power sector. And, to reduce the complexity of the problem, this study does not take into account the CO_2 emissions resulting from the manufacturing and construction of the generators or storage and transmission system. oIn the study, only OCGT emissions and coal combustion are taken into account.

2.5 SOFTWARE IMPLEMENTATION

The model was implemented in free software energy modeling framework ‘Python for Power System Analysis (PyPSA)’ Version 0.15.0 [18], which is developed at the Frankfurt Institute for Advanced Studies (FIAS).

3. **DATA**

3.1 RENEWABLE ENERGY SOURCES POTENTIAL

Geographical factors limit the further development of RES capacities, in particular solar and wind power. In this model, the renewable energy capacity at each bus is optimized to increase the size of wind and solar power plants, but the geographic potential $G_{max,s}$ limits this expansion.

To calculate the potential limits, a normal installation density is used in the present study. For example, the distance between two onshore wind turbines is 10 MW/km^2, and the available land area to be installed in each locality is 5% of the area of each [19]. With solar energy, the development of PV power plants is reduced by land use restrictions, so this ratio is only 0.2 % and a density of 150MW/km^2 [17]. To simplify the calculations, rooftop solar systems were not considered.

3.2 LOAD, WIND AND SOLAR TIME SERIES

Modeling hourly data on wind and solar capacity is based on the Renewable Energy Atlas [20,22] combined with analytical weather data from Climate Forecast System Reanalysis (CFSR) [23], including technical specifications of WTs and solar PV systems. For the calculation, interpolations of the WT power curves were performed [24] and by simulating the radiation for the PV power plants [25].

The time-domain data are denoted with $\partial_{n,s,t}$ and determined per unit of capacity. The product of $\partial_{n,s,t} \cdot G_{n,s}$ is the maximum capacity of RES at time t. Besides, different geographic factors of wind and solar generate different energy due to the change in weather conditions. To simplify the model, index $\partial_{n,s,t}$ do not change when the capacity is expanded.

Table 1

Results of Vietnam electricity demand forecast under the Electricity Planning VII [26]

	Unit	**2015**	**2020**	**2025**	**2030**
Commercial electricity nationwide	GWh	141.8	227.7	336.7	456.4
Maximum capacity nationwide	MW	25.3	41.1	60.7	81.8

With load data on time-domain $d_{n,t}$ the forecasting data for Vietnam's electricity consumption in 2030 is provided by Vietnam Electricity Corporation. Table 1 presents the estimated average annual electricity demand per GDP per capita. Moreover, the predicted figures depend on regional, economic, and climate characteristics. Fluctuations of the load in an area show seasonal, weekly, and day variations. The distribution of loads at different times of the day is shown in Fig. 1.

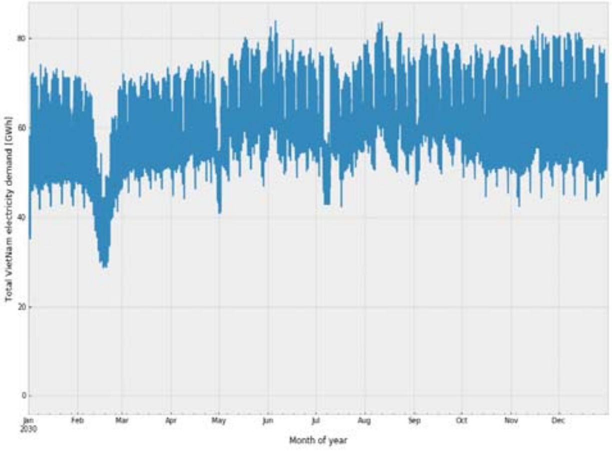

Fig. 1. – Total Vietnam Electricity Demand in 2030 [26].

3.3 GRID TOPOLOGY

In the history of Vietnam's electricity system, including the North and South, the northern grid area has a large concentration of coal and hydroelectric power sources. The South had an additional charge and in 1994, the Ministry of Energy implemented the road construction procedure of 500kV super high voltage wire. Due to the particular terrain, the 500kV ultra-high-voltage line has a length of 1,500km being the longest line in the world. After years of improvement and development, the high-voltage system has been completed.

