Czech Technical University in Prague

Faculty of Electrical Engineering

Doctoral Thesis

2024

Ing. Jakub Šrom

Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Electrical Power Engineering

THE POWER SYSTEM OPERATION UNDER THE NEW ENERGY CONDITIONS BY USING MARKET-BASED INSTRUMENTS

Doctoral Thesis

Ing. Jakub Šrom

Prague, 2024

Ph.D. Program: Electrical Engineering and Information Technology (P2612)
Branch of study: Electrical Power Engineering (3907V001)

Supervisor: ***Doc. Ing. Zdeněk Müller, PhD.***
Supervisor-Specialist: ***Ing. Igor Chemišinec, PhD., MBA***

Abstract

This dissertation aims on the study and determination of the possible effects of trading on short-term markets on the operation of the transmission system, including the assessment of legislative impacts and regulation on both the current state and the future outlook. The thesis provides an overview of the current state of market opportunities for both market participants and transmission system operators with an emphasis on the significant impact of the development of renewable resources on system operation. Individual types of market participants and their priorities are briefly described. Attention is paid to the technical effects of the operation of transmission networks on trading in short-term markets. Also mentioned are current technical limitations to the development of trading in times as close as possible to the delivery, including regulatory pressure to shorten this time. A significant part of the work is the evaluation of outages of the largest unit in the transmission system over several years and the evaluation of the effect of trading on short-term markets to eliminate the effect of the outage on the operation of the transmission system.

After performing the analyses, a case study was conducted of four possible states on short-term markets – different variants of trading period lengths and intervals in which the system imbalance is evaluated. The outage of the biggest unit in the transmission system was always considered, and together with the optimal situation on the short-term markets, the impact on the operation of the transmission system was evaluated from the point of view of system imbalance and activation of ancillary services by the transmission system operator.

The contribution of the work is also a summary of legislative impacts on the future operation of the transmission system together with the development of short-term markets and a possible continuation from the point of view of the transmission system operator on its possibilities of further use of short-term markets in combination with markets with ancillary services.

Keywords: transmission system operation, short-term electricity markets, imbalance, ancillary services, outage of the unit.

Abstrakt

Disertační práce se zaměřuje na studium a určení možných vlivů obchodování na krátkodobých trzích na provoz přenosové soustavy včetně posouzení legislativních dopadů a regulace jak na stávající stav, tak na budoucí výhled. V práci je uveden přehled současného stavu tržních možností jak pro účastníky trhu, tak pro provozovatele přenosové soustavy s důrazem na významný dopad rozvoje obnovitelných zdrojů na provoz soustavy. Stručně jsou popsány jednotlivé typy účastníků trhu a jejich priority. Pozornost je věnována technickým dopadům provozu přenosových sítí na obchodování na krátkodobých trzích. Rovněž jsou zmíněna současná technická omezení rozvoje obchodování v časech co nejblíže dodávce, včetně regulatorního tlaku na jejich zkracování. Významnou část práce tvoří zhodnocení výpadků největších bloků v soustavě v průběhu několika let a zhodnocení vlivu obchodování na krátkodobých trzích pro odstranění vlivu výpadku na provoz přenosové soustavy.

Po provedení analýz byla provedena případová studie čtyř možných stavů na krátkodobých trzích – různé varianty délek obchodních period a intervalů, v nichž se vyhodnocuje systémová odchylka. Byl vždy uvažován výpadek největšího bloku v soustavě a spolu s optimálním stavem na krátkodobých trzích se vyhodnocoval dopad na provoz přenosové soustavy z pohledu systémové odchylky a aktivace podpůrných služeb ze strany provozovatele přenosové soustavy.

Přínos práce tvoří rovněž souhrn legislativních dopadů na budoucí provoz přenosové soustavy společně s rozvojem krátkodobých trhů a možné pokračování z pohledu provozovatele přenosové soustavy na jeho možnosti dalšího využití krátkodobých trhů v kombinaci s trhy s podpůrnými službami.

Klíčová slova: provoz přenosové soustavy, krátkodobé trhy s elektřinou, odchylka, podpůrné služby, výpadek bloku.

Acknowledgement

In the first place I would like to express my special gratitude to my supervisor, Zdeněk Müller for his supervision, advice and guidance from the very early stage of this work.

I convey special acknowledgment to supervisor-specialist Ing. Igor Chemišinec, PhD., MBA for his worth advice concerning the legislation related to problems discussed in my dissertation as well as giving me extraordinary experiences throughout the work.

Many thanks go in particular to my colleagues at OTE, a.s. where most of the data used for the dissertation are come from.

I would like to thank all members of staff in the department of Electrical Power Engineering for their assistance, kindness and helpful discussions.

Last, but not least, I would like to thank my family, namely to my dear wife Vendula for her support and love and also to our kids Anna and Karolína. I love you.

Table of Content

List of Figures

1. Introduction

The increasing energy demands, environmental constraints, regulation and new visions of the power supply industry and other changes in energy market result in the fact that existing transmission systems are often operated and stressed to their limits and occasionally beyond the performance capability of their original design in order to maximize the profit. The electricity trading and requirements of the producers and consumers don't often respect physical laws for electricity flows and it results in further transmission systems loading. One of the cases is so called loop flows between particular areas in large countries or even among more countries which result from different capabilities of individual transmission systems. This fact causes international connections loading and reducing of their capacity for other necessary of wanted utilization.

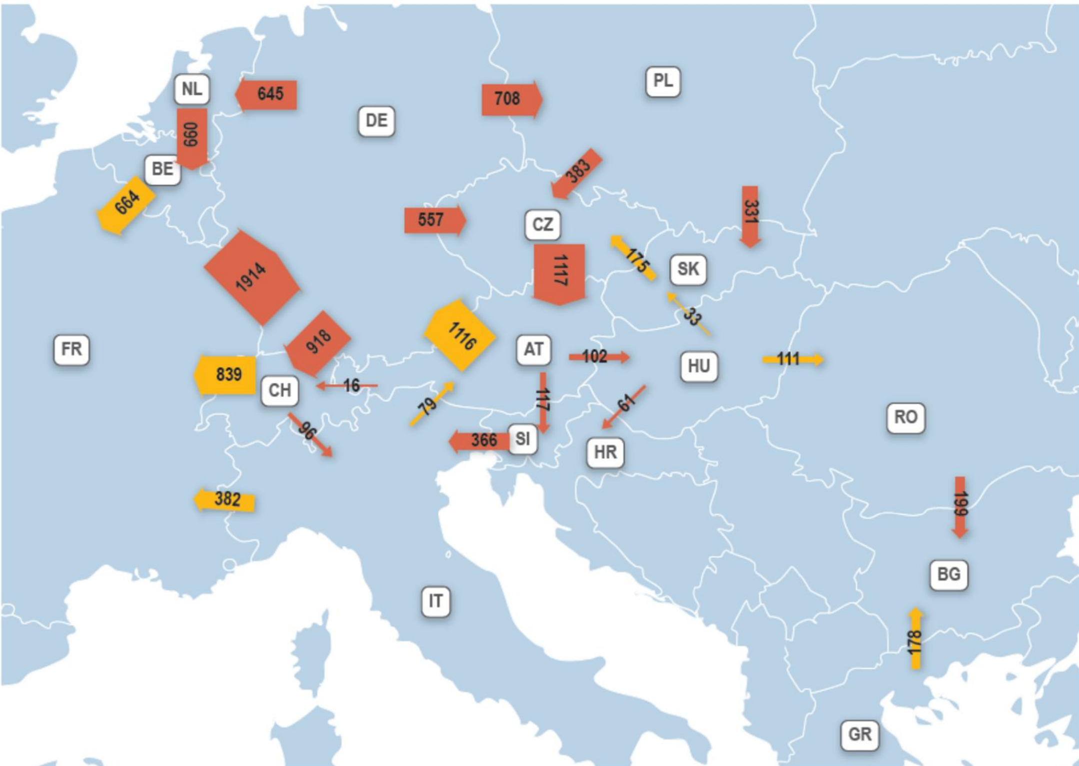

Figure 1: Average oriented unscheduled flows in Continental Europe. Source: [6]

TSOs also meet steady-state control as well as dynamic stability problems. However, new transmission lines construction is difficult, if not impossible, because of environmental, ownership or political reasons. The new lines construction thus can't usually keep pace with the growing renewable sources capacity, changes in the structure and geographical layout of the supply and planned energy demand. To ensure that the economical, reliable and secure operation of the existing grid is maintained under these conditions, the need for various aspects of power flow management within the power systems is becoming increasing.

Very important influence has also the legal framework that is covered by the Clean energy for all Europeans (CEP) that updated old energy market rules and introduced new ones, while also encouraging the necessary public and private investments based on market signals. A part of the package is focused to establish a modern design for the EU electricity market, adapted to the new market – more flexible, more market-oriented and prepared to integrate a greater share of renewable sources.

Actual proposal increases the current EU-level target of at least 32%' of renewable energy sources in the overall energy mix to at least 40% by 2030, which represents doubling the current renewables share of 19.7% in just a decade.[1] But electricity has to be also produced and delivered to consumers in sufficient volume when there is no wind or sun. Markets have to meet the needs of renewable energy and attract investment in the resources, like energy storage, that can compensate for variable energy production. The market must also provide the right incentives for consumers to become more active and to contribute to keeping the electricity system stable.

The dispatching of the electricity system becomes more and more challenging. The tools as usage of harmonized balancing products (i.e. Ancillary services), which the Transmission system operator currently use, need to be supported by "the market tools" to allows market participants actively react to market signals and to be available when the market most needs them. [11]

The short-term markets can be considered as the one which certainly can help to better integrate the variable and distributed generation, and as the result to remove market distortive measures and ensure the security of supply, promotes fair competition between market participants and incorporating new technologies contribute to the network security and reliability.[12]

[1] Delivering the European Green Deal Package base on https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0082.01.ENG&toc=OJ:L:2018:328:TOC

2. Goals of the thesis

The liberalized market has brought new, in particular from market point of view, aspects to the conditions of transmission system operation. **The initial technical view in the operation of the transmission system, from the perspective of the TSO's control room, is no longer sufficient, and market mechanisms need to be taken into account**. This includes encouraging market participants, especially consumers, to become more active in the electricity market. The significant increase in renewables, characterized by intermittent production according to the current weather conditions, also places high demands on finding also non-technical solutions for the system management. These changes are stated in the European legislation known as the “Clean Energy Package”, which was adopted with the aim “*to establish a modern design for the EU electricity market, adapted to the new realities of the market – more flexible, more market-oriented and better placed to integrate a greater share of renewables*” [13].

Mainly “The Directive on common rules for the internal market for electricity (EU) 2019/944” and “Regulation on the internal market for electricity (EU) 2019/943” they show the direction that individual market participants, including transmission system operators, will follow. These two key documents emphasize the involvement of customers in the processes on the electricity market, and for transmission and distribution system operators it also anticipates the construction of new market management systems and places high demands on the support of further integration of renewables in the system. In terms of securing reliable supply, it places great emphasis on strengthening cross-border trade, greater integration of national markets and competition as a fundamental pillar for boosting energy investments while maintaining the goal of decarbonizing European electricity systems by 2050.

The main goals of the thesis are:

- Description of the electricity market
- Analysis of the current technical possibilities of power system control
- Deep analysis of the new market tools (Market mechanisms resulting from new European legislation) with respect to the power system and electricity market and their operational characteristics.

- The possibilities to prevent emergency situations in the electricity power systems by using market mechanisms
- Analysis of possible options in cooperation between power systems operation and electricity market.
- To prepare a case study on behavior between technical and business world in the transmission system.

3. Electricity market model

The liberalized market has not only brought new opportunities to involve individual market participants in electricity trading, but also brings greater complexity in the management of the electricity system. The ever-increasing share of decentralized generation with a high proportion of intermittent energy sources (mainly renewable) – such as wind and solar power plants, places high demand on TSO´s to ensure a balanced power system and to maintain nominal frequency in the electricity system. For transmission system operators, this means careful planning of a sufficient volume of Ancillary services and subsequently to activate these back-up sources or otherwise obtain regulating energy. The price for regulating energy is one of the most important aspects in determining the price of the imbalance. If the price of regulating energy at a given hour is high, the corresponding imbalance price is at least at the same level. Financial losses on the part of market participants, who have an imbalance at a given time, are noticeably increasing. The aim of this article is not to analyze processes on the part of the TSO, but to point out the existence of other opportunities that will help to solve exceptional situations in the transmission system.

