

Resilience of the Power Grid in Southeast Europe in the Context of Coordination and Balance

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Abstract: Bulgaria, Romania, Greece, Croatia and Slovenia lie at the south-eastern edge of the Continental Europe synchronous area, where the system split of 8 January 2021 started and where a voltage collapse blacked out large parts of four transmission systems on 21 June 2024. This paper reviews how the five systems are tied into the European arrangements for frequency control, cross-border balancing and regional coordination, using EU network codes, ENTSO-E and ACER documents and peer-reviewed studies up to October 2026. All five TSOs take part in imbalance netting. Romania and Croatia are not yet connected to the aFRR platform, and on the mFRR platform only Slovenia operates in normal mode. Neither disturbance was traced to a lack of balancing reserves; the investigations point to large flows, undetected overloads and missing voltage support. A framework is proposed that places ancillary services in the phases of a disturbance and defines five dimensions for comparing the systems.

Keywords: ancillary services, power system resilience, electricity balancing, TSO coordination, Southeast Europe.

JEL: L94, Q41, Q48

I. INTRODUCTION

The south-eastern part of the Continental Europe (CE) synchronous area has had two large disturbances in less than four years. On 8 January 2021 a busbar coupler in the Ernestinovo substation in Croatia tripped on overload. The cascade that followed split the synchronous area in two, and the parts were resynchronised about an hour later (ENTSO-E, 2021). On 21 June 2024 two 400 kV lines in Montenegro and on the Albania–Greece border tripped on short circuits caused by vegetation. A voltage collapse followed in large parts of the transmission systems of Albania, Montenegro, Bosnia and Herzegovina and Croatia (ENTSO-E, 2025a). A third episode was commercial. In summer 2024 evening prices in most Southeast European bidding zones reached up to 1,000 EUR/MWh, mainly because flexible resources were lacking when solar output fell in the evening and cross-border capacity was limited (ACER, 2026).

Each of these episodes tested ancillary services. In EU law the term covers balancing services and non-frequency services: steady-state voltage control, fast reactive current injection, inertia for local grid stability, short-circuit current, black start and island operation (Directive (EU) 2019/944, Art. 2(48)–(49)). The rules for procuring and exchanging them are spread over the guidelines on system operation and on electricity balancing and the network code on emergency and restoration (Regulation (EU) 2017/1485; 2017/2195; 2017/2196). Since 2024, national regulators or designated

entities must also report on flexibility needs over at least the next five to ten years (Regulation (EU) 2024/1747, inserting Art. 19e into Regulation (EU) 2019/943).

Research on the region has looked at market coupling (Makrygiorgou et al., 2020), national market design (Beus et al., 2018; Sousounis et al., 2023) and the frequency response in the 2021 split (Ippolito et al., 2021), mostly one topic at a time. This paper takes the five EU members of the region: Bulgaria, Romania, Greece, Croatia and Slovenia. It asks how their ancillary services are organised and coordinated across borders, what the disturbances show about them, and how their contribution to resilience can be compared.

II. THEORETICAL FRAMEWORK

Panteli and Mancarella (2015) frame power system resilience around high-impact, low-probability events and distinguish measures that make the grid stronger from operational measures that make it smarter. Panteli et al. (2017) quantify it with a resilience trapezoid: after an event the system passes through disturbance progress, a degraded post-disturbance state and restoration, and each phase has its own time-dependent metrics. The same paper separates operational resilience, which depends on how the system is run, from infrastructure resilience. The IEEE task force summarised by Stankovic et al. (2023) argues that resilience should be treated as a measured performance indicator in planning and operation, next to cost and reliability, and accepts that complete resilience is not economic.

Rebours et al. (2007) compared the technical features of frequency and voltage control services in several systems, CE among them, and proposed a common terminology. In CE the frequency containment reserve (FCR) is dimensioned for a reference incident of 3,000 MW in each direction and must be fully activated within 30 s at a deviation of ± 200 mHz (Regulation (EU) 2017/1485, Art. 153, Annex V). Automatic and manual frequency restoration reserves (aFRR, mFRR) then bring frequency back to its nominal value. As converter-connected generation displaces synchronous machines, inertia falls and frequency moves faster after an imbalance, which changes how the system has to be modelled and controlled (Milano et al., 2018). ENTSO-E (2023) concludes that a system split must always be assumed possible and that a minimum level of inertia has to be defined.

