International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2025, 15(1), 357-363.

An Integrated Analysis of Technical and Economic Problems to Support Power System Constraints with a Highly Dependence of Thermal Power Plants

Jorge Ivan Silva-Ortega[1], Hernan Hernandez Herrera[2]*, Idi Amin Isaac Millan[3], Jorge Wilson Gonzalez Sanchez[3], Zaid Garcia-Sanchez[4], Yamile Díaz Torrez[5], John William Grimaldo-Guerrero[6]

[1]Universidad de la Costa, Barranquilla, Colombia, [2]Universidad Simon Bolivar, Facultad de Ingenierías, Barranquilla, Colombia, [3]Universidad Pontificia Bolivariana, Medellín, Colombia, [4]Universidad de Cienfuegos, Cuba, [5]Universitat de les Illes, España, [6]Universidad de la Costa, Barranquilla, Colombia. *Email: hernan.hernandez@unisimon.edu.co

Received: 16 August 2024 **Accepted:** 14 November 2024 **DOI:** https://doi.org/10.32479/ijeep.17182

ABSTRACT

In a centralized wholesale power system market scenario, the transmission and distribution constraints limit dispatch and require additional generation to support an integrated area known as Security Generation. This one must be covered in each area, and its cost transferred to the final users. The security generation cost gets higher when operation implicates the use of thermal power plants whose price equation depends on international fuels costs. This paper examines the consequences of a high reliance on thermal power plants. It focuses on scheduled reserves affecting electricity unit costs and the potential for constraints to lead to long-term consequences. The paper analyzes the security generation behavior based on reports and uses a real scenario to support simulations and decisions, evidencing monthly cost and an estimated CO_2 emission. Results show the direct cost-saving potential of investing in renewable projects and technology. The paper can allow to replicate the analysis in comparable areas and regions with similar challenges.

Keywords: Ancillary Service, Power System Constraints, Thermal Power Plants, Security Generation

JEL Classifications: K29, Q47, Q48

1. INTRODUCTION

An electric power system is a set of interconnected systems, operating areas, elements, and telecommunications used to support electricity to final users (Kundur, 1994). To keep a reliable and secure operation and dispatch, ancillary services support the power system, being all those services required to guarantee stability, integrity, and a post-contingency secure operation (Duncan Glover and Sarma, 2003). Ancillary Services include operating reserves, frequency control, reactive control, voltage control, security generation, among others. The Security Generation is the additional generation to support reliability, security, and stability conditions (Carvajal et al., 2013; Ministerio de Minas y Energía, 1999; Ximena and Quintero, 2013).

An integrated power system dispatch requires the participation of power plants considering transmission and distributions constraints. All agents must guarantee the balance, considering unavailability of elements, constraints, and technical losses to support a secure operation (IET, 2007; Kuffel et al., 2000). The technical and operational security criteria guarantee the coordinated dispatch and operation of the areas. The Security Generation emerges because of these criteria (Ministerio de Minas y Energía, 1999). The planning process requires the Security Generation assignment inside the power system area to support electricity service and dispatch (Vázquez et al., 2002).

Security Generation gets higher when exists bulked systems exist and a lack of power system expansion. This medium- and long-term planning scenario must consider units available to be scheduled and attend the scenarios based on reliability and security criteria (Teeparthi and Kumar, 2018). The paper highlights a Security Generation scenario in areas with high dependency of thermal power plants where constraints (Technical an operational) require Security Generation to guarantee dispatch, however, its operations get expensive and users rely on a high-cost electricity service. Also, CO_2 regional emission because of generation activities compromise national policy goals. A real scenario is presented, evidencing the economic implications of Security Generation in electricity costs. Finally, the conclusions describe opportunities and to be considered in these areas with similar scenarios.