One of the most important opportunities for market participants is their involvement in the short-term electricity markets. On the Czech market, these short-term electricity markets are organized by OTE (Market Operator). These markets are a day-ahead (spot) market (DAM) allowing trading on the day before the delivery date and also an intraday market (IM) allowing cross-border trading up to 60 minutes before the delivery hour starts and this is followed by local trading up to 5 minutes before the delivery hour starts.

These markets allow market participants to trade at a time close to the day or hour of delivery. Long-term trading primarily serves to ensure long-term price and expected load/generation, while short-term markets allow market participants to respond effectively to exceptional operational or trading situations. The aim and purpose of the short-term markets is not only to reduce the risk of imbalance, but also to increase security and reliability of supply and to offer the last opportunity for market participants to buy or sell electricity.

Spot markets are tightly interlinked with financial markets. Electricity is firstly traded as long-term finical product, for example year contract traded 3 years in advance. Then could be traded as month product within actual year, and the periods are shortening as possible.

But all this electricity contracts have to be at the end physically settled. And the short-term or spot markets serves also for this physical settlement. There is not traded virtual electricity as financial product but the real energy that could cause real imbalance and have an impact on the transmission system unless traded on the basis of real production and consumption.

The following Fig. 3.1 shows the link between the individual market types.

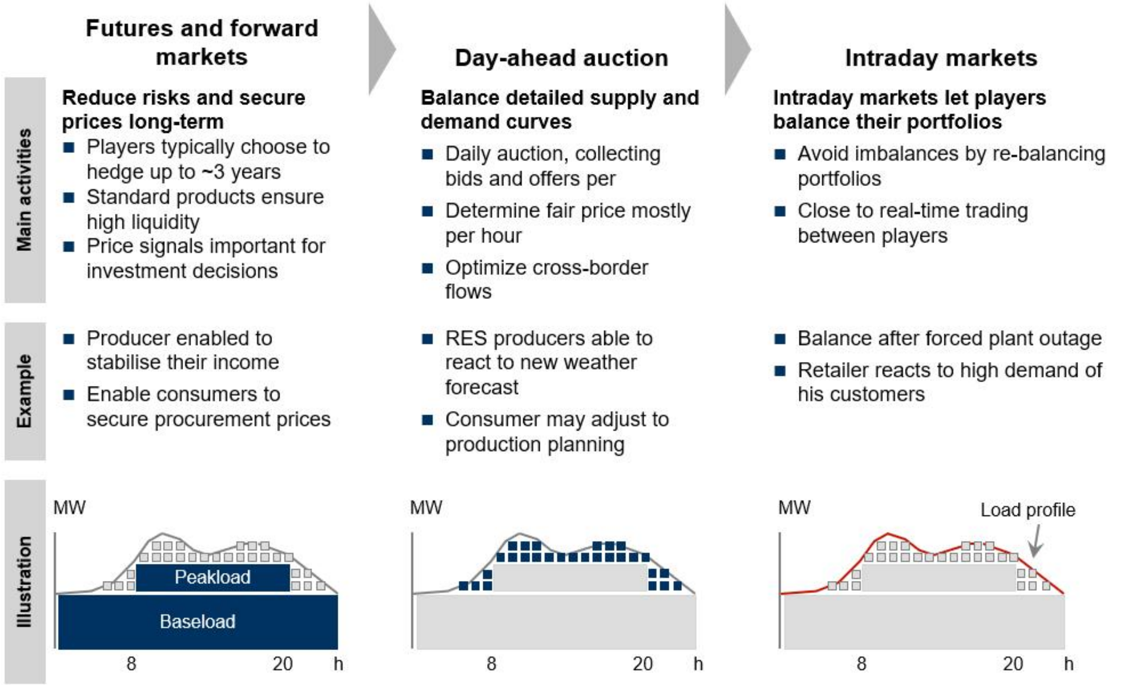

Figure 2: Main use cases of financial and spot markets2

[2] Source: Europex Market Vision Paper

3.1. The roles of individual market participants

3.1.1. TSO

The role of Transmission System Operator (TSO) is unique in the market environment because it is holder of the exclusive license for transmission of electricity. TSO are responsible for safe and balanced transmission system at all times.

Each TSO shall be responsible for procuring balancing services from balancing service providers in order to ensure operational security.[3]

TSOs are responsible for calculating and managing the volume of interconnection capacity to be made available to other market participants.

TSO also can buy on the short-term markets electricity for covering the losses in the transmission system.

The detailed guideline on electricity balancing and resulting TSOs responsibilities are governed by COMMISSION REGULATION (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing[4]. Certain essential functions related to the operation of the balancing market are carried out by third parties rather than by the Transmission System Operators (TSOs).

The tasks performed by delegated operators include, among others, imbalance calculation and settlement, data publication related to electricity balancing markets and issuing of the rules related to balancing markets and imbalance settlement. These tasks are essential for the electricity market to work efficiently and represent the link between the physical exchange of electricity and the financial outcomes.[5]

---

[3] COMMISSION REGULATION (EU) 2017/2195 of 23 November 2017establishing a guideline on electricity balancing

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R2195&from=EN

[5] Source: Europex Paper: The Essential Tasks of Delegated Operators in the Electricity Market

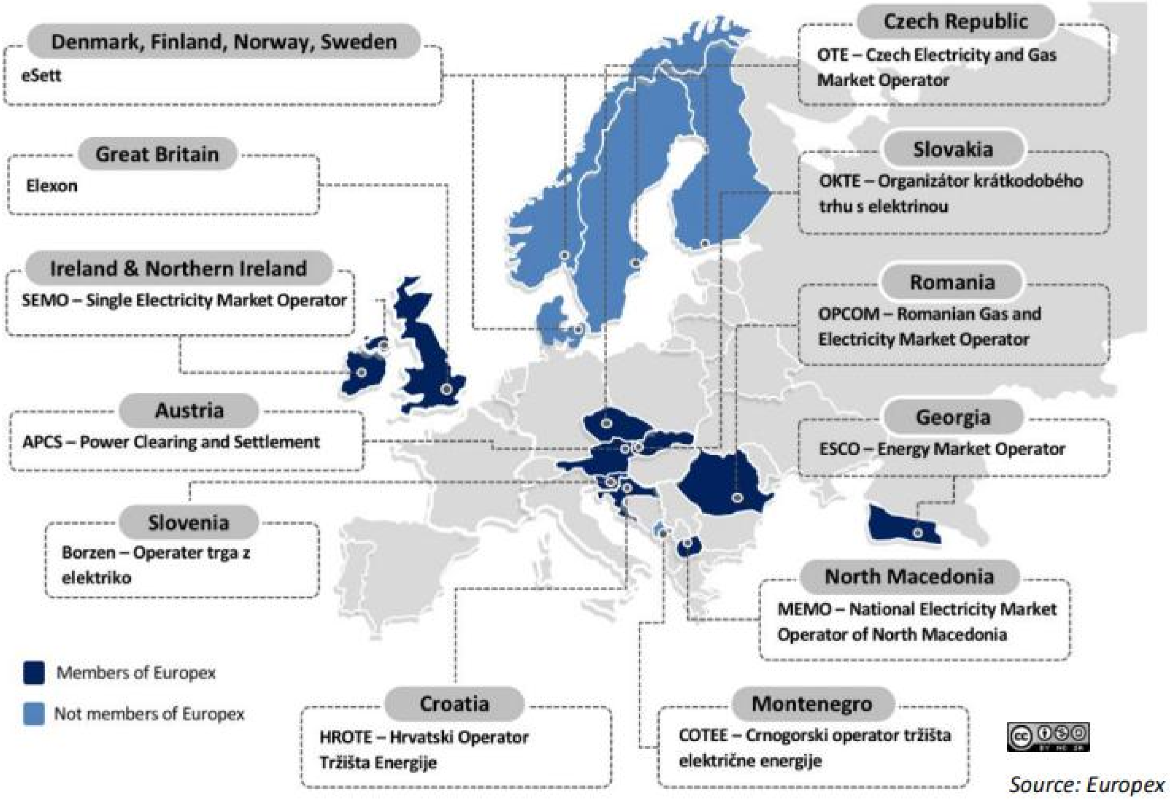

Figure 3: Delegated operators active across European markets[6]

3.1.2. NEMO

Nominated electricity market operator (NEMO) are the organizations mandated by the competent authority (NRA) to run the day-ahead and intraday integrated electricity markets in the EU.

A NEMO is an entity that acts as a market operator in national or regional markets to perform, in cooperation with TSOs, single day-ahead coupling (SDAC) and single intraday coupling (SIDC). In particular, each NEMO is responsible for the implementation of the MCO (Market Coupling Operator) function which is carried out in coordination with other NEMOs.

NEMOs are responsible for:

- Collecting orders from market participants;
- Assessing the results calculated by the MCO function;
- Informing market participants about the results of their orders;

[6] Source: Europex

- Acting as central counter parties for clearing and settlement of the exchange of energy resulting from SDAC and SIDC;
- Establish jointly with relevant NEMOs and TSOs back-up procedures for national or regional market operation;
- Where applicable, in line with CACM Regulation, coordinate with TSOs to establish arrangements concerning more than one NEMO within a bidding zone and perform SDAC and/or SIDC in line with the approved arrangements. (Not applicable in the Czech Republic)

3.1.3. Trader – producer

Holder of a license for Power generation who is also holders of a license for Electricity trading. His primary goal is to maximize profits and optimize the operation of their generating facilities.

3.1.4. Trader – consumer

Mainly big consumer of electricity who is also holder of a license for Electricity trading. His primary goal is to minimize costs by lowering the price and optimize volumes of supplied electricity with electricity demand of his facilities.

3.1.5. Trader – supplier

Electricity supplier to end customers and holder of a license for Electricity trading. His primary goal is to minimize costs by lowering the price and optimize volumes of supplied electricity with aggregated demand of his consumer portfolio.

3.1.6. Trader – supplier + producer

Electricity supplier to end customers, holder of a license for Electricity trading and holder of a license for Power generation or owner of generation rights of some generation portfolio (e.g. renewable sources, cogeneration etc.). His primary goal is to minimize costs by lowering the price and optimize volumes of supplied electricity with aggregated demand of his consumer portfolio.

3.1.7. Trader – speculator

Holder of a license for Electricity trading with no supply or demand portfolio who the practice risky transactions in an attempt to profit from short term fluctuations in the market value.

Some kind of speculative trading may be possible also for all previously mentioned types of traders, but not as dominant part of their strategy.

4. Transmission system operation

4.1. Role of ČEPS

ČEPS, a.s., as Czech TSO, is the sole holder of the Electricity transmission license granted by the Energy Regulatory Office under the Energy Act. ČEPS, a.s. is responsible for ensuring reliable operation and development of the transmission system within the interconnected European systems (voltage level 400 kV and 220 kV and selected lines 110 kV), for providing System Services, for ensuring cross-border transmission (cross-border power exchanges including transits) and for coordinating cooperation with foreign transmission systems.

ČEPS, a.s., is responsible for the flow management of in the transmission system and operation of the central Control Center, which is superior in defined activities to the technical Control Centers of DSOs. ČEPS, a.s., provides connection to the transmission system as it is responsible for the operation and maintenance of 43 substations with 78 transformers and also 3,780 km of 400 kV lines and 1,737 km of 220 kV lines.

Important role of ČEPS, a.s., is to ensure the planning, preparation of operation and reliable operation of the electricity system in real time. ČEPS, a.s., provides commercial metering on cross-border lines and at the points of connection of production facilities and distribution systems and the transmission of metered data to the Market Operator.

ČEPS, a.s., organizes the market for Ancillary services to ensure the balancing in case of system imbalance. Part of its role is to ensure non-discriminatory access to the transmission system, including cross-border trade. ČEPS, a.s., provides market participants with an operational and market information within the Market Transparency. ČEPS, a.s., is a member ENTSO-E, the European Network of Transmission System Operators for Electricity.