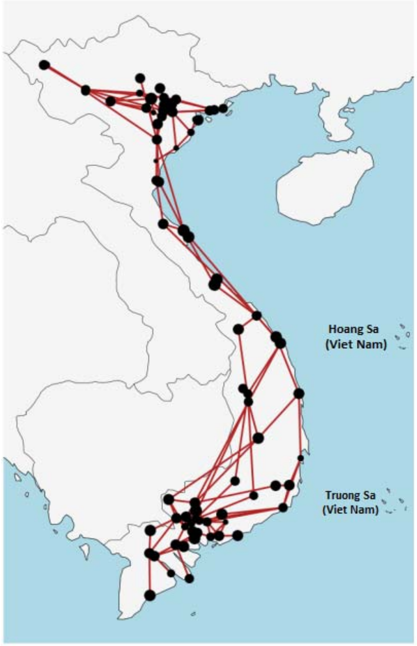

Fig. 2. – Electrical network model with 81 substations. The connections between the buses and the adjacent supply areas were made with 500 kV-power lines.

This model consists of 81 buses with a voltage of 500 kV, Fig. 2. This model represents the most extensive transmission model in Vietnam. To reduce the complexity of the calculations, sources, and loads for the lower voltage levels are integrated in the nearest bus. The connections between the buses are made through 500 kV power lines.

3.4 CALCULATIONS ASSUMPTIONS FOR COSTS

Table 2 presents all the cost calculation assumptions, with the cost of capital at a discount rate of 7% over the life of the installation [24].

Table 2

Cost assumptions considered from [27].

RES type	**Overnight Cost [Eur]**	**Unit**	**Marginal cost [Eur/MWh]**	**FOM[a] [%/a]**	**Lifetime [a]**	**Efficiency**
Wind offshore	2506	kWel	0	3	25	1
Solar PV utility	425	kWel	0	3	25	1
Open cycle gas turbine (OCGT)	400	kWel	50	4	30	0.39
Pumped hydro storage	2000	kWel	0	1	80	0.87 (charge) 0.87 (discharge)
Run-of-river	3000	kWel	3	2	80	0.9
Hard coal	1400	kWel	25	3	30	0.45

[a] Fixed Operation and Maintenance (FOM) cost provided as a percentage of the overnight cost per year.

Investment in transmission lines is calculated as follows: with pair costs converter of c_{CP} = 150,000 Eur/MW, if the lines operate on DC, and n-1 safety factor $f_{n\text{-}1} = 1.5$ and Ct investment costs are interpolated length, from State Grid Corporation's budget reports [28] HVDC, HVAC, and UHVAD. Fixed maintenance and operating costs for transmission power lines are 2 % of the initial investment cost [27].

4. MODEL RESULTS

4.1 LONG-TERM INVESTMENT

In 2030, Vietnam's energy demand is enormous. To meet this need, the Vietnamese government needs to consider the path to avoid wasting resources and losing its real advantages. In this section, are highlighted some long-term investment strategies in Vietnam.

4.1.1 LONG-TERM INVESTMENT IN THE ELECTRICITY SYSTEM

By 2030, according to the VII plan of the Ministry of Industry and Trade, the required nationwide installed capacity of Vietnam's electricity system is over 80 GW. Therefore, it is necessary to invest in the right type of power plant so that it is optimal from economical and technical point of view. Therefore, after optimizing the model, following the BAU (Base as Usual) scenario, Table 2 shows that coal-fired thermal power with the characteristics of cheap investment. The relatively lows cost operation and maintenance remain a priority. The development of renewable energy is concentrated in the southern coastal areas, and solar energy is distributed evenly across the country. Gas-fired thermal power is going to be built in the southern region, in order to offer flexibility in the supply of electricity and gas for the southern load, an area with relatively low hydroelectricity.

Along with that is, the increase of stored energy is also encouraged to develope. The first hydroelectric power plant in Vietnam, with a capacity of 1200 MW was developed in the south of Vietnam. The potential of hydropower plant has reached saturation, so it only develops slightly but still plays a crucial role in supplying electricity

4.1.2 MARGINAL ABATEMENT COST

Figure 3 presents the MAC curves, which are constructed through the investment cost of an MWh power unit of many scenarios in 2030, thereby providing useful information to help policymakers in meeting energy needs by 2030.