2. POWER SYSTEM CONSTRAINTS

The power system real dispatch considers a power flow analysis including security constraints to guarantee the secure and reliable operation of a power system involving elements power limits and control range of operation. As results, it is possible to estimate the Security Generation as results following equations expressed as follows (Kundur, 1994).

$$P_i - jQ_i = V_i^* \sum_{j=1}^{n} Y_{ij} V_j \;\; i = 1, 2, 3, \ldots, n \tag{1}$$

Considering a secure scenario prepared for a contingent scenario (C), the security constraints must be calculated for each area considering the following equation and constraints (Yang et al., 2018).

$$f\left(P_g^{(c)}, Q_g^{(c)}, v^{(c)}, \theta^{(c)}\right) = P_i - jQ_i \;\; m = 1, 2, 3, \ldots, n \tag{2}$$

Constraints attempt to power system normal operation. The ISO used to estimate a reliable scenario considering an n-1 contingency involving technical and operational constraints. A technical constraint relates to elements and system limit operation, highlighting voltage regulation. The operational constraints are those that compromise the security of supply in the event of contingencies or unplanned operational changes in an SEP. The listed constraints used to be considered in power system analysis (Yang et al., 2018).

Active power limit:

$$P_{ij}^{(c)} = h_P^{ij}\left(v^{(c)}, \theta^{(c)}\right) \rightarrow \left(i, j\right) \in k \;\; ; c \in \{0\} \cup C \tag{3}$$

Reactive power limit:

$$Q_{ij}^{(c)} = h_P^{ij}\left(v^{(c)}, \theta^{(c)}\right) \rightarrow \left(i, j\right) \in k \;\; ; c \in \{0\} \cup C \tag{4}$$

Active power balance:

$$\sum_{g \in G_i} P_g^{(c)} - P_{d,i} = \sum_{ij \in K_i} P_{ij}^{(c)} \rightarrow i \in N; c \in \{0\} \cup C \tag{5}$$

Reactive power balance:

$$\sum_{g \in G_i} Q_g^{(c)} - Q_{d,i} = \sum_{ij \in K_i} Q_{ij}^{(c)} \rightarrow i \in N; c \in \{0\} \cup C \tag{6}$$

Active operating limit:

$$\left(P_{ij}^{(c)}\right)^2 + \left(Q_{ij}^{(c)}\right)^2 \le \left(S_{ij}^{max}\right)^2 \rightarrow \left(i, j\right) \in K; c \in \{0\} \cup C \tag{7}$$

Active power generation ranges:

$$P_g^{min} \le P_g^{(c)} \le P_g^{max} \rightarrow \;\; g \in G \;\; ; c \in \{0\} \cup C \tag{8}$$

Reactive power generation ranges:

$$Q_g^{min} \le Q_g^{(c)} \le Q_g^{max} \rightarrow \;\; g \in G \;\; ; c \in \{0\} \cup C \tag{9}$$

Voltage limit range: $v_{min} \le v_i^{(c)} \le v_{max} \rightarrow i \in N \;\; ; c \in \{0\} \cup C$ (10)

Angle voltage range:

$$\theta_{ij}^{min} \le \theta_{ij}^{(c)} \le \theta_{ij}^{max} \rightarrow \;\; \left(i, j\right) \in K \; ; c \in \{0\} \cup C \tag{11}$$

Active power generation ramps:

$$\left|P_g^{(c)} - P_g^{(0)}\right| \le \; P_g^{ramp} \rightarrow \;\; g \in G \;\; ; c \in \{0\} \cup C \tag{12}$$

Reactive power generation ramps:

$$\left|v_g^{(c)} - v_g^{(0)}\right| \le v_g^{ramp} \rightarrow \;\; g \in G \;\; ; c \in \{0\} \cup C \tag{13}$$

The Security Generation, assigned by ISO to each power plant, contributes to reducing power losses. It also provides voltage control to support stability. Also, it supports a reliable scenario by considering the n-1 contingency. This additional generation covers the extra cost of conventional power plants available in the area. It also provides an additional income stream beyond dispatch activity (Wood et al., 2014). These power plants address constraints in the area and help manage the trade-off between power generation and demand (Carvalho et al., 2013; Glismann and Nobel, 2017; Lund et al., 2015).

3. MATERIALS AND METHODS

3.1. Collecting Information and Responsibilities

To examine scenarios and evaluate Security Generation participation, a case study was conducted in a power system area with high thermal dependence called North-PS. The research considered 2 years of operation of power plants scheduled supporting dispatch, Security Generation and other services. The research considered the following steps to analysis North-PS collected data:

- The first criterion to be considered is the participation of power plants by activities. Table 1 presents a typical day's scheduled power plants listed as Dispatch (D) or Security Generation (S). The classification also considered other activities or constraints such as Allowed Tests (AT), Not Allowed Tests (NT), Audits (AU), Inputs Ramp (RI), and Outputs Ramp (RO)
- The scenario considered elements availability and operation limits, including power lines and power transformers, to set technical constraints
- The Total Generation Contribution (TGC) is the total 24 h of active power supported by a power plant
- The TGC was listed and organized by hours and day for each agent
- The information is organized and supported by scenarios modeled in power factory DIgSILENT
- The analysis considered only the thermal power plants considered declared as dispatchable.