4.2. System Services

The System Services (SyS) serve to ensure safe and reliable operation of the Transmission System, the quality of electricity transmission and to ensure the requirements for the Transmission System operation resulting from international cooperation within the ENTSO-E. The ČEPS provides the following SyS:

1) Maintaining of electricity quality

Following technical and organizational tools are used to for this Service:

- Maintaining of the summary power reserve for the provision of frequency containment process (Primary frequency control)
- Frequency restoration process (Secondary frequency and power control)
- Secondary voltage control
- Tertiary voltage control;
- Retaining the sinusoidal shape of the voltage waveform
- Ensuring transmission stability

The criteria for assessing the quality of electricity are based on valid technical standards.

2) Maintaining of the power balance in real time

Following technical and organizational tools are used to for this Service:

- Automatic frequency restoration process (Secondary frequency and power control)
- Manual frequency restoration process (Tertiary power control)
- Use of the operating reserve

The criteria for assessing the quality of maintaining the power balance and the export/import balance are based on the recommendations applicable within ENTSO-E.

3) Restoration of the power supply

The Restoration plan is used as the main tool together with ancillary services Island operation capability and Black start capability.

The criteria for assessing the quality of the restoration of the power supply are based on the regulations in force within ČEPS, a.s. and ENTSO-E.

4) Dispatch control

In addition to the resources already mentioned above, this service also includes:

Ensuring the safety of operations through a defense plan and operating instructions,

on network transmission capacity management (active power flows) through network configuration, redispatching, counter-trading.

The criteria for assessing the quality of dispatch control are based on regulations and operating instructions valid within ČEPS, a.s. and ENTSO-E.

4.2.1. Maintaining the summary power reserve for frequency containment process (primary frequency control)

Maintaining the summary power reserve for frequency containment process means obtaining of this backup power in the specified amount and quality (with set droop and required dynamics).

Primary frequency control is based on the so-called “principle of solidarity” in an interconnected power system. This means that when the power balance between the load and the generation is disturbed (e.g. by a unit outage or load change), all power sources in the interconnected power system involved in the primary frequency control participate in restoring the power balance, regardless of the control areas. The purpose of the primary frequency control is therefore to increase (decrease) the power, and thus stop the decrease (increase) of the frequency deviation in a time interval of several seconds. Mathematically, this power response ΔP depends on the instantaneous frequency deviation Δf from the nominal value as follows:

$$\Delta P = -\lambda * \Delta f \quad \text{[MW, MW/Hz, Hz], where} \qquad (22)$$

λ … control area power frequency characteristic.

Power reserves for the primary frequency control of each of the control areas are set as maximum volume to be covered in response to a shortfall in generation capacity equal to or less than 3 000 MW. Ensuring this power reserves is a basic obligation of TSOs, i.e. a condition for synchronous cooperation of the interconnected system. It follows that each control area maintains set total power reserve for primary frequency control with a given total droop.

4.2.2. Frequency restoration process (Secondary frequency and power control)

Frequency restoration process automatically maintain power balance of the control area (power flows with neighboring systems at agreed values) as well as the nominal value of the frequency.

The Secondary frequency and power control is provided by the automatic controller located at the ČEPS Control Room. Power plant units providing AnS aFRR (Secondary control) and measurement of the cross-border power flows are connected to this secondary controller. The controller itself works according to the so-called "principle of non-intervention", which means that the caused power imbalance, indicated by a change in frequency and deviation in cross-border power flows, is compensated only by the affected control area, where the power imbalance occurred. The individual Area Control Error G (ACE) is calculated as the sum of the power control error and the frequency control error:

$$G = \Delta P + K * \Delta f \quad \text{[MW, MW, MW/Hz, Hz], where} \tag{23}$$

ΔP … deviation of power flows power from the planned value

K … set parameter, which should theoretically equal the power characteristic λ, so that the principle of non-intervention applies ideally.

ACE needs to be controlled to zero on a continuous basis and it cannot to be confused with the system imbalance.

When restoring the power balance, the Secondary control follows the Primary control so as to replace the power reserves provided on the "principle of solidarity" in the interconnected system within 15 minutes from the moment of power imbalance. The process is realized by sending the required power setpoints from the secondary controller to the units providing AnS aFRR (Secondary control).

4.2.3. Tertiary power control

Tertiary power control maintains the required secondary control backup.

Tertiary power control is used to replace the depleted secondary control backup, i.e. the power that was used by the Frequency restoration process.

4.2.4. Secondary voltage control

Secondary voltage control automatically maintains the specified voltage in the pilot node of the transmission system. The voltage setpoint is provided by tertiary voltage control.

The task of the Secondary voltage control is to maintain the set voltage in the pilot nodes using an automatic voltage controller that responds to the deviation of the actual voltage from the voltage setpoint in the pilot node and determines the required reactive power for its operation. The required reactive value is sent to power plant providing Ans Secondary Voltage and Reactive Power Control.

If there is more than one unit involved, pilot node has to be equipped with a so-called group reactive power controller, which divides the required reactive power into individual units according to the set key.

When the pilot node is switched to island operation, the Secondary voltage control is disconnected from the tertiary control system (remote voltage control) and switched to the mode of the local voltage control.

4.2.5. Tertiary voltage control

Tertiary voltage regulation coordinates the specified voltages in the pilot nodes for safe and economical operation of the EC as a whole.

Tertiary control involves a process of optimization, using calculations based on the real time measurements, in order to adjust the settings of units that influence the distribution of reactive power.

4.2.6. Ensuring transmission stability

Control and coordination activity consisting of ensuring the stability of the ensuring the transmission stability of the power flows and damping of power oscillations in the system.

The operation of interconnected transmission systems requires the control of static and dynamic stability of the transmission. This check is performed by ČEPS by monitoring and evaluating the measured events in real time and by stability calculations. Based on the analysis, measures are proposed for setting the excitation limits, amplification of excitation controllers and setting of power system stabilizers (PSS) in the excitation controllers of individual generators. These issues are also addressed by the Defense Plan in measures against swinging and loss of synchronism.

4.2.7. Restoration of the power supply after complete or partial disintegration of the system (loss of power supply)

The process consisting of unit starts without supply of external voltage (black start), gradual recovery of network voltage and power supply of users according to predetermined priorities, as well as island operation of network parts and gradual phasing of individual islands.

In the event of a major system failure that is not handled by conventional means (described in the Defense Plan), a blackout may occur, or the system may fail partially. In the event of such failures, ČEPS must ensure that the operation is restored to normal. For this purpose, the Restoration Plan was created, which is developed into the operating instructions of the DSO control rooms and regularly trained and some of its parts are tested in operation. An example could be the start of units without the supply of external voltage and power (black start) and the ability of island operation of the power plant units.

4.2.8. Retaining the sinusoidal shape of the voltage waveform

Passive functions (monitoring and control) and active functions (filters).

With the development of semiconductor technologies, the number of these devices powered from higher voltage levels is growing. This can cause distortion of the voltage (pulses, content of higher harmonics, etc.), which in turn negatively affects other users. Therefore, ČEPS has the right to monitor and measure the "purity" of the sinusoid, identify the sources of failures and propose measures.

4.3. Ancillary Services

ČEPS uses Ancillary Services provided by individual users of the transmission system to provide System Services. ČEPS thus achieves the safe and reliable functioning of the transmission system.

4.3.1. Frequency Containment Process (FCP)

Formerly known as Primary frequency control. The frequency containment process (FCP) is a local automatic process provided by primary control circuits and consists of a precisely defined change in the power output of a unit in response to a frequency deviation from its set value. The value of the required change in generating unit power output in response to a system frequency deviation is determined by the droop of primary frequency control.

$$\Delta P = -\frac{100}{\delta} * \frac{Pn}{fn} * \Delta f \, , \text{ where} \qquad (24)$$

ΔP ... *required change of active power[MW]*

P_n ... *nominal power of the unit [MW]*

Δf ... *frequency deviation from its set value [Hz]*

δ ... *droop of primary frequency control [%]*

f_n ... *set frequency (usually nominal value 50 Hz)*

A primary control reserve must be available at all the time, when the service is provided, and the unit has to be able to deploy the whole primary control reserve within 30 seconds after the imbalance occurs.

4.3.2. Automatic Frequency Restoration Process (aFRP)

Formerly known as Secondary power control. Automatic Frequency Restoration Process (aFRP) is the process of changing the value of the power output of the concerned power plant unit, as required by the automatic load frequency controller.

Automatic frequency restoration reserve (aFRR) has to be available at all the time, when the service is provided, and the activation time of full aFRR is 10 minutes after the request.

4.3.3. Manual Frequency Restoration Process within 5/15 minutes (MFRP5, MFRP15+, MFRP15-)

Formerly known as Tertiary power control (30 minutes) or Minute Reserve (5 minutes and 15 minutes). The manual Frequency Restoration Process within 5/15 minutes is a process of changing the power output of a concerned unit, as requested by ČEPS Control Centre.

Manual Frequency Restoration Reserve (mFRR) must be deployed within 5/15 minutes after the request from ČEPS Control Center.

The mFRR5 can be provided e.g. in the form of an increase in unit power output, start of hydro power plant, suspension of pumping (at pump storage power plants), or disconnection of the relevant load from the transmission system.

The mFRR15+ can be provided e.g. as an increase in unit power output, discontinuation of pumping (at pump storage hydro power plants), or disconnection of the requested load from the transmission system.

The mFRR15- can be provided e.g. in the form of lowering power output or connection of the load into the transmission system.

4.3.4. Secondary Voltage and Reactive Power Control

Secondary voltage and reactive power control (SVQC) is an automatic control of reactive output of the power plant units to maintain the set voltage value at pilot nodes of the transmission system.

4.3.5. Island operation capability

Island operation capability (IO) is the capability of a power plant unit to supply an isolated part of the power system. Island operation is characterized by high demands on the control capabilities of the unit, because significant changes in frequency and voltage due to the fact that the unit operates in an isolated part of the system may occur. This ability is essential for preventing and dealing with an Emergency state.

The power plant unit has to be able to:

- switch to island operation;
- island operation;

- re-connection of the island to the transmission system (another island);

4.3.6. Black start capability

Black start capability contains the capability of a generating unit to start up without an external power supply, the capability to reach a given voltage, the possibility of connecting to the transmission system and its power supply in island mode. This AnS allows restoration of supply from a total or partial blackout (a loss of supply) when the main aim is to quickly and safely return to the normal operational state in the affected part of the transmission system.

4.4. European balancing platforms

The future of the Ancillary services is in the cross-border sharing of regulating energy that is stated in the new pan-European Electricity Balancing Guideline (EBGL) that obliges TSOs to cooperate and to some extent harmonize the rules for balancing service providers and balance responsible parties; sets out the rules and conditions for sharing of reserves and exchange of balancing capacity; harmonizes the activation methods, standard products and pricing for balancing energy, and harmonizes some aspects of national imbalance settlement mechanisms (in summary called as "balancing market").

One of the main requirements of EBGL [14] is the implementation of four balancing platforms - IGCC, PICASSO, MARI and TERRE.

- PICASSO (Platform for the International Coordination of Automated frequency restoration and Stable System Operation) is a European platform for exchange of balancing energy from frequency restoration reserves with automatic activation (aFRP). The activation has to be done by common merit order list in which all the balancing energy bids are ordered from the cheapest to the most expensive one.
- MARI (Manually Activated Reserves Initiative) is a European platform for the exchange of balancing energy from frequency restoration reserves with manual activation (mFRR). The activation has to be done by common merit order list created for every 15 minutes.
- TERRE (Trans European Replacement Reserves Exchange) is a European platform for exchange of balancing energy from replacement reserves (RR). Standard RR balancing

product can be compared to a product that was traded on Balancing market operated by OTE, a. s. until the end of 2019.

- IGCC (Imbalance netting) is a real-time mutual exchange of imbalances of interconnected electricity systems. The exchange prevents the activation of secondary control ancillary services and supply of secondary control energy against each other respectively. It expands possibilities for exchange of cross-border balancing energy with European TSOs and thus increases the efficiency in managing control zones. Imbalances are exchanged via cross-border transmission capacities left after the gate closure time of cross-border intraday allocation, so cross-border capacity available to market participants is not diminished.

Another important aspect of EBGL is the separation of the purchase of positive and negative ancillary services and marginal valuation of regulating energy, which means that for the whole volume of regulating energy will be the same final price.