The CO$_2$ emission reduction scenario is compared to the BAU (Base as usual) scenario. With only a small additional investment, the system reduces 10-25 % of the actual emissions. However, to reduce over 50 % of system emissions, is needed to invest a more significant amount of money for infrastructure development such as transmission lines and ancillary services represented by storage systems. However, in this study, is used the least costly scenario and still ensures the technical properties to calculate the following sections.

In the BAU scenario, according to the marginal cost curve, Vietnam's electricity system spent more than 40 Eur invested in each MWh energy unit. Besides that the European, South African and Chinese averages electric systems cost, the corresponding investment is 76 Eur/MWh, 31 Eur/MWh, 60 Eur/MWh [29–31] . The results show that in the future with a reasonable grid codes, Vietnam's electricity system costs are relatively ideal compared to the world.

On the other hands, to reduce the operating costs of the system, thereby reducing the price of electricity in the market, the BAU scenario needs to be analyzed from the perspective of operating the system according to the retail electricity market. There the price is no longer determined by the generator but also by the load side. To analyze this scenario in the retail electricity market, in the next section, is evaluated the optimal short-term operation in the electricity market.

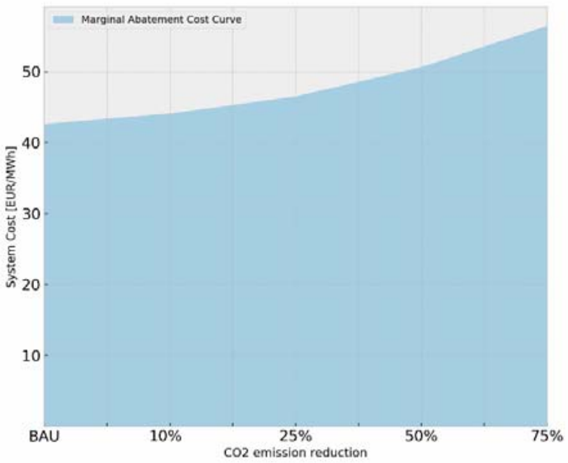

Fig. 1 – Marginal cost curve reducing emissions for Vietnam's electricity system in 2030.

4.2 THE OPERATION IN THE ELECTRICITY MARKET

With an energy demand of 2030 more than 456,000 GWh, every day, Vietnam's power system produces and consumes more than 60 GWh of electricity, depending on the specific characteristics of each region but at each additional busload. Figure 2 shows marginal cost curve for reducing emissions in Vietnam's electricity system.

It can be observed that the load spread evenly from North to South because the economic development policy of the Vietnamese government in 2030 was to diversify and evenly distribute factories throughout the territory of Vietnam. In the South, the load is higher than the rest because this is the economic engine of the country.

4.2.1 SHORT-TERM OPERATION

To meet the high demand for energy in 2030, a short-term operation plan in which the generators work together to satisfy the economic-technical optimization is needed. In Figure 3 are presented the type of generators based on coal, hydropower and renewable energy. Coal-fired, large-capacity hydroelectric generation systems which have little change in capacity are suitable for long-term load base. Other power generation systems, such as gas thermal power plants that have a high operating cost, are suitable for peak coverage. Gas-fired power plants contributing to stabilize the peak of the electricity system are concentrated in the southern region of Vietnam in comparison with relatively few hydroelectric plants.

On the other hand, for thermal power generators the ability to increase capacity in a short time is relatively limited. However, this is a type of electricity with a high price range. It is still arranged to run in the background to ensure system stability. Hydroelectricity, in contrast, has greater flexibility than thermal power thanks to dams and reservoirs, helping to store energy and change capacity easily.