Table 1: Example of a daily thermal power plants participation.

General Power generation unit information							Hours																								
Agent	Unit	Area	Act. Priority	Area	Type	Fuel	Agent	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Gen1	A	North	2	SubA_ Op1	Thermal	Natural Gas	Gen1	RO																							
Gen1	B	North	2	SubA_ Op1	Thermal	Natural Gas	Gen1	RO																							
Gen2	A	North	1	SubA_ Op1	Thermal	Natural Gas	Gen2	S	S	S	S	S								S	S	S	S	S							
Gen2	A	North	2	SubA_ Op1	Thermal	Natural Gas	Gen2	D	D				D	D	D	D	D	D						D	D	D	D	D	D	D	D
Gen3	A	North	1	SubA_ Op3	Thermal	Coal	Gen3	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Gen3	A	North	2	SubA_ Op3	Thermal	Coal	Gen3	D	D	D	D	D									D	D	D		D	D	D	D	D	D	D
Gen3	B	North	1	SubA_ Op3	Thermal	Coal	Gen3	S					S	S	S	S	S	S	S						S						
Gen3	B	North	2	SubA_ Op3	Thermal	Coal	Gen3	D	D	D	D	D								D	D	D	D	D	D	D	D	D	D	D	D
Gen4	A	North	1	SubA_ Op2	Thermal	Natural Gas	Gen4				S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Gen4	B	North	1	SubA_ Op2	Thermal	Natural Gas	Gen4	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Gen4	C	North	2	SubA_ Op2	Thermal	Natural Gas	Gen4	D	D	D																D	D	D	D	D	
Gen5	A	North	1	SubA_ Op1	Thermal	Natural Gas	Gen5																			S	S	S	S	S	S
Gen5	A	North	2	SubA_ Op1	Thermal	Natural Gas	Gen5	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	

3.2. Statistical Analysis

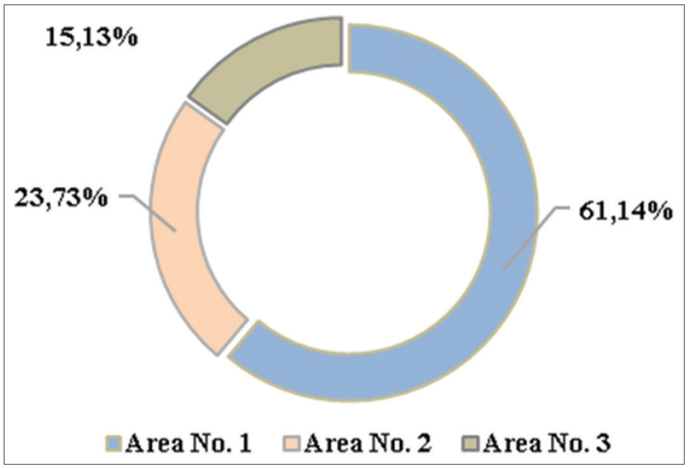
The statistical analysis aims to identify behavior of Security Generation. The generation duration curves (GDC) characterize the participation on each area establishing a probability of its occurrence. The analysis considered three indices:

The supportability index measures the proportion between the TGC and the Global Firm Energy (GFE). It highlights the responsibility of power plants in the scenarios to support electricity service measured between 0% and 100% as described in equation 14. A value not > 50% means that system security is high and exists reserves to support operation. Between 50% and 65% involves security and ISO require in a mid-term period (5 years) include more power plant units on the area. A supportability index > 65% implicates a risk scenario affecting power system security.