Emergency state

Emergency state in the power system can be declared during some extraordinary events, natural disasters or emergency conditions. TSO is allowed to reduce or turn off electricity supplies in the whole area or in its part in this case. This activity is given by the so-called regulation and shutdown plan. All consumers and other subjects must obey these actions and the TSO can reduce the influence of the market. Emergency actions can reduce the transmitted power in some regions, mainly in particular lines, so that they are not overloaded for a long time and the whole system can be operated further without any other failures or large supply interruptions.

Harmonization within the EU is also taking place in this area, the most important documents concerning this issue are:

- Emergency and Restoration Network Code (ER NC) [15]

  Commission Regulation (EU) 2017/2196 establishing a network code on electricity emergency and restoration, sets out rules for the management of the transmission system in case of emergency or blackout, as well as other different system critical states (defined in SO GL).

- System Operation Guideline (SO GL) [16]

Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation sets harmonized rules for TSOs, DSOs and SGUs (significant grid users), in order to provide a legal framework for the operation of the interconnected transmission system (e.g. regional cooperation of TSOs, data exchange etc.) to maintain system security and to achieve other Union-wide objectives.

4.5. Description of technical procedures in transmission system operation

4.5.1. Transmission Issues

Finding the most effective and cost-effective solutions to the various issues limiting transmission performance is becoming still more interesting as the competitive electricity supply environment has become a standard in Europe. Different power flow control methods, procedures, strategies and technologies can provide the key to these solutions. These strategies must maintain the level of reliability which consumers expect even in the event of considerable structural changes, such as a loss of large generating unit or a transmission line, and loading conditions, such as the continuous variations in power consumption.

The mentioned issues are:

Dynamic and stability issues are related to dynamic performance of the power system. Transient stability describes the ability of the power system to survive the first few seconds after a major disturbance and can be improved by extracting energy from the sending end of the network, supplying energy to the receiving end respectively by increasing the synchronizing power between both ends. Voltage stability problem is a slow process caused by progressive increase in load and can be improved by voltage support, e.g. by using reserve devices, coordinating system load tap-changers, automatic undervoltage load shedding or generator control action.

Voltage and reactive power control issues are related to voltage constraints in the power system. Low voltage at heavy load can be a limiting factor under steady state conditions. The corrective actions include correcting the power factor and compensating the reactive losses in lines by supplying reactive power. High voltage at light load is an undesirable occurrence in the transmission and distribution systems and may be diminished using mechanically switched shunt capacitors or reactors to supplement the action of tap changers. Low voltage as well as high voltage following outages can exceed the voltage limits so that corrective actions have to be taken to avoid further equipment damage.

Power flow issues are generally related to controlling the active power in the power system for better utilization of the transmission system elements, minimization of losses, limiting flows to contract paths etc.

Thermal issues are generally related to thermal limits caused by a change in the network configuration during outages and can be overcome by rearranging the network or by adding a power flow control equipment.

4.5.2. Control Measures

There are many cases and situations when the electricity systems or any of its parts needs to be controlled. The reason can be reaching a limit according to the mentioned transmission issues, a sudden unbalance in the system or a long-time demand for changes in the system. The realized measures can concern the producer side, the consumption side or the transmission lines.

Control devices in the transmission system

There are devices in the transmission systems which have been installed for many years in order to improve transmission line parameters. Passive elements with constant or step-changed values are the most spread, namely series capacitors for the line reactance compensation at long transmission lines, series reactors for reducing short-circuit currents, shunt reactors for voltage control or shunt capacitors for reactive power compensation and voltage support. Another type is phase-shifting transformers which are special transformers enabling to change the output voltage phase and thus to control power flows. Also, power electronic components and converters have recently started to be used in power systems more and more.

Control on the production side

In case of unbalance between production and consumption in the power system, the TSO must be able to control active power output of power plants to return back system frequency to its rated value. This P-f regulation is realized with so called primary (FCR), secondary (aFRR) and tertiary (mFRR) regulation in the power plants. For this purpose, ancillary services are provided by the producers and utilized by TSO who is responsible for a reliable and secure electricity system operation and must provide system services. Similarly, services connected with Q-U regulation are provided and realized for keeping the voltage in system points in the prescribed range.

5. Impact of new energy legislation

5.1. Clean Energy Package[7]

The new EU energy rulebook – called the Clean energy for all Europeans package – marked a significant step towards implementing the energy union strategy, published in 2015. Winter Package consists of eight new laws to facilitate the transition to a 'clean energy economy' and to reform the design and operation of the European Union's electricity market. These rules shall bring considerable benefits from a consumer perspective, from an environmental perspective, and from an economic perspective.

1. **Energy performance in buildings**

Buildings are responsible for approximately 40% of energy consumption and 36% of CO2 emissions in the EU, making them the single largest energy consumer in Europe.

2. **Renewable energy**

With a view to showing global leadership on renewables, the EU has set an ambitious, binding target of 32% for renewable energy sources in the EU's energy mix by 2030.

3. **Energy efficiency**

Putting energy efficiency first is a key objective in the package, as energy savings are the easiest way of saving money for consumers and for reducing greenhouse gas emissions. The EU has therefore set binding targets of at least 32.5% energy efficiency by 2030, relative to a 'business as usual' scenario.

4. **Governance of the Energy Union**

The package includes a robust governance system for the energy union, under which each Member State is required to establish integrated 10-year national energy and climate plans (NECPs) for 2021 to 2030. Based on a common structure the NECPs outline how EU countries will achieve their respective targets on all dimensions of the energy union, including a longer-term view towards 2050.

Electricity market design elements consist of four dossiers - a new electricity regulation, and amending electricity directive, risk preparedness and a regulation outlining a stronger role for the ACER.

[7] Source: https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en

5. Electricity Regulation

A further part of the package seeks to establish a modern design for the EU electricity market, adapted to the new realities of the market – more flexible, more market-oriented and better placed to integrate a greater share of renewables.

6. Electricity directive

Provides consumers with more tools for active participation in the energy market, introduces measures to improve retail market competition and sets out principles to ensure that aggregators can fulfil their role as intermediaries between customers and the wholesale market.

7. Risk preparedness

Regulation provides:

- new common methods for the identification of possible electricity crisis scenarios at national and regional levels,
- ensure maximum preparedness against electricity crises and effective management thereof through the preparation and publication of risk-preparedness plans by Member States developed on the basis of the electricity crisis scenarios identified,
- help national authorities prevent and manage crisis situations in cooperation with each other in a spirit of solidarity,
- and ensure that markets can work as long as possible.

8. ACER

A regulation outlining a stronger role for the Agency for the Cooperation of Energy Regulators (ACER).

ACER's main role currently is confined to coordination, advising and monitoring. ACER is the body established to provide regulatory oversight for situations which cover more than one Member State. The role of ACER as coordinator of the action of national energy regulators has been preserved and additional competences have been assigned to ACER in those areas where fragmented national decisions of cross-border relevance would lead to problems for the internal Energy Market.

The Clean energy for all Europeans is a significant step towards the implementation of the energy union strategy that is built on five closely related and mutually reinforcing pillars:

1. **Security, solidarity and trust -** diversifying Europe's sources of energy and ensuring energy security through solidarity and cooperation between EU countries
2. **Fully integrated internal energy market** - enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers
3. **Energy efficiency** - improved energy efficiency will reduce dependence on energy imports, lower emissions, and drive jobs and growth
4. **Climate action and decarbonizing the economy** - the EU is committed to a quick ratification of the Paris Agreement and to retaining its leadership in the area of renewable energy
5. **Research, innovation and competitiveness** - supporting research in low-carbon and clean energy technologies and innovation to drive the energy transition and improve competitiveness.

5.2. Capacity Allocation and Congestion Management (CACM)

Commission Regulation (EU) 2015/1222 establishing a guideline on Capacity Allocation and Congestion Management is a key piece of legislation for the single market in electricity. It sets out minimum harmonized rules for single day-ahead and intraday market coupling, including methods to calculate the capacity on cross-border lines. Importantly, CACM provides the legal basis for the designation of nominated electricity market operators (NEMOs), outlines their tasks associated with market coupling and provides a framework for their cooperation with the TSOs.

6. Use of market-based instruments to support transmission system operation

6.1. Opportunities for trading and the use of market measures to support transmission system operation

With the massive development of renewable sources, the possibilities for enabling the consumption and transformation of produced surplus and cheap electricity are also developing for its use in times of its scarcity and high prices.

Among the most important ways of using these surpluses and supporting decarbonization are hydrogen, electricity storage (especially battery) and the development of electromobility.

6.1.1. Hydrogen

Hydrogen produced with renewable energy (or nuclear energy, or fossil fuels using carbon capture and storage (CCS)) can help to decarbonise a range of sectors, including transport, chemicals, and iron and steel industry, where it has proven difficult to reduce emissions. Hydrogen-powered vehicles would help to eliminate CO_2 emissions and improve energy security. Hydrogen can be used with renewables in the electricity system, being one of the few options for storing energy over longer periods (days, weeks, months).

Colors of Hydrogen based on used the energy source [38]

Black or brown hydrogen refers to hydrogen produced by coal gasification. The black and brown colors sometimes indicate the coal type: bituminous (black) and lignite (brown). This process generates significant CO_2 emissions (19 tCO_2/tH_2).

Grey hydrogen refers to hydrogen produced from fossil fuels, mainly by steam gas reforming or coal gasification. It generates significant CO_2 emissions, between 10-19 tons of CO_2 tCO_2/tH_2. Over 95% of the world's hydrogen consumption is grey hydrogen.

Blue hydrogen is produced mainly from natural gas by steam gas reforming, paired CCS. Blue hydrogen has a much lower carbon intensity than grey hydrogen, with estimates ranging from 1-4 tCO_2/tH_2. Although using CCS increases costs, blue hydrogen remains the cheapest "clean" alternative to grey hydrogen.

Green or renewable hydrogen is produced from renewable energy sources like wind and solar through a process known as water electrolysis, where an electrolyzer splits water molecules into oxygen and hydrogen. No CO2 emissions are generated during the production process. Today, green hydrogen costs are significantly more than those of grey hydrogen. It accounts for less than 0.1% of the world's hydrogen production.

Yellow hydrogen refers to green hydrogen produced from solar energy. It does not generate CO2 emissions. Estimates suggest that yellow hydrogen may become the cheapest form of renewable hydrogen in the medium term.

Pink hydrogen is produced by water electrolysis powered by nuclear power, a clean but non-renewable energy source that does not generate CO2 emissions.

Purple hydrogen is produced by water electrolysis using nuclear power and heat.

Red hydrogen is produced by the high-temperature catalytic splitting of water using the heat and steam generated from nuclear plants. This process requires much less electricity than traditional electrolysis.

Turquoise hydrogen is hydrogen produced from natural gas under a process known as methane pyrolysis. In this process, natural gas is decomposed into hydrogen and solid carbon at high temperatures. Currently, turquoise hydrogen is still in the early development stage.

Orange hydrogen refers to emerging processes that produce hydrogen using plastic waste as a feedstock. It may offer a solution to both the clean energy problem and issues surrounding plastic waste disposal. Orange hydrogen remains in the early development stages, with various technologies and production processes, including pyrolysis, microwave catalysis, and photo-reforming, under evaluation.

White hydrogen, also known as natural hydrogen, is naturally generated within the Earth's crust through interactions between water molecules and iron-rich minerals at high temperatures and pressures. As water reacts with these minerals, it releases hydrogen gas. There are no strategies to exploit this hydrogen at present.

6.1.2. Battery storage

Battery storage technologies are essential to incorporate renewable energy (mainly solar generation) into the electricity system with positive financial aspect for all parties (TSOs, DSOs, owners, other consumers). Battery storage systems shall play an important role between green energy supplies and electricity demands. The main aim shall be to store electricity in times of overgeneration and low prices to high demand times with higher prices. This also help to eliminate high peek generation costs and lower the peek prices for customers.

6.1.3. Electrical vehicles

Electric vehicles are the preferred technology to decarbonise road transport, a sector that accounts for around 15% of global energy emissions. Ambitious policies continue to be critical to growth in electric vehicle markets.

There are also visions to use parked and connected EVs as battery storage that can be used in both directions (based on individual EV setting related to minimal battery state).

So, the main point here is related to state of the electricity system, there are basically 2 main ways how EVs could be charged.

First one is for EVs used for transport to work, so then they are charged during the day and e.g. overgeneration from PV generation is used.