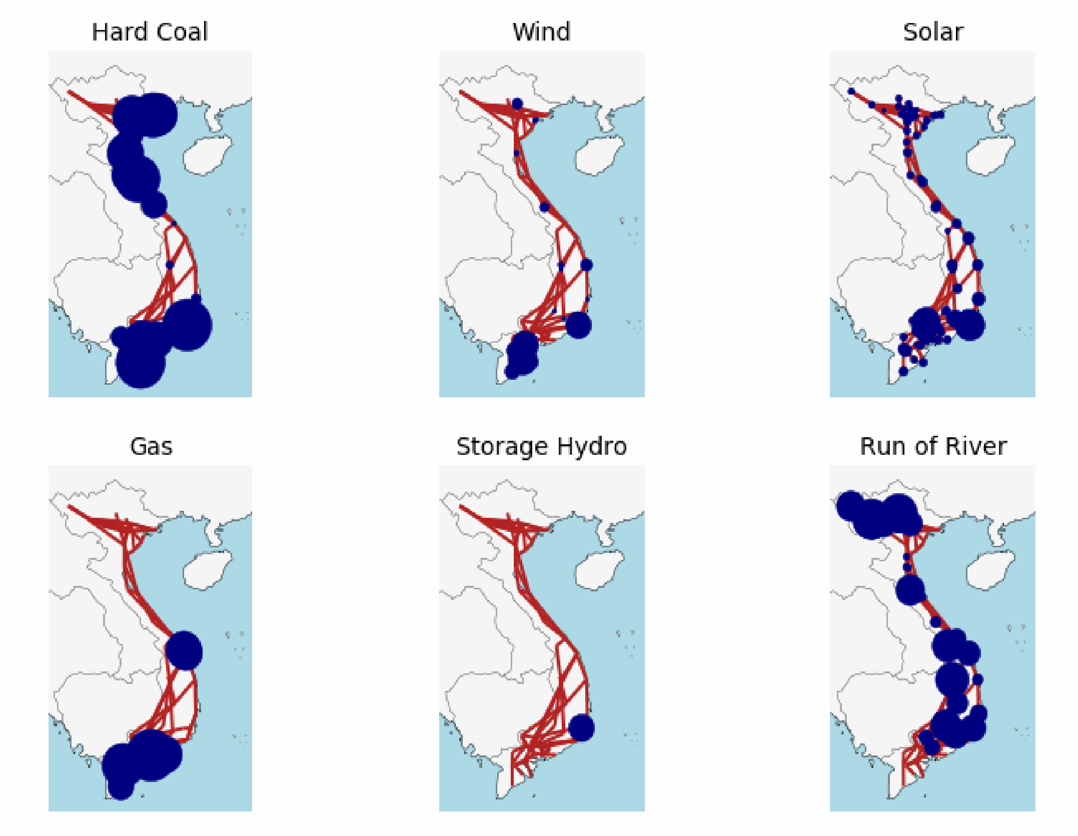

Fig. 2 – The regional distribution of generation technologies.