Table 2: Maximum available capacities of areas

Areas	Number of units (UND)	IGC (MW)	GFE (MW)	Demand (MVA)	TGC (MW)
1	14	1740.6	1528	693.58	1508
2	7	701.6	593	420.47	404
3	3	418.6	378	584.36	290
Total:	24	2860.8	2499	1698.41	2202

Figure 1: Area responsibilities to support electricity



$$Supportability\ Index\ (\%) = \frac{TGC}{GFE} \tag{14}$$

The loadability index measures the proportion between the TGC respect the installed generation capacity (IGC) as described in equation 15. It highlights the responsibility of power plants participation respect the sum of all power plant nominal reference value. A value great that 50% implicates possible reliability problems during contingencies.

$$Loadability\ Index\ (\%) = \frac{\text{TGC}}{\text{IGC}} \tag{15}$$

The availability index is the power in an area to support operation or contingency scenarios presented during operation being the opposite to loadability index (Equation 16).

$$Available\ Index\ (\%) = \left[1 - \left(\frac{TGC}{IGC}\right)\right] \tag{16}$$

3.2.1. Identifying areas with a high thermal dependence

The case study selected provides a power system of a region with an energy generation matrix composed only by conventional and combined cycle thermal units. The paper considered (UPME, 2022), to support the study case, while the data to analyze the case

Figure 2: GFE and maximum demand required in areas considering the highest scenario reported

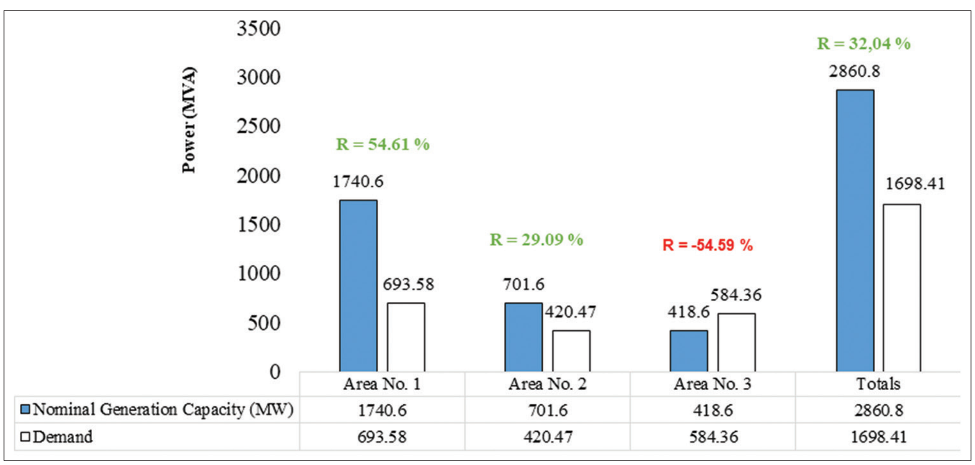


Table 3: Statistical analysis to evaluate security in North-PS area

North-PS (Power System)	IGC (%)	GFE (%)	TGC (%)	Supportability index (%)	Loadability index (%)	Availability index (%)
Area 1	60.84	61.14	68.48	98.69	86.64	13.36
Area 2	24.52	23.73	18.35	68.13	57.58	42.42
Area 3	14.63	15.13	13.17	76.72	69.28	30.72
Total	100	100	100	88.12	76.97	23.03

Figure 3: GDC curves for study case. (a) Stadistical SGen participation in North-PS. (b) A GDC for SGen in North-PS and areas