Second one is for EVs that are used in fleets that are on the move during the day and charging is possible only out of business hours, so mainly during the night. There is lost the advantage of using solar generation.

6.1.4. Comparison of Battery Electric Vehicle and Hydrogen Fuel Cell Electric Vehicle

There was examined simulation for the difference in operation of Battery Electric Vehicle (BEV) and Hydrogen Fuel Cell Electric Vehicle (HFCEV) used as Postal car that resulted more in favor of BEV - travelled distance that the electric vehicle that runs on fuel cells without refueling turns out to be shorter (approximately 90 km for BEV and 65 km for HFCEV)[39].

So, based on the results of the simulation, so far better BEV for the operation but worst from the transmission system operation as the solar generation cannot be used for charging of this type of EV.

On the other hand, the advantage of using HFCEVs for the transmission system is in the variability of the hydrogen generation in the time and possibility of storing the hydrogen for longer periods until it is needed.

6.2. Short term electricity markets

6.2.1. Day-ahead market

The day-ahead electricity market in the Czech Republic is organized in form of daily auction ant it is based on the implicit allocation of cross-border capacities (Market Coupling - MC). Day-ahead market started in cooperation with the Slovakia, later Hungary was connected and finally in 2014 Romanian market was connected. This cooperation was known under the name 4M MC.

CACM goal was finished in June 2021 when 4M MC region was connected with the MRC region (Multi-Regional Coupling – countries from Southern, Western and Northern Europe) and pan European cross zonal day-ahead electricity market was created - Single Day-ahead Coupling (SDAC).

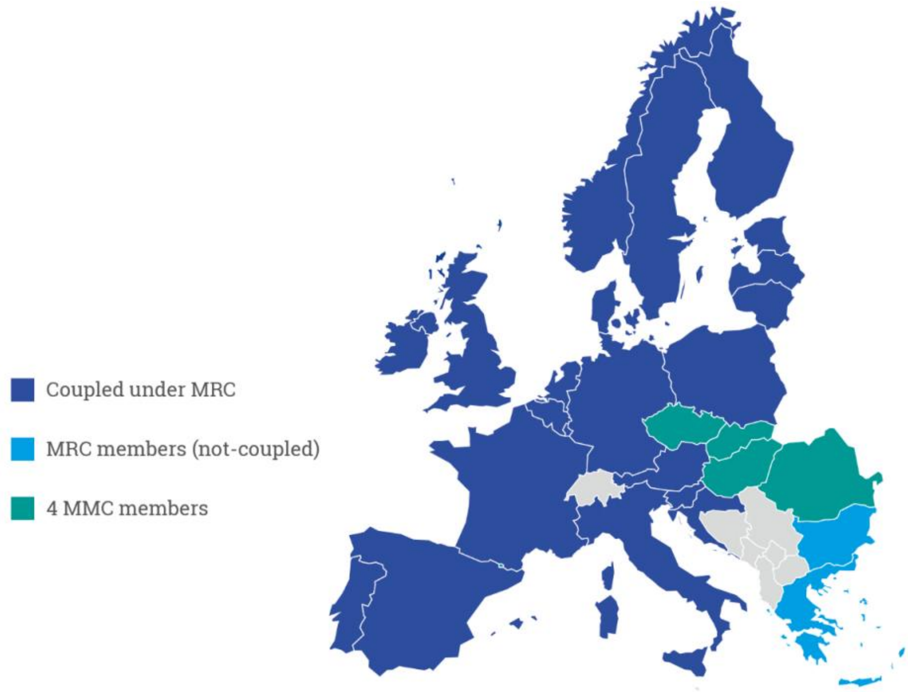

Figure 4: MRC and 4M MC regions for day-ahead trading until June 2021

Figure 5: SDAC countries for day-ahead trading since June 2021[8]

Through the day-ahead market, market participants may meet their needs regarding the purchase or sale of electricity for the next day in all trade areas without the need to explicitly acquire transmission capacity.

Due to the implemented PCR solution (Price Coupling Regions), market participants may use a broader bid structure, including also block bids and their combinations and also regionally specific products (as PUN in Italy (Prezzo Unico Nazionale) or MIC in Spain and Portugal (Minimum Income Condition)). This allows them to create different production and consumption scenarios at different price levels, and thus enhance the possibility to implement their business strategy on the day-ahead market. At the same time, traders can submit an unlimited number of bids.

[8] Source: https://www.nemo-committee.eu/sdac

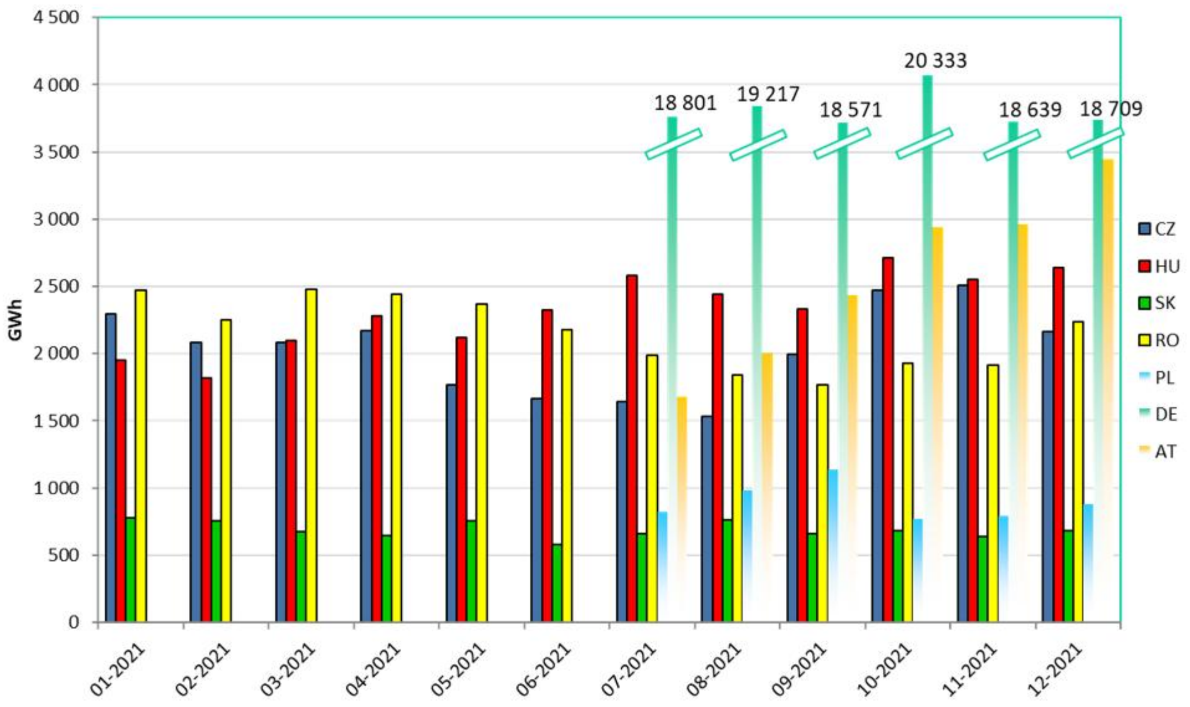

Figure 6: Monthly volumes of electricity traded within 4M MC and our neighboring countries in SDAC after its creation in 2021

6.2.2. Intraday market

The intraday electricity market allows traders to offer or demand electricity anonymously on the basis of continuous matching during delivery day until the limit time of 60 minutes before the start of the delivery hour.

The local intraday electricity market serves as a reliable indicator of the state of the transmission system. And also, it plays an important role in preventing and resolving emergency situations in the power system.

This type of trading gives market participants opportunities to react to many different situations on the market, e.g., the development of their consumption estimations or changes in the production of intermittent sources. Although it is an anonymous market, it provides comprehensive market information. The submitted bids reflect actual market prices, market liquidity, and real-time changes in prices and volumes. This summary information changes during the time, the difference between the price of the offer for sale and the purchase determines the spread. Thus, market participants are at any time able to assess their potential in the electricity market. This includes assessing the actual prices and the offered volumes of electricity, whether it is possible to generate additional trading profits or to sell or buy the necessary electricity to avoid imbalance and consequently the financial damage resulting therefrom. The development of traded quantities and prices on the intraday electricity market can also act as an indicator of the situation in the power system in cooperation with, for example, the system imbalance published on the TSO's website. Examples of such conditions may be inaccurate predictions of solar power generation, when the production surplus could lead to significant price drops, and vice versa. Mainly at lower-than-expected production, there could be a significant increase in prices and quantities, as the market is reacting on the market participants that are trying to fulfill the planned production by purchasing on the intraday market. Other examples might be public holiday or weather developments that could significantly affect electricity consumption, and last but not least, an unexpected system power outage may occur.

The importance of the intraday market in the Czech Republic has further increased in connection with its integration with other European intraday electricity markets on 19 November 2019. The integration of the OTE intraday market took place on 3 out of 4 cross-border profiles - with Germany, Austria, and Poland. The cross-border trading remained unchanged for the Czech-Slovak border. A major change was the shift from explicit trading of cross-border capacities to the implicit trading. Explicit trading means that cross-border capacity and electricity are traded separately, while within the implicit cross-border capacity trading is cross-border capacity acquired together with electricity if the cross-border bids are matched. Another difference between explicit and implicit trading is that explicit trading works on the principle of bilateral electricity contracts. Within the implicit continuous trading, traders can anonymously trade electricity from all countries where the transmission capacity is available from/to the Czech Republic.

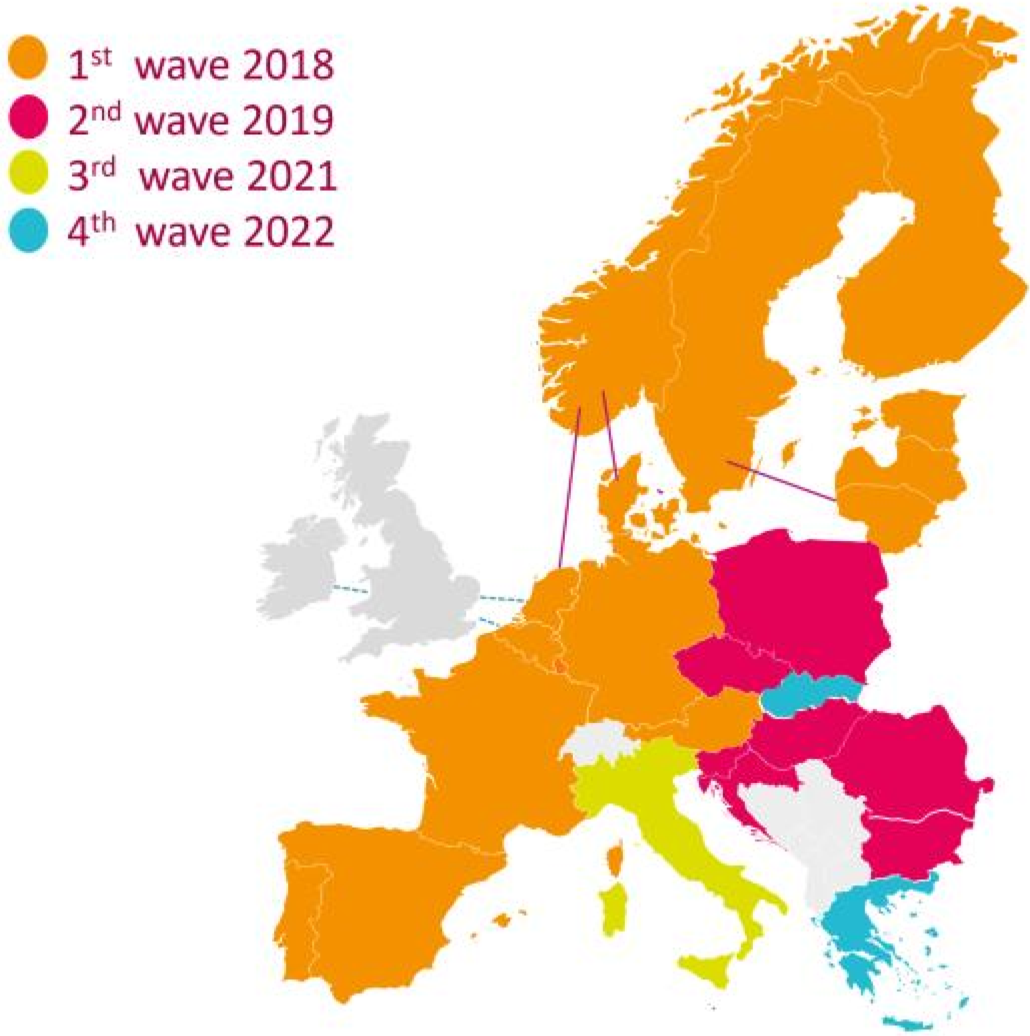

Figure 7: Map of SIDC countries and phases of expansion, also referred to as "waves" [9]

[9] Source: https://www.nemo-committee.eu/sidc

7. Market tools used to ensure safe operation

The intraday electricity market has an increasingly important role within the electricity market. For market participants, this is the last option where they can, even shortly before the delivery date, respond to the current situation in the electricity grid or in their production, to buy or sell electricity. This article introduces real life examples of the contribution of the intraday market towards the prevention and resolution of emergency situations in the electricity system. This article also shows the positive contribution of the integration of the intraday electricity market into the Single Intraday Electricity Market in Europe (SIDC).