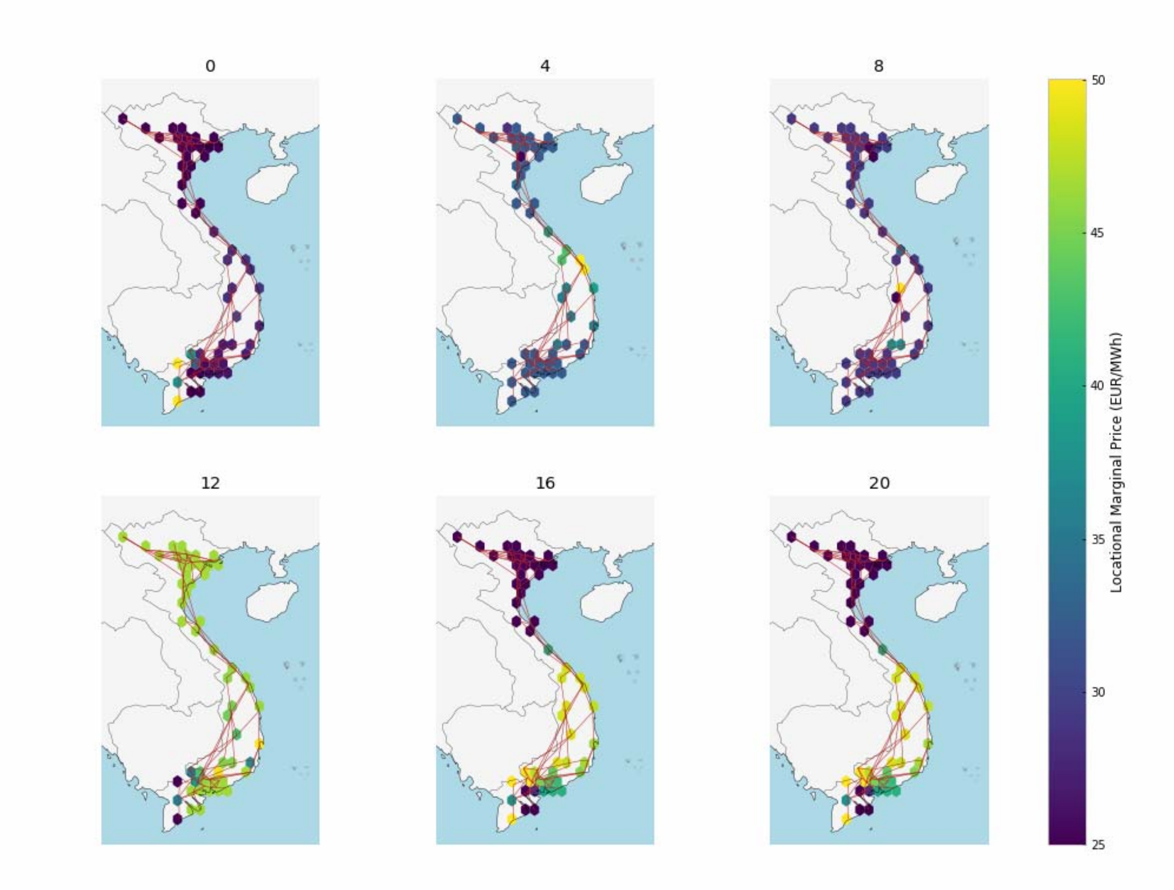

Fig. 3 – The locational marginal prices for snapshots on the network.

4.2.2 MARGINAL COST IN THE ELECTRICITY MARKET

For pricing in the market during short-term operation, this study chooses to maximize the surplus when exchanging electricity. Locational Marginal Cost is a value that depends on the operating costs of the source and the profit when the load uses energy.

When using the optimal value of the price range as the price of electricity trading, the economic balance of power generation and consumption is maximized. Besides, the price of the electricity market will be decided by the seller when the demand is less than the generation capacity; otherwise, the buyer sets the market price when the demand is greater than the generating capacity. Thus, the price range is determined according to the difference between the availability of the natural resource and load required for each locality. Differences in the price range between regions due to transmission limitations or congestion in the distribution system is considered a rental cost to send capacity.

Future electricity market operators manage this fee according to the principle of transferring electricity from the low-price node to the high-price node (buy it low, sell it high). Figure 4 shows the price range for each region in Vietnam in 2030, at 0:00, when the local load is quite low, the plants in the region are thermal and hydro power that meet the demand. Thus, the price range is determined according to the operating cost of the selling side of the thermal power plant, and this is 25 EUR/MWh. In the southern region, the load is large, so the thermal and hydroelectric plants don't have enough capacity to meet and is needed to mobilize more gas thermal power with operating costs of 50 EUR/MWh to meet peak load.

From 04:00 to 08:00 during the day, the demand for energy decreases and then increases slightly compared to 00:00 hours. According to the operation of Vietnam's electricity system, the baseload is still due to the contribution of capacity by thermal power. However, at this time, peak loads in localities fluctuate slightly; the operator must adjust the capacity to get the stability of the system with the help of hydropower plants. Therefore, the price range is now fluctuating with the increase or decrease of the capacity of the hydroelectric plant from 25–35 EUR/MWh. However, in the Central Highlands region, the geographic limitations that result in energy scarcity, with the more demand now leads to some areas with a high marginal price.