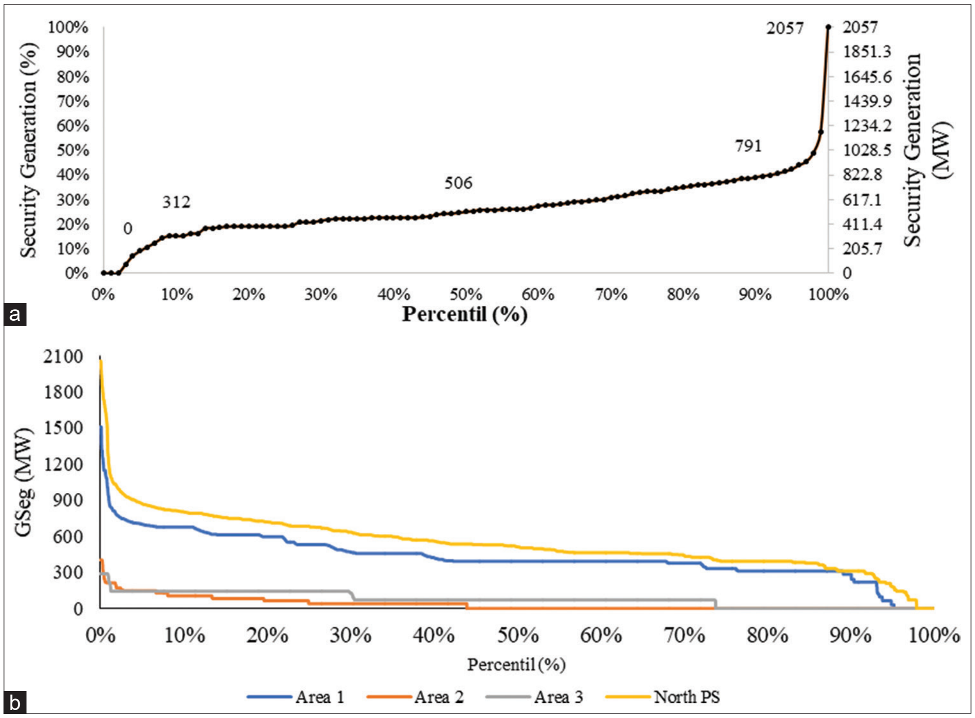


Figure 4: Typical security generation cost

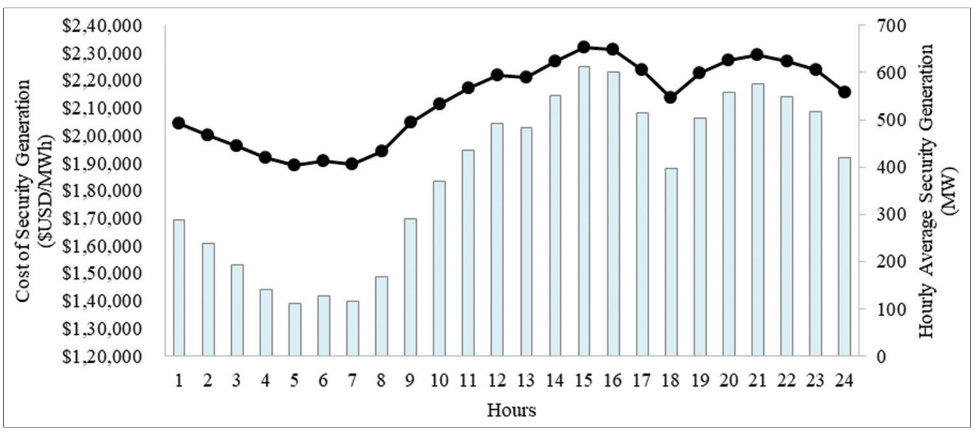


Table 4: SGen requeirements considering typical statistical data

Statistics data	North-PS	Area 1	Area 2	Area 3
	MW	MW	MW	MW
Mean	540.86	428.30	36.11	76.46
Standard deviation	229.56	184.09	53.62	57.76
Standard error	1.73	1.39	0.41	0.44
Mode	392.00	392.00	0.00	72.00
Minimum	0	0	0	0
Median	513	392	0	72
Percentile (95%)	871	701.05	149	144
Maximum	2057	1508	404	290

used ISO public information (Comañia de Expertos en Mercados S.A. E.S.P; XM, 2024), while previous studies helped to support North-PS operation (Cervantes-Bolivar, 2018; Silva-Ortega et al., 2017; Silva et al., 2018). The North-PS has the following characteristics:

- The case study considered three areas
- The case study is a section of a national power system that operates based on a centralized dispatch model
- The North-PS support its operation and constraints only with thermal power plants. Security Generation is fully supported with thermal power plants
- The thermal power plants within the North-PS not only take part in the dispatch, but also develop the ancillary services required by the area
- The thermal technologies use gas, oil and carbon to operates.

4. RESULTS AND DISCUSSION

4.1. Statistical Analysis

Table 2 summarizes the maximum available unit capacities on each area. It also lists the global firm energy according (GFE) and maximum demand on each area. The greater availability of thermal power plants is on Area 1 with 14 units. Area 1 has enough IGC to support demand. However, importations are considered based on daily dispatch.

Otherwise, each area has different IGC values. Figure 1 shows that the available GFE are 61.14% (Area No. 1), 23.73% (Area No. 2) and 15.13% (Area No. 3). The analyzed information showed that Area No. 3 has constraints during maximum scenarios.