Cross-border balancing has been studied mainly as a market design problem. Doorman and van der Veen (2013) compared design options. A common merit order performed best, and reserving cross-border capacity for balancing was an obstacle to exchange. For PICASSO, the European aFRR

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platform, Backer et al. (2023) name cost savings and a lower use of activation energy as the expected benefits.

Work on Southeast Europe is thinner. Makrygiorgou et al. (2020) simulated trading between Greece, North Macedonia, Bulgaria, Serbia and Romania and obtained higher welfare and closer prices with flow-based capacity calculation than with available transfer capacities. Beus et al. (2018) reported that the Croatian balancing market existed on paper but was not operational, and that larger plants had to provide primary reserve without payment. For Greece, Sousounis et al. (2023) argue that voltage control based on grid assets alone no longer suffices with variable generation and discuss a voltage control market next to the balancing market. Giannakopoulos et al. (2025) use Greek market and frequency data to compare battery participation in the day-ahead and FCR markets. Ippolito et al. (2021) reproduced the recorded frequencies of the 2021 split in simulation and showed that the order in time of imbalances and defence actions shapes the frequency response. Birkebaek and Carlini (2018) describe how regional security coordination grew from voluntary TSO initiatives into a task under the network codes, based on common grid models.

III. METHODOLOGICAL FRAMEWORK

The study is a document review. Three groups of sources were used: EU legal acts in force; reports, decisions and platform records of ENTSO-E and ACER, read up to 6 October 2026; and peer-reviewed papers from IEEE, Elsevier and MDPI, found through publisher searches and checked against their DOI records. National grid codes and TSO market rules were not reviewed, so the paper does not compare national prequalification or remuneration.

The following research questions were defined:

RQ1: How are the five TSOs connected to the European arrangements for frequency control, cross-border balancing and regional coordination?

RQ2: What did the disturbances of 2021 and 2024 show about the ancillary services and coordination available in the region?

RQ3: How can the contribution of ancillary services to resilience be assessed so that the five systems can be compared?

RQ1 is answered with a status table built from the platform records (4.1), RQ2 with the findings and recommendations of the ENTSO-E investigation panels (4.2), and RQ3 with a framework based on the resilience phases of Panteli et al. (2017) (4.3).

IV. RESULTS

4.1. Ancillary services and coordination structures

Frequency control in CE is organised in load-frequency control (LFC) blocks. Bulgaria, Romania and Greece each form their own block, while Slovenia and Croatia share the SHB block with Bosnia and Herzegovina (ENTSO-E, 2025b). FCR is dimensioned for the synchronous area as a whole. Frequency restoration reserves are dimensioned per LFC block, and their activation is being opened to cross-border exchange through IGCC for imbalance netting,

PICASSO for aFRR and MARI for mFRR, the platforms required by Regulation (EU) 2017/2195. Table 1 shows where the five TSOs stood in October 2026.

Table 1: Participation of the five TSOs in European balancing and coordination arrangements, status on 6 October 2026.

TSO (country)	LFC block	RCC	IGCC	PICASSO (aFRR)	MARI (mFRR)
ESO (BG)	ESO	SEleNe CC	03/2023	02/2025	02/2026 ^a
Transelectrica (RO)	TEL	SEleNe CC, TSCNET	12/2021	expected 04/2027	not connected
IPTO (GR)	IPTO	SEleNe CC	06/2021	03/2025	expected 2028
HOPS (HR)	SHB ^b	TSCNET	02/2019	not connected	postponed
ELES (SI)	SHB ^b	TSCNET	02/2019	07/2026	07/2026

^a island mode, no bids or demands submitted; ^b with NOS BiH. Dates are month of go-live. Sources: ENTSO-E (2025b, 2026a–e), ACER (2025b).