At noon, the system load is quite large. The electrical system at this time needs continuous coordination of types of generators such as coal power, hydropower, wind power, solar power, and storage. So, the marginal cost now is a combination of the total operating costs of the plants and reaches 40–45 EUR /MWh.

From 16:00 to 20:00 during the day, the evening load is one step higher than in the early morning. It is noticeable in Figure 4 that there are 2 individual color bands, bright colors with high marginal costs of 50 EUR/MWh concentrated in the South, dark colors with marginal costs of 25 EUR/MWh.

Because the North concentrates most of the primary energy sources in Vietnam, but the South is the center of electricity consumption, the local loads in the North easily meet energy demand at a reasonable cost. In contrast, in the South with significant power demand, regional energy costs are expensive when it is needed here.

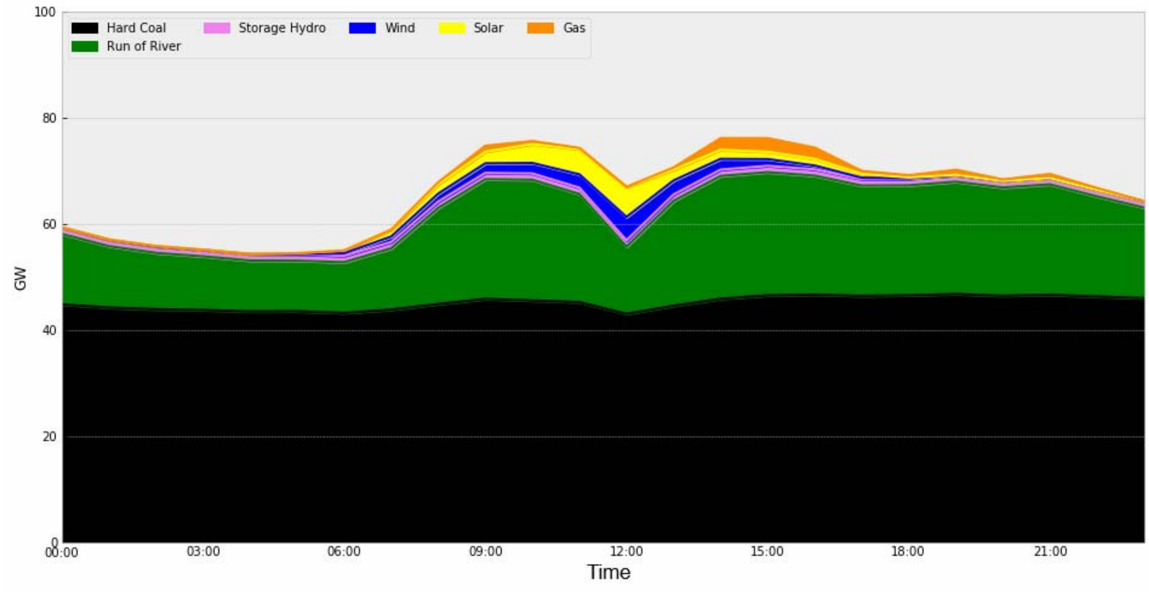

Fig. 4. – The hourly dispatch grouped by the carrier for the chosen day of the Vietnamese power system.

In the following years, to balance marginal costs across regions in Vietnam, operators have two current options: firstly, to invest in the North-South transmission system, thereby operating the electricity market by the method of buying cheap in the North and selling expensive in the South; secondly, encourages the construction of low-cost renewable energy power plants in the South of Vietnam while promoting economic development policies to increase energy demand in Northern Vietnam.

5. **CONCLUSIONS**

In this paper, an economic and technical model is developed and optimized to test the impact of renewable energy sources on system costs in Vietnam's electricity market. This model includes renewable energy produced by wind, solar and hydroelectric storage, and classical energy sources such as thermal and hydro power. With careful consideration of the effects of operating costs and capital costs, the price of electricity is determined in a competitive electricity market in 2030.

In later studies, the benefits of pairing with other energy sectors (heating and transportation) will be analyzed. Such studies give an understanding of the importance of sectoral collaboration in energy distribution, and it creates a more cost-effective, efficient, and stable system for the stability of the Vietnam's future large renewable energy interconnection network.

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