7.1. Influence of German wind generation on Czech DAM

Trading on the day-ahead market is strongly associated with the need for a good prediction of renewables. In the Czech Republic, it is mainly the production of solar power plants, but due to the close contact with the German market, it becomes necessary for traders to predict production in the German wind if they want to succeed on the market. Given the considerable correlation of prices on the German day-ahead market, it is clear that market participants are receiving predictive model results similar to those in Western Europe. We can also demonstrate this from the example in September 2018, when after about 3 months there was a higher production of German wind power plants. Limited production had a significant effect on prices, which is also apparent from average prices in individual months, when it was 57.72 EUR/MWh in August and 55.85 EUR/MWh in September. Even the daily average prices over the weekends were not as significantly different from the prices on working days as it is usual.

Wind started to be significant during the weekend September 22 and 23 when the baseload price fall to 31,88 EUR/MWh on Saturday and 43,52 EUR /MWh on Sunday.

Predictions for the next days that were available online are below also with the CZ DAM baseload prices.

- Mo 24/9 - expected wind generation = 47% Pins – CZ Baseload = 39,11 EUR/MWh
- Tue 25/9 - expected wind generation = 13% Pins – CZ Baseload = 65,45 EUR /MWh
- We 26/9 - expected wind generation = 33% Pins – CZ Baseload = 51,43 EUR /MWh
- Thu 27/9 - expected wind generation = 31% Pins – CZ Baseload = 53,41 EUR /MWh

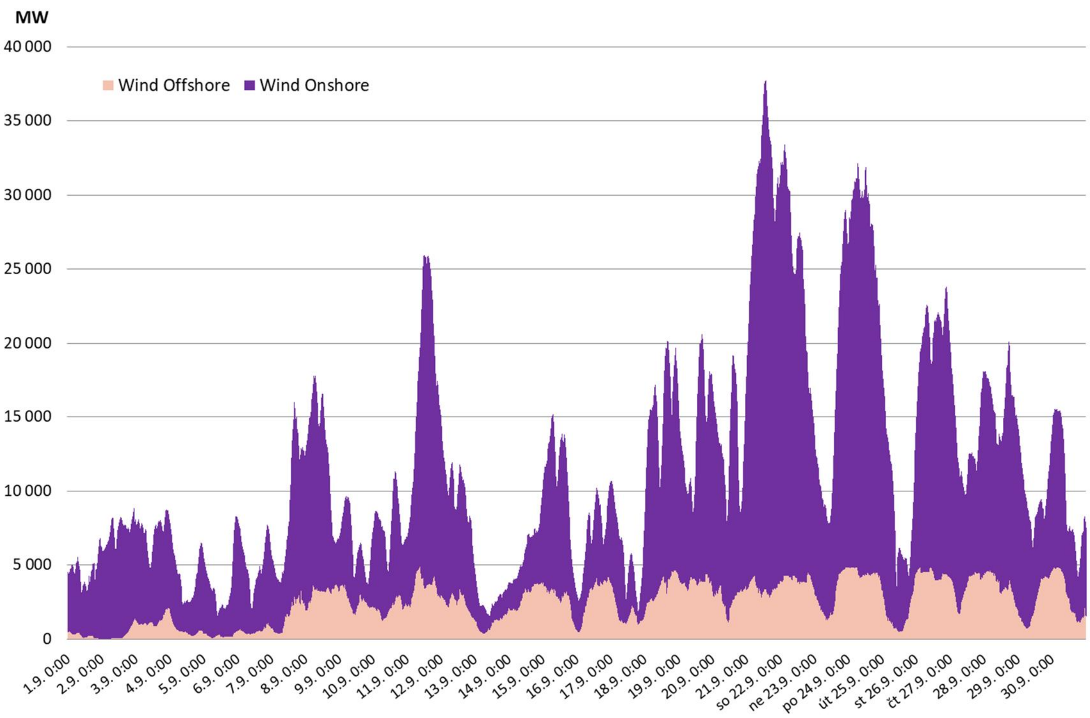

Figure 8: German onshore and offshore wind generation during September

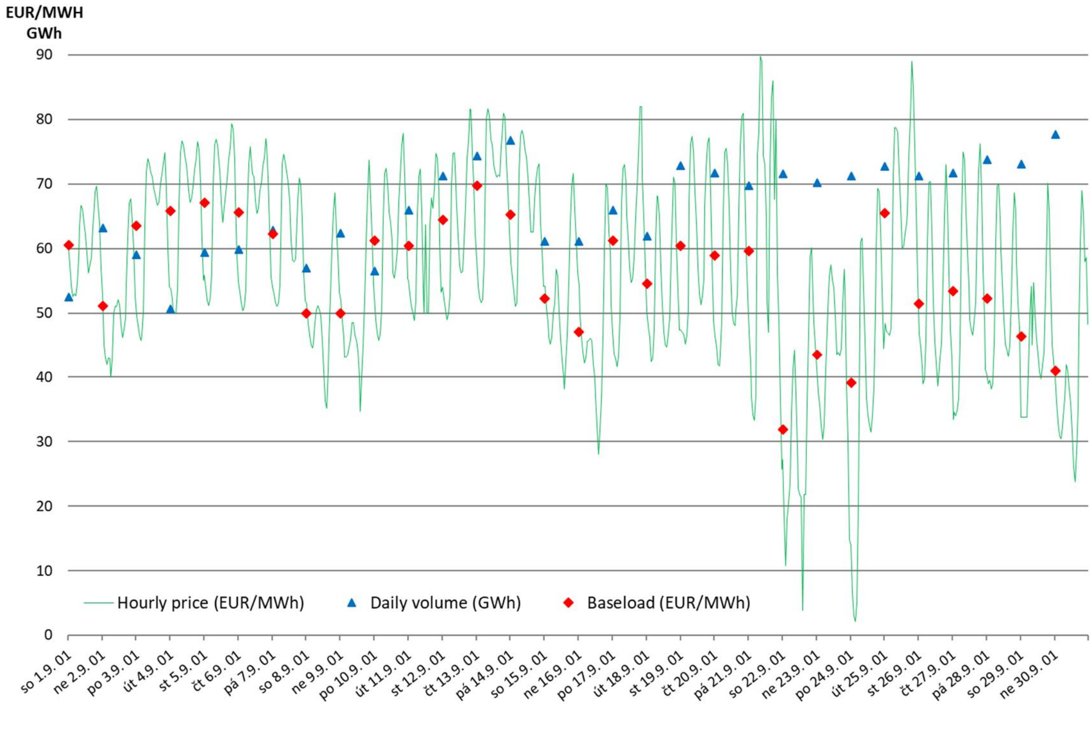

Figure 9: Results of Czech day-ahead market during September

If we compare the predicted and actual values of wind power production in Germany, it is clear that values are similar and that the resulting day-ahead market prices also correspond to them. Fig.6.3 also shows the reason for the higher price of baseload on Sunday (23/9) when there was a significant drop in wind production, but since it was a non-working day the increase in prices is not so high. Even more striking contrast is between Monday and Tuesday. Wind production on Monday (24/9) was about 26 TWh, which corresponds to the baseload price of 39.11 EUR/MWh. Compared to Tuesday (25/9) when the total wind production was less than 10 TWh and it is corresponding with a high baseload price of 65.45 EUR/MWh. Even in the next two days, it is obvious that wind production was in line with the expected state and the resulting day-ahead market prices correspond accordingly.

It is also evident that the price curve retains its classic shape with two maxima, but their absolute values correspond to wind power production. If we look at the details too, it is also incredible that the peak generation was expected on Saturday (22/9) at 14th delivery hour.

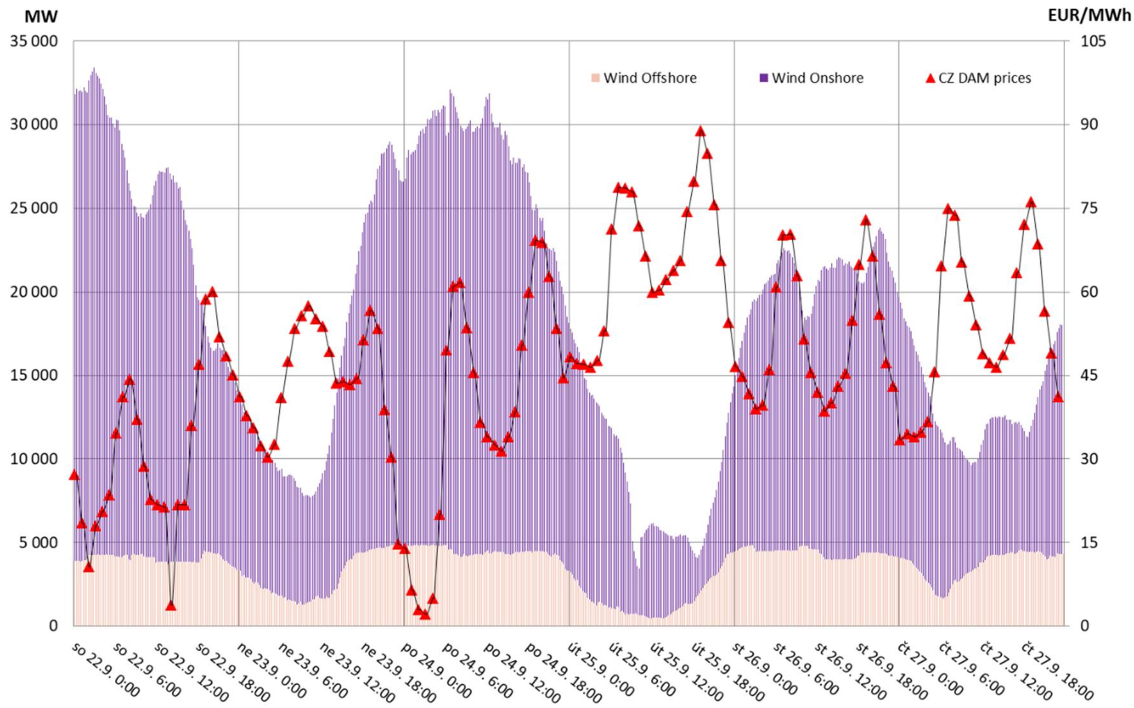

Figure 10: German wind generation and its influence to Czech DAM prices

7.2. Market measures for resolving non-standard conditions in the electricity system

7.2.1. Outage of biggest unit in the transmission system

There is a rising the influence of IM in case of solving exceptional situations in the transmission system. The IM is creating price signals that results in “price spreads” between demand and supply. Typical examples of a major operational event were the failure of some power plants in the electricity grid, on 14 September 2018 and on 22 January 2020. The first example shows the impact of a power outage of 400 MW. The first 200 MW unit was shut down after 5 am and the second 200 MW unit was shut down at about 7:25 am. This outage data is available on transparency platforms (see also [5] and [6]), where producers have to publish information on outages and planned outages of their sources bigger than 50 MW[10]. Fig. 6.4 illustrates that due to an outage, it was necessary to activate significant volume of Ancillary service for 6 hours. In the concerned hours, the volume of traded electricity decreased as a result of the relatively large supply constraints in the power system, where traders tried to use their electricity primarily to reduce their imbalance. It caused maximum trading prices to exceed 100 EUR/MWh during the outage. However, by comparing prices on the market with the price of the imbalance in given hours, it shows that buying electricity for 173 EUR/MWh at 12th delivery hour was cheaper for the buyer than if it was settled by the imbalance price, which was 197 EUR/MWh at that hour. The limited volume of electricity available during the concerned hours was also affected by the fact that IM was not yet connected to foreign markets at that time, and thus the availability of electricity on the intraday market was limited by the size of the Czech market. The emergency situation in the power system was stabilized at 12th delivery hour. This was subsequently reflected in the intraday market at 13th delivery hour when an already significant volume of electricity was traded.