Imbalance netting is the most complete layer: all five TSOs take part, Bulgaria being the last to join, in March 2023 (ENTSO-E, 2026e). The energy platforms are less advanced. Bulgaria and Greece joined PICASSO in early 2025 and Slovenia in July 2026; Transelectrica has notified its regulator of an expected accession in April 2027, and HOPS had not connected by October 2026 (ENTSO-E, 2026a, 2026b). On MARI, Slovenia went live in July 2026. Bulgaria connected in February 2026 but operates in island mode without submitting bids or demands, Croatia has postponed accession because a local IT project is late, and Greece expects to connect within 2028 (ENTSO-E, 2026c, 2026d).

The delays are not limited to the region. By the legal deadline of July 2024 only four Member States' TSOs were active on PICASSO, and the integration of balancing capacity markets remains limited (ACER, 2025a). ACER also noted that PICASSO lets TSOs that are not yet connected offer available transfer capacity on their borders, so Bulgaria and Greece could exchange with the rest of Europe before Hungary and Romania connect. Hungary's TSO joined PICASSO in October 2026 (ENTSO-E, 2026a), so Romania is now the remaining gap on the EU land route between Bulgaria and the Central European members of the platform.

Regional coordination is split between two centres. SEleNe CC in Thessaloniki serves ESO, IPTO and Transelectrica, together with Terna, for the SEE and Greece–Italy capacity calculation regions; TSCNET in Munich serves ELES, HOPS and Transelectrica for the Core and Italy North regions (ACER, 2025b). Romania is the only one of the five that works with both. The tasks of these centres, among them coordinated security analysis and outage planning coordination, are set by Regulation (EU) 2019/943 (Art. 37).

Peer-reviewed accounts of the national arrangements are few. Greece launched its markets under the European target model, balancing included, on 1 November 2020 (Sousounis et al., 2023), and in 2018 the Croatian balancing market was not yet operating (Beus et al., 2018). For non-frequency services, TSOs must use market-based

procurement unless the regulator finds it economically inefficient and grants a derogation (Directive (EU) 2019/944, Art. 40(5)). The search found no peer-reviewed study of how voltage control is procured in Bulgaria, Romania, Croatia or Slovenia. Sousounis et al. (2023) treat a Greek voltage control market as an arrangement still to be designed, with TSO–DSO procedures and standard products to be agreed.

4.2. Evidence from the 2021 and 2024 disturbances

Before the 2021 split, cold weather in Central and Western Europe had produced a market-driven flow of about 3.4 GW from the south-east to the north-west (ENTSO-E, 2021). The Ernestinovo busbar coupler tripped at 14:04:25, and further trips separated the system at 14:05 CET. Frequency in the south-east area rose at 300 mHz/s to 50.6 Hz. In the north-west it fell at 60 mHz/s to 49.74 Hz, and the French and Italian defence plans disconnected about 1,300 MW and 400 MW of contracted industrial load. HOPS led the resynchronisation, which was completed at 15:08. The south-east peak was three times the ± 200 mHz deviation at which FCR is fully activated, and in that area a protection scheme in Turkey also shed 975 MW of generation (ENTSO-E, 2021). Ippolito et al. (2021) used their model of the event to examine scenarios with missing defence actions and lower inertia. ENTSO-E (2021) recommended fast support beyond classical FCR and measures to compensate for falling inertia.

The 2024 incident developed differently. The affected area was importing heavily when the Ribarevine–Podgorica 2 line tripped at 12:09 and the Zemblak–Kardia line between Albania and Greece followed at 12:21. The voltage then collapsed, and 2,214 MW of generation was lost (ENTSO-E, 2025a). The investigation names high imports, insufficient voltage support and the loss of 400 kV lines as the main factors. Its root causes include the lack of N-1 detection of overloads after the first outage and the failure to detect the potential voltage instability of the area. The outage planning coordination run by SEleNe CC, SCC and TSCNET had shown no security alerts. In Croatia the Split area blacked out, and HOPS restored it from the 220 kV level. The recommendations ask TSOs to assess voltage stability in operational planning, to assess voltage and reactive power for low-voltage situations and to consider under-voltage load shedding (ENTSO-E, 2025a).