To evaluate the percentage of thermal power plant responsibility within the entire power system, Table 3 shows the percentage of IGC for each area. The MPG shows that Area 1 also has a high demand responsibility, with a support level of 68.48%. The Supportability Index reached 98.69% in the critical scenario for Area 1. This area has cases that require the total participation of thermal power plants. Area 2 has supported electricity with a 68.13% of the firm energy responsibility, while Area 3 has supported the service reaching a 76.72%. The Loadability Index is highest in Area 1, at 86.64%, while Areas 2 and 3 have values of 57.58% and 69.28%, respectively. The overall North-PS area shows a Supportability and Loadability Index >75% and an Availability Index suggests the need to improve security.

4.2. Technical Constraints

Figure 2 compares the GFE for all areas, highlighting a generation availability of 32.04% for the entire North-PS. Area No. 1 has the highest power plant reserves, with a reserve of 54.61%. Area No. 2 has reached its security level, while Area No. 3 requires electricity imports to meet demand and avoid rationing. The North-PS operates with 2.202 MW, while the current demand is 1.698,41 MW. This implies an export of 503.49 MW to other areas. It is also possible to suggest that the existing participation margin of power plants is helping to manage constraints in the areas. However, ISO and utilities should review the security of these areas to prevent electricity rationing in future critical scenarios.

4.3. Security Generation Estimation and Analysis

Table 4 presents the Security Generation statistics for the observation period in the North-PS. The mean value was 540,86 MW. Historical data showed 2057 MW as maximum value required to support Security Generation. However, in 95% of the reported scenarios, the Security Generation requirements did not exceed 871 MW. A similar analysis of individual areas revealed that Security Generation is not always required on each area being supported from Area No. 1.

Figure 3 shows a the GDC from the areas to support Security Generation. It describes the highest Security Generation required (2057 MW), and the median value equal to 513 MW. In the reviewed case, 10% of the scenarios require < 312 MW, which represents 12,48% of the GFE declared in Table 1 for the North-PS. A similar GDC was developed for each area as shown in Figure 4. The Area No. 1 follows similar behavior to the North-PS. Technical and operational constraints used to be supported from Area No. 1 to other areas.

4.4. Security Generation economic implications and CO_2 emissions

A typical day of Security Generation to support power system constraints incurs high costs in the area where the service is required. The cost of operating a thermal power plant in the area ranges from \$124.87 USD to \$429.76 USD, depending on the availability of fuel in the international market. The fossil fuels used in North-PS include coal, natural gas, and oil.

The thermal power plant with the highest market share has an energy production cost of \$344 USD, which is used to estimate the approximate CO_2 emissions. On a typical day, the cost of Security Generation in the North-PS can reach up to \$4.466.782 USD, equivalent to providing 12.99 TWh of energy. Figure 4 illustrates the typical daily Security Generation support and its cost. Annually, Security Generation in the North-PS represents an estimated cost of \$1.630.375,37 billion USD. This is equivalent to 5.2 Mt CO_2 per year, driven to support power system constraints in the North-PS.

5. CONCLUSIONS

The scenarios analyzed in this paper conclude that there is a high dependence on thermal power plants in certain areas to support electricity service. Security Generation to support constraints is not an exception. Thermal power plants act as a backup to ensure reliability and security, particularly in post-contingency scenarios. During the analysis, the authors propose new indices for evaluating thermal power plant participation in terms of supportability, loadability, and availability. The Supportability Index concept reveals that the system's security levels have compromised, showing an availability index of only 28,09%.

The proposed Generation Duration Curve (GDC) helps to identify critical scenarios where a system becomes dependent on Security Generation. Based on the selected case study, the research detected a high participation of thermal power plant to support Security Generation service. In most of the scenarios, the Security Generation mean value was 540.86 MW, representing 21.64%. In critical scenarios, North-PS can require up to 82.31% (2057 MW). These findings suggest the necessity to support electricity supply and manage constraints in the North-PS by using new power plants, which would represent an annual cost of \$1.63 billion USD. The comparison was made considering 2 years of observations (XM 2024).

However, these new power plants must avoid the use of fossil fuels and instead focus on zero-emission technologies that align with energy transition and climate change policies. Current thermal power plants typically produce 5.2 Mt of CO_2 per year. Future work should include developing a Security Generation forecast to identify requirements based on potential constraints. This will help reduce reliance on current methods and ensure the continued operation of the area by utilizing other available resources, diversifying the energy matrix.