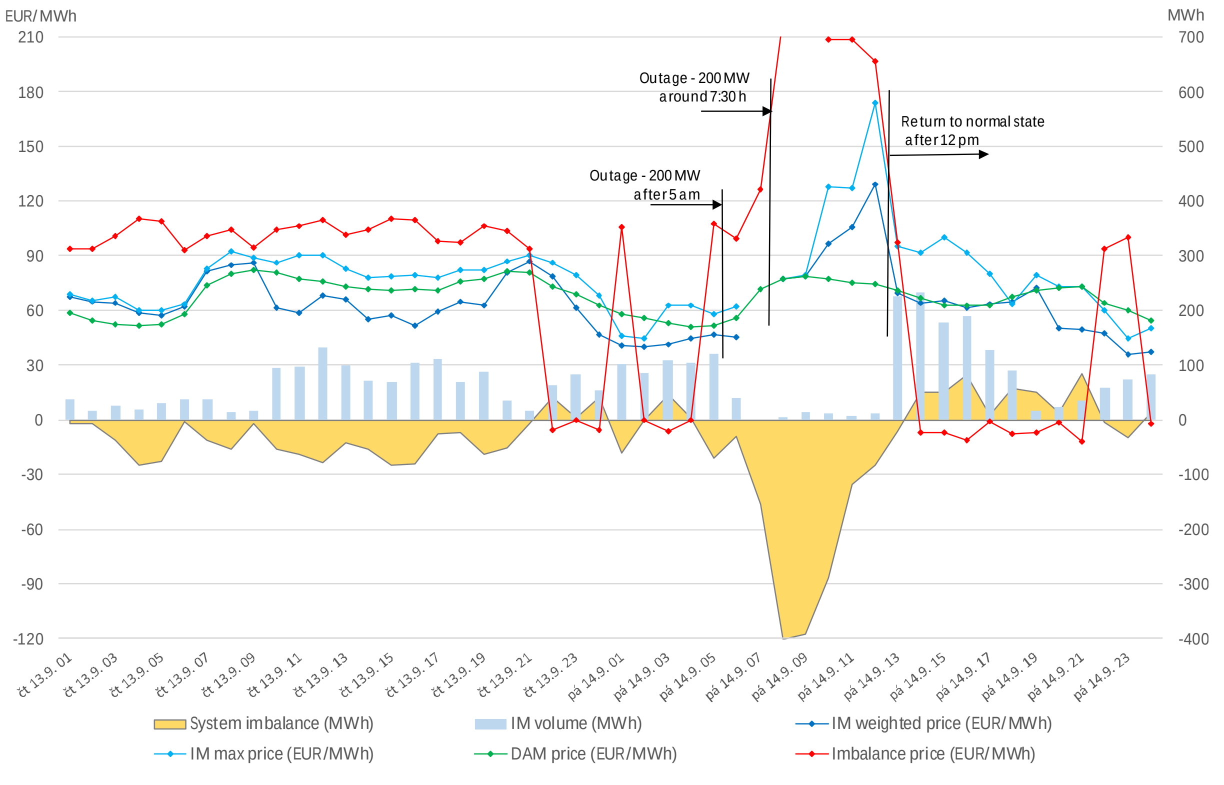

Figure 11: The situation in the power system and on the market on 13.9. and 14.9.2018

[10] See REMIT regulation - Regulation (EU) No 1227/2011 of the European Parliament and of the Council of 25 October 2011 on wholesale energy market integrity and transparency.

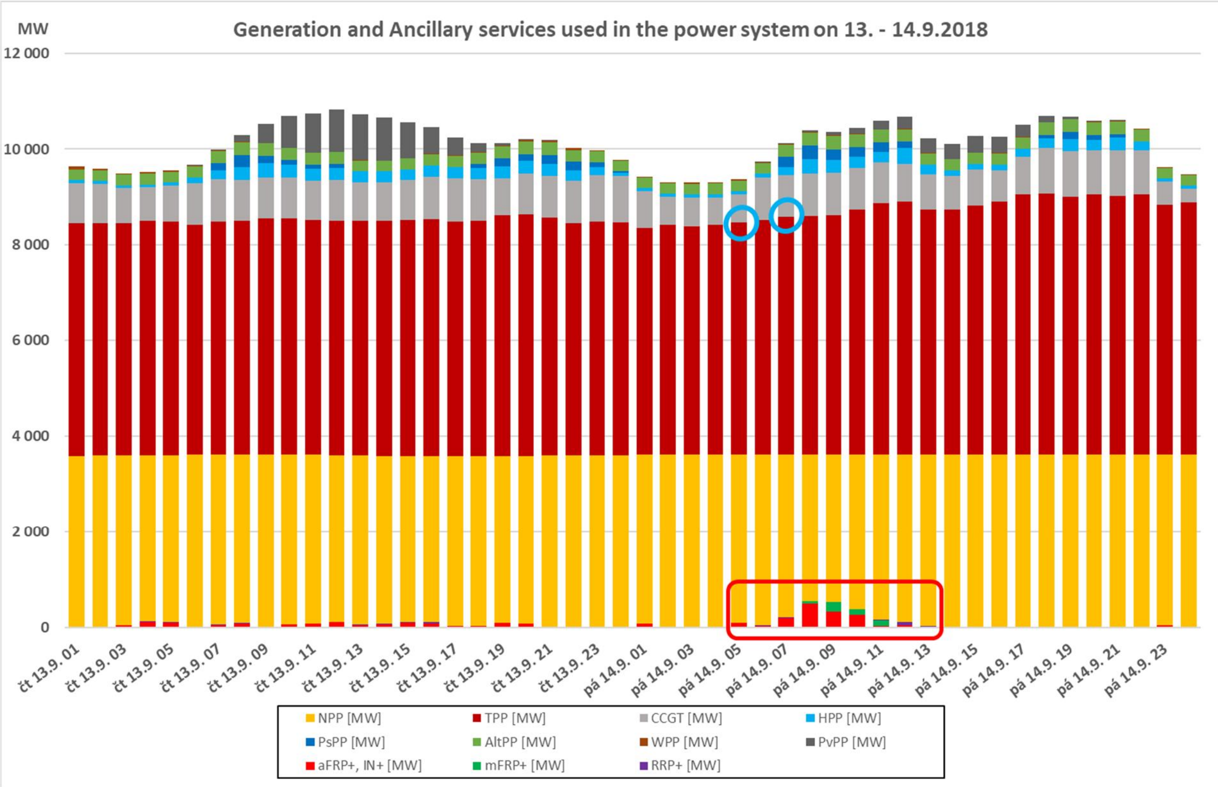

Figure 12: Generation and Ancillary services used in the power system on 13. - 14.9.2018

It is interesting to compare it with a similar situation, on 22 January 2020, when the positive impact of IM integration with foreign markets was significantly reflected. Fig. 6.5 shows that although the lost in production on this day was higher (the first outage of 500 MW at 14h for and then at around 16:45 another outage of 1,030 MW) than in the first example above (on 14/9/2019), the market reaction and trading on the intraday market was considerably different. The outage of the first unit was compensated by the activation of other power plants or other regulatory mechanisms on the TSO side. After the second outage, International regulation energy (RE) was also activated to support local activation of Ancillary services. At the same time, traders managed to purchase a large part of the lost electricity volume on the intraday market already at the first tradable hours, i.e. 19^{th} and 20^{th} delivery hour. Subsequently, the system imbalance at 20^{th} delivery hour was close to zero (-38 MWh) and at 21^{st} delivery hour was system imbalance in surplus of 127 MWh. So, it can be concluded that, in particular, power plants that were in counter-imbalance in the previous hours, thus helping to reduce the volume of activated Ancillary services, did not anticipate such a rapid return to the "normal" state and contributed to re-regulation of the system to a surplus.

After the outage of the second unit at 17^{th} delivery hour, the system imbalance was -208 MWh and the imbalance price was calculated to 397 EUR/MWh, at 18^{th} delivery hour the system imbalance rose to -1,417 MWh and the imbalance price was close to the price of the previous hour i.e. 402 EUR/MWh. The system imbalance was lowered to -648 MWh at 19^{th} delivery hour and the imbalance price also decreased to 333 EUR/MWh and as was mentioned before, at 20^{th} delivery hour the imbalance was only -38 MWh with the imbalance price 102 EUR/MWh.

Trading after the outage was following - within 15 minutes to the end of the trading on 19^{th} delivery hour, 175 trades were concluded with a total volume of 971 MWh, with an average price of 117 EUR/MWh and a maximum price of 130 EUR/MWh. Trading on 20^{th} delivery hour also increased after the outage, 1,628 MWh in 289 trades (out of a total 2,336 MWh traded) were traded with an average price of 91 EUR/MWh and a maximum price of 151 EUR/MWh. Same situation was for 21^{st} trading hour, when was traded 1,848 MWh in 384 trades (out of a total 1,941 MWh traded) with an average price of 77 EUR/MWh and a maximum price of 120 EUR/MWh[11].

When comparing these two presented situations in the system and their impact on trading and the associated costs, it is clear that the interconnected intraday market has significantly helped to resolve non-standard state in the power system. The implementation of the SIDC and its principles resulting in the international interconnection of the intraday electricity markets have helped to ensure a sufficient amount of tradable electricity for market participants. Specifically, a much larger outage with a double system imbalance, as well as a double price for imbalance, resulted in lower maximum and average trading prices, while satisfying the demand for missing electricity.

[11] Source: OTE, a.s., public website - https://www.ote-cr.cz/cs/kratkodobe-trhy/elektrina/vnitrodenni-trh

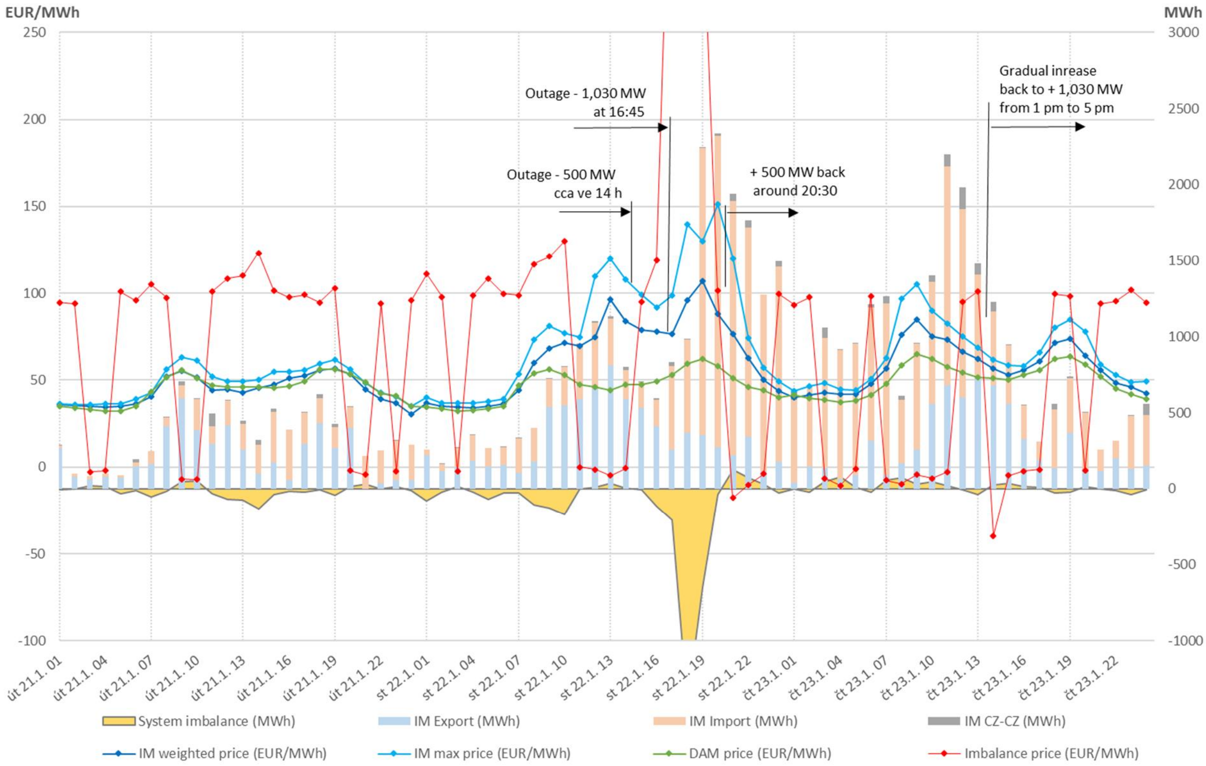

Figure 13: The situation in the power system and on the market on 21.1.-23.1.2020