The Iberian blackout of 28 April 2025 moved in the opposite direction, with fast voltage increases and cascading generator disconnections, but its final report again points to gaps in voltage and reactive power control and to differences in voltage regulation practices (ENTSO-E, 2026f). Voltage control was deficient in both events, and it is also the service on which the reviewed sources give the least information for the five systems.

The summer 2024 price episode adds a planning side. ACER (2026) found that planned network maintenance contributed to the limited cross-border capacity, and it recommends better regional coordination of outage planning and curative remedial actions, faster use of grid-enhancing technologies and the removal of market barriers for small flexibility providers.

4.3. A framework for assessing ancillary-service resilience

The framework in Figure 1 places each ancillary service in the phase of a disturbance where it acts, following the trapezoid of Panteli et al. (2017). A preventive phase in operational planning is added, because several of the 2024 root causes belong to that stage. The services are grouped into five dimensions:

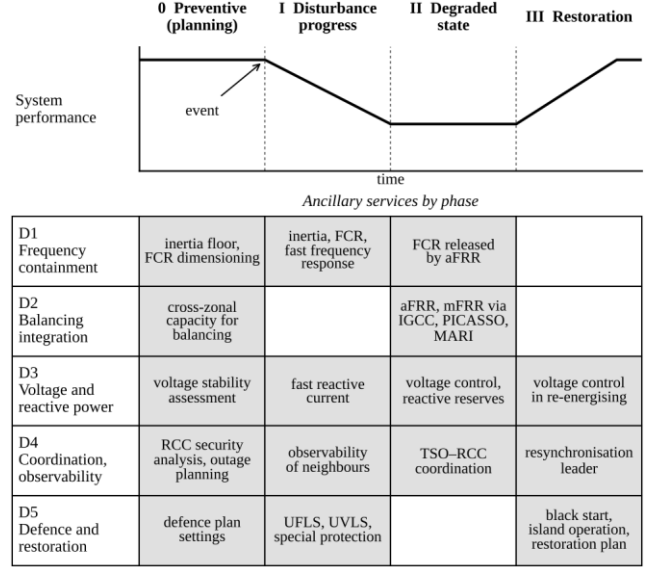


Figure 1: Ancillary services and assessment dimensions D1–D5 by phase of a disturbance, built on the resilience trapezoid of Panteli et al. (2017).

D1. Frequency containment – inertia and rate of change of frequency, FCR from fast sources such as batteries, and the settings of frequency-dependent defence plans.

D2. Balancing integration – connection to IGCC, PICASSO and MARI, cross-zonal capacity available for balancing, and access for small providers.

D3. Voltage and reactive power – the form of procurement of voltage control under Art. 40 of Directive (EU) 2019/944, voltage stability assessment in operational planning, and dynamic voltage control by converter-connected plants.

D4. Coordination and observability – the coverage of neighbouring grids in each TSO's observability area and the use of RCC security analysis and outage planning, including with non-EU neighbours.

D5. Defence and restoration – under-frequency and under-voltage load shedding, black-start capability, and tested resynchronisation and restoration plans under Regulation (EU) 2017/2196.

To compare systems, each dimension i is scored for system c on a scale from 1 to 5, and the scores are combined as:

$$ASRI_c = \sum_{i=1}^5 w_i s_{ci}$$

where $ASRI_c$ is the ancillary-service resilience index of system c , s_{ci} the score of system c on dimension i , and w_i the weight of dimension i , with the weights summing to 1.

Weights are set by expert assessment and should follow the exposure of each system: for an import-dependent area like the one that collapsed in 2024, D3 and D4 would carry more weight than D2.

With public sources only D2 can be scored today. On that dimension Slovenia has the most complete access, Bulgaria and Greece follow, and Romania and Croatia take part only in imbalance netting. For D1, D3, D4 and D5 the reviewed sources give no comparable figures per system, and the investigation reports describe only the systems involved in each event. Scoring those dimensions needs data from the TSOs.