The paper emphasizes the urgent need to explore new alternatives for replacing thermal generation plants with solutions like energy storage systems, non-conventional renewable energy sources, system control mechanisms, and dynamic compensation. These technologies can help reduce or limit the need for Security Generation and minimize thermal dependence in the North-PS.

REFERENCES

Carvajal, S.X., Serrano, J., Arango, S. (2013), Colombian ancillary services and international connections: Current weaknesses and policy challenges. Energy Policy, 52, 770-778.

Carvalho, M., Pappu, V., Pardalos, P. (2013), Optimization and Security Challenges in Smart Power Grids. Gainesville: Springer.

Cervantes-Bolivar, B. (2018), Pronostico Del Crecimiento de Demanda de Energía Eléctrica En El Área Caribe Colombiana Para Proyectar La Generación Por Seguridad. Colombia: Universidad de la Costa.

Comañia de Expertos en Mercados S.A. E.S.P (XM). (2024), Despacho Térmico. Available from: https://www.xm.com.co/paginas/generacion/despacho-termico.aspx

Duncan Glover, J., Sarma, M. (2003), Sistemas de Potencia: Analisis y Diseño Potency Systems. Ciudad de Mexico: Ciencias e Ingeniería.

Glismann, S., Nobel, F. (2017), A Framework for Ancillary Services Design. In: 14th International Conference on the European Energy Market (EEM). Dresden, Germany: IEEE. p1-6.

IET. (2007), Haddad, M., Warne, D., editors. Advances in High Voltage Engineering. London, United Kingdom: Institution of Engineering and Technology - IET.

Kuffel, E., Zaengl, W.S., Kuffel, J. (2000), High Voltage Engineering. 2nd ed. Boston: Butterworth-Heinemann.

Kundur, P. (1994), Power System Stability and Control. New York: McGraw-Hill.

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J. (2015), Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renewable and Sustainable Energy Reviews, 45, 785-807.

Ministerio de Minas y Energía. (1999), CREG 038 de 1999. Consideraciones de Los Agente y Terceros Intersados, Los Criterios Para Definición de La Generación de Seguridad, La Asignación de Las Mismas Entre Los Agentes Del SIN y Las Bases Sobre Las Cuales Se Modificarán Las Disposiciones Vigente. Colombia.

Silva, J.I., Isaac, I., Valencia, G., Escorcia, Y.C. (2018), Demand energy forecasting using genetic algorithm to guarantee safety on electrical transportation system. Chemical Engineering Transactions, 67, 787-792.

Silva-Ortega, J.I., Daza-Guzmán, J.D., Candelo-Becerra, J., Rueda-López, J.C., Umaña-Ibáñez, S., Salas-Navarro, K., Mercado-Caruso, N., Palacio-Bonill, A. (2017), Modelo de 75 nodos para evaluar la operación en estado estable de una red de sub-transmisión de energía eléctrica. Espacios, 38(6), 10.

Teeparthi, K., Kumar, D. (2018), Security-constrained optimal power flow with wind and thermal power generators using fuzzy adaptive artificial physics optimization algorithm. Neural Computing and Applications, 29(3), 855-871.

UPME. (2022), Estudios de Conexión. Available from: https://app.upme.gov.co/InfoEstudiosConexion/Home/Login [Last accesed on 2022 May 08].

Vázquez, C., Rivier, M., Pérez-Arriaga, I.J. (2002), A market approach to long-term security of supply. IEEE Transactions on Power Delivery, 17(2), 349-357.

Wood, A., Wollenberg, B., Sheblé, G. (2014), Power Generation, Operation, and Control. New Jersey: John Wiley & Sons, Inc.

Ximena, S., Quintero, C. (2013), Análisis de Servicios Complementarios En Sistemas de Potencia Eléctricos En Ambientes de Mercados. Colombia: Universidad Nacional de Colombia.

XM. (2024), Generación de Seguridad Por Área Operativa. Available from: https://sinergox.xm.com.co/restric/paginas/historicos/gensegporareope.aspx [Last accessed on 2022 May 09].

Yang, Z., Zhong, H., Xia, Q., Kang, C. (2018), Review of the OPF problem: Challenges, solutions, and state-of-the-art algorithms. Journal of Energy Engineering, 144(1), 04017075.