CONCLUSION

The five EU systems of Southeast Europe share FCR and imbalance netting with the rest of Continental Europe, but their access to the aFRR and mFRR platforms ranges from full connection in Slovenia to imbalance netting only in Romania and Croatia. Neither investigation traced its event to a shortage of balancing reserves. In 2021 the system split under a large south-east to north-west flow; in 2024 overloads and voltage instability went undetected in an importing area that lacked voltage support. The panels' recommendations concern fast frequency support, inertia, operational planning, observability and voltage control, which balancing market integration does not address on its own. The proposed framework adds these dimensions to the assessment. Its scores for frequency containment, voltage, coordination and restoration depend on TSO data that are not public, and the Western Balkan systems involved in 2024 lie outside the scope adopted here.

REFERENCES

- Backer, Martijn, Keles, Dogan, & Kraft, Emil (2023). The economic impacts of integrating European balancing markets: The case of the newly installed aFRR energy market-coupling platform PICASSO. *Energy Economics*, 128, 107124. <https://doi.org/10.1016/j.eneco.2023.107124>
- Beus, Mateo, Pavić, Ivan, Štritof, Ivona, Capuder, Tomislav, & Pandžić, Hrvoje (2018). Electricity Market Design in Croatia within the European Electricity Market—Recommendations for Further Development. *Energies*, 11(2), 346. <https://doi.org/10.3390/en11020346>
- Birkebaek, Jens Møller, & Carlini, Enrico Maria (2018). Regional Coordination of Power System Operations. In: 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), 1–6. <https://doi.org/10.1109/EEEIC.2018.8494208>
- Doorman, Gerard L., & van der Veen, Reinier (2013). An analysis of design options for markets for cross-border balancing of electricity. *Utilities Policy*, 27, 39–48. <https://doi.org/10.1016/j.jup.2013.09.004>
- Giannakopoulos, Giannis T., Papadaskalopoulos, Dimitrios A., Karasavvidis, Makedon D., & Vovos, Panagis N. (2025). Profitability Analysis of Battery Energy Storage in Energy and Balancing Markets: A Case Study in the Greek Market. *Energies*, 18(4), 911. <https://doi.org/10.3390/en18040911>
- Ippolito, Mariano G., Musca, Rossano, & Zizzo, Gaetano (2021). Analysis and Simulations of the Primary Frequency Control during a System Split in Continental Europe Power System. *Energies*, 14(5), 1456. <https://doi.org/10.3390/en14051456>
- Makrygiorgou, Despoina I., Andriopoulos, Nikos, Georgantas, Ioannis, Dikaiakos, Christos, & Papaioannou, George P. (2020). Cross-Border Electricity Trading in Southeast Europe Towards an Internal European Market. *Energies*, 13(24), 6653. <https://doi.org/10.3390/en13246653>
- Milano, Federico, Dörfler, Florian, Hug, Gabriela, Hill, David J., & Verbič, Gregor (2018). Foundations and Challenges of Low-Inertia Systems (Invited Paper). In: 2018 Power Systems Computation Conference (PSCC), 1–25. <https://doi.org/10.23919/PSCC.2018.8450880>
- Panteli, Mathaios, & Mancarella, Pierluigi (2015). The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience. *IEEE Power and Energy Magazine*, 13(3), 58–66. <https://doi.org/10.1109/MPE.2015.2397334>
- Panteli, Mathaios, Mancarella, Pierluigi, Trakas, Dimitris N., Kyriakides, Elias, & Hatziaargyriou, Nikos D. (2017). Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems. *IEEE Transactions on Power Systems*, 32(6), 4732–4742. <https://doi.org/10.1109/TPWRS.2017.2664141>
- Rebours, Yann G., Kirschen, Daniel S., Trotignon, Marc, & Rossignol, Sébastien (2007). A Survey of Frequency and Voltage Control Ancillary Services—Part I: Technical Features. *IEEE Transactions on Power Systems*, 22(1), 350–357. <https://doi.org/10.1109/TPWRS.2006.888963>
- Sousounis, Marios-Charilaos, Floros, Epameinondas, Paterakis, Fotios-Konstantinos, Dikaiakos, Christos, & Moraitis, Ioannis (2023). Voltage Control Market Integration: Technical and Regulatory Challenges for the Greek Electricity Market. *Energies*, 16(5), 2306. <https://doi.org/10.3390/en16052306>
- Stankovic, Aleksandar M., Tomsovic, Kevin L., De Caro, Fabrizio, Braun, Martin, Chow, Joe H., Čukalevski, Ninel, et al. (2023). Methods for Analysis and Quantification of Power System Resilience. *IEEE Transactions on Power Systems*, 38(5), 4774–4787. <https://doi.org/10.1109/TPWRS.2022.3212688>

Reports and official documents:

- ACER (2025a). Progress of EU electricity wholesale market integration – 2025 Monitoring Report. European Union Agency for the Cooperation of Energy Regulators, 5 November 2025. Available at: <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-2025-Electricity-market-integration.pdf>
- ACER (2025b). Regional Coordination Centres' (RCC) reporting obligations in 2024 – ACER monitoring report. December 2025. Available at: <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-2025-RCC-monitoring-report-for-2024.pdf>

ACER (2026). Increasing cross-zonal capacity and system flexibility in Southeast Europe: ACER report to the Energy Union Task Force – 2026 Monitoring Report. 20 May 2026. Available at: <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-Monitoring-Report-Increasing-SEE-cross-zonal-capacity-and-flexibility-2026.pdf>

ENTSO-E (2021). CE SA Separation on 08 January 2021 – ICS Investigation Expert Panel, Final Report: Executive Summary. 15 July 2021. Available at: https://eepublicdownloads.azureedge.net/clean-documents/SOC%20documents/SOC%20Reports/entsoe_CESysSep_Executive_Summary_210715.pdf

ENTSO-E (2023). Project Inertia – Phase II: Updated frequency stability analysis in long term scenarios, relevant solutions and mitigation measures. 8 November 2023. Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/sdc-documents/231108_Project_Inertia_Phase_II_First_Report_FOR_PUBLICATION_clean.pdf

ENTSO-E (2025a). Grid Incident in South-East Europe on 21 June 2024 – ICS Investigation Expert Panel, Final Report. 25 February 2025. Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2024/entsoe_incident_report_240621_250225_02.pdf

ENTSO-E (2025b). Determination of LFC blocks for the Synchronous Area Continental Europe, amended version of 8 February 2025. Available at: https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/SAFA_for_RG_CE/Policy_on_LFCR_-_A7_-_SOGL_A141.2_CE_LFC_blocks_dertmination.pdf

ENTSO-E (2026f). Final Report on the Grid Incident in Spain and Portugal on 28 April 2025. 20 March 2026. Available at: <https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/>

Websites:

ENTSO-E (2026a). PICASSO. Official website. Available at: https://www.entsoe.eu/network_codes/eb/picasso/

ENTSO-E (2026b). PICASSO Accession Roadmap, version 15, 26 February 2026. Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Network%20codes%20documents/Implementat/picasso/PICASSO_Accession_Roadmap_FEB_2026.pdf

ENTSO-E (2026c). MARI. Official website. Available at: https://www.entsoe.eu/network_codes/eb/mari/

ENTSO-E (2026d). MARI Accession Roadmap, version 15, 26 February 2026. Available at: https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Network%20codes%20documents/NC%20EB/2026/MARI_Accession_Roadmap_FEB_2026.pdf

ENTSO-E (2026e). Imbalance Netting (IGCC). Official website. Available at: https://www.entsoe.eu/network_codes/eb/imbalance-netting/

Legal acts:

Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation. OJ L 220, 25.8.2017, 1–120.

Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. OJ L 312, 28.11.2017, 6.

Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration. OJ L 312, 28.11.2017, 54.

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (recast). OJ L 158, 14.6.2019, 125.

Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast). OJ L 158, 14.6.2019, 54–124.

Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024 amending Regulations (EU) 2019/942 and (EU) 2019/943 as regards improving the Union's electricity market design. OJ L, 2024/1747, 26.6.2024.