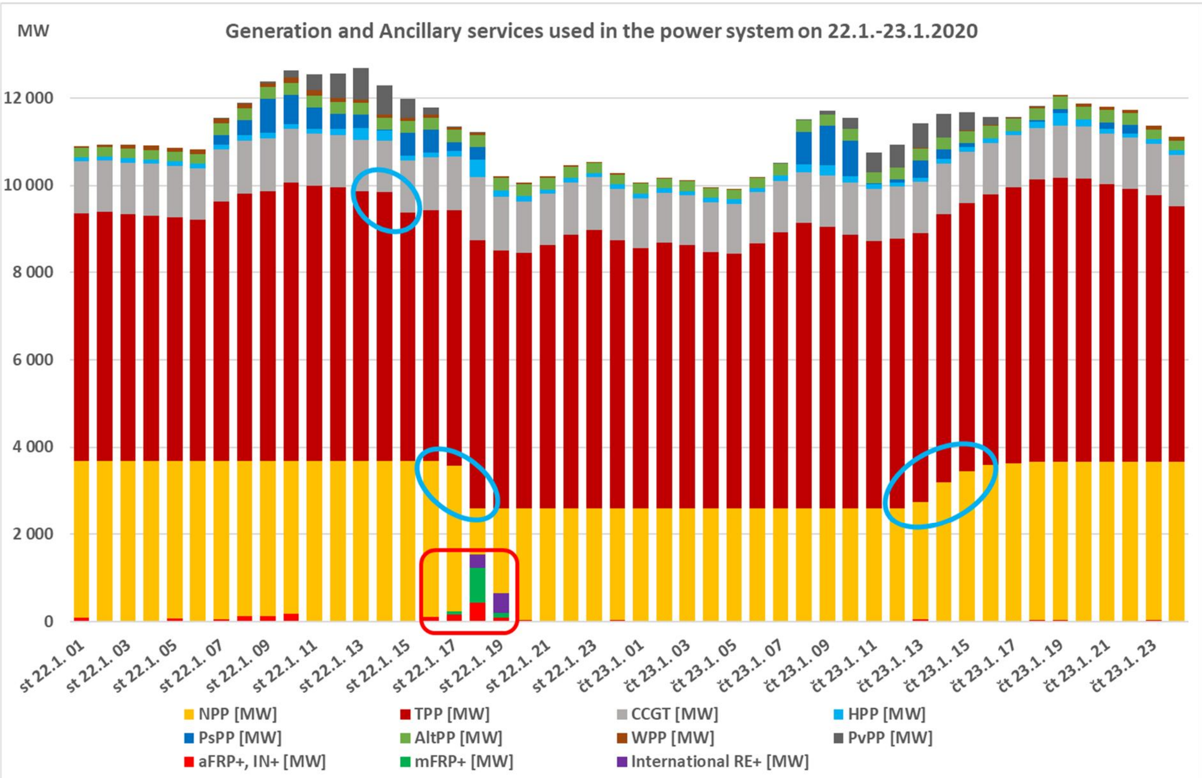

Figure 14: Generation and Ancillary services used in the power system on 22.1.-23.1.2020

7.2.2. Outage of biggest unit in the transmission system with low cross border capacity in June 2021

Figure 15 shows the outage of 1,030 MW unit after the fall of the output line V52 because of the strong wind at around 23:30.

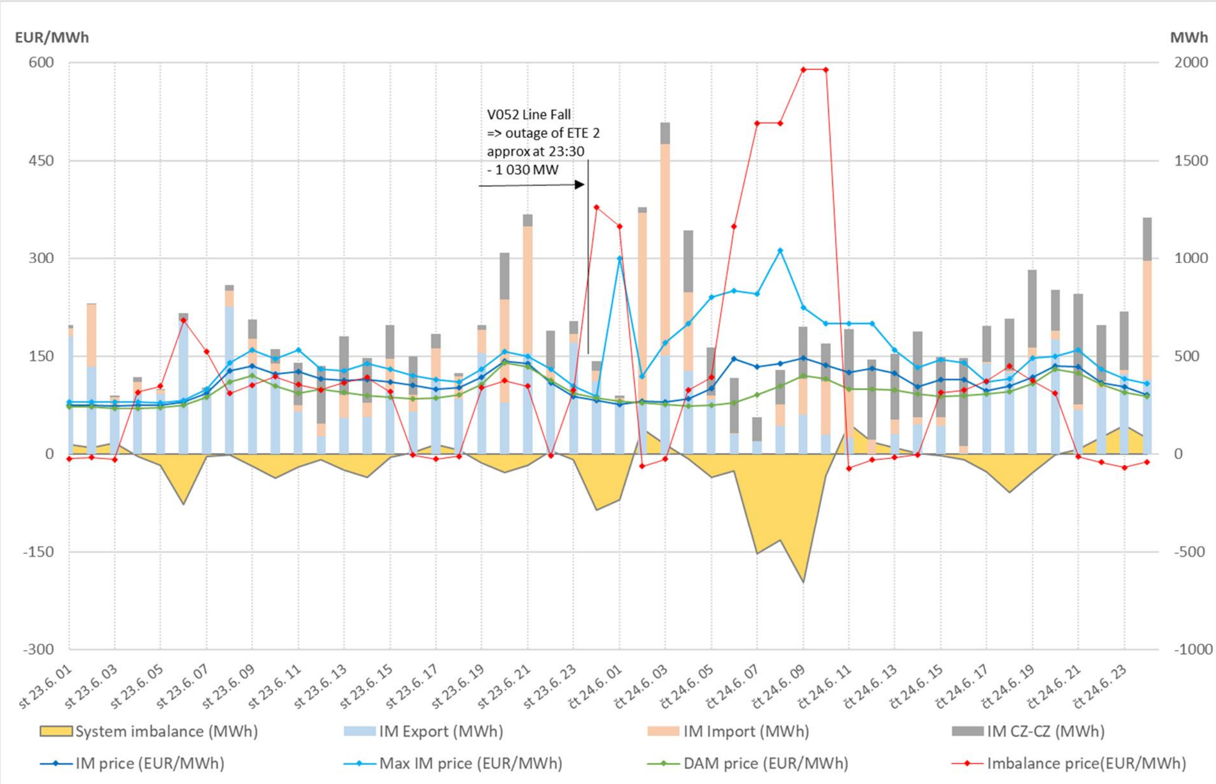

Figure 15: The situation in the power system and on the market on 23. - 24.6.2021

So, the first two impacted delivery hours was covered by activation of 300 MWh, resp. 230 MWh of ancillary services activated by TSO (see Figure 16) with combination of the activation of other units, the system imbalance was -285 MWh, resp. -230 MWh.

The first tradable hour on the market was 2nd delivery hour of June 24 where was bought 972 MWh of imported power (pink column), so the System Imbalance was positive. Positive imbalance was also in 3rd delivery hour of June 24 where was bought 1,083 MWh of imported power was traded. Since 4th delivery hour there was lack of cross border capacities for the rest of the day. There was traded only 399 MWh from abroad and increased the volume of local trades to 318 MWh (grey column). In the next 4 hours there was nearly no import from the market. As the missing power was not covered by the trading, there was activated 516 MWh of AnS during 7th delivery hour, 447 MWh of AnS during 8th delivery hour and 671 MWh of AnS during 9th delivery hour. Imbalance price raised up to 600 EUR/MWh in these hours even the max prices on IM market was less than 300 MWh. But the low liquidity of local market did not allow to lower the imbalance of impacted market participant.

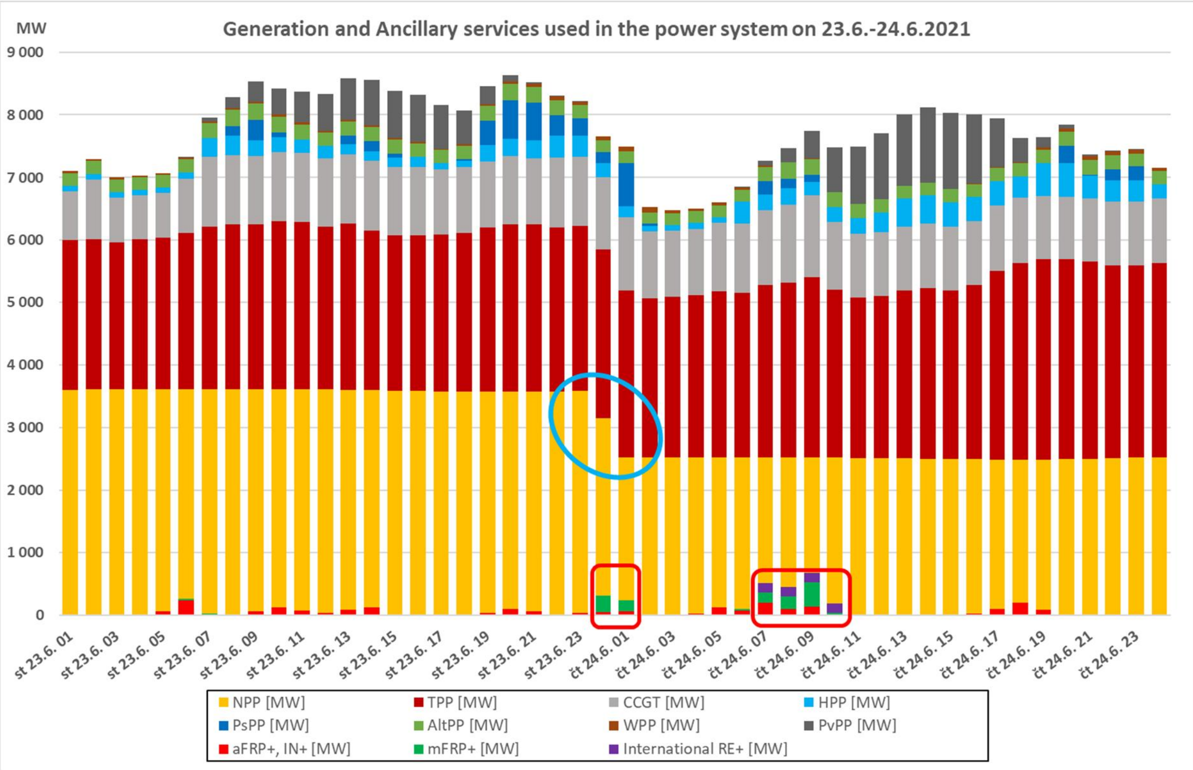

Figure 16: Generation and Ancillary services used in the power system on 23.-24.6.2021

7.2.3. Outage of biggest unit in the transmission system in June 2022

Figure 17 shows the situation in the power system around the outage of 1,030 MW unit at around 16:40 on Wednesday 29.6.2022.

So, there was three impacted delivery hours where the activation of AnS was necessary. There was activation of 140 MWh of Ancillary Services by TSO and with combination of the activation of other units (mainly Hydro Power Plants and Pumped-Storage Power Plant), it results in the System Imbalance -153 MWh (see also Figure 18) in 17th delivery hour. During the 18th delivery hour was activated 618 MWh of AnS and System Imbalance was -685 MWh and in 19th delivery hour, there was activated 255 MWh of Ancillary Services and total System Imbalance in this hour was -278 MWh. Next delivery hours were not directly impacted by this outage in the sense of activation of Ancillary Services by TSO.

The imbalance price raised in these hours between 1.200 and 1.600 EUR/MWh (red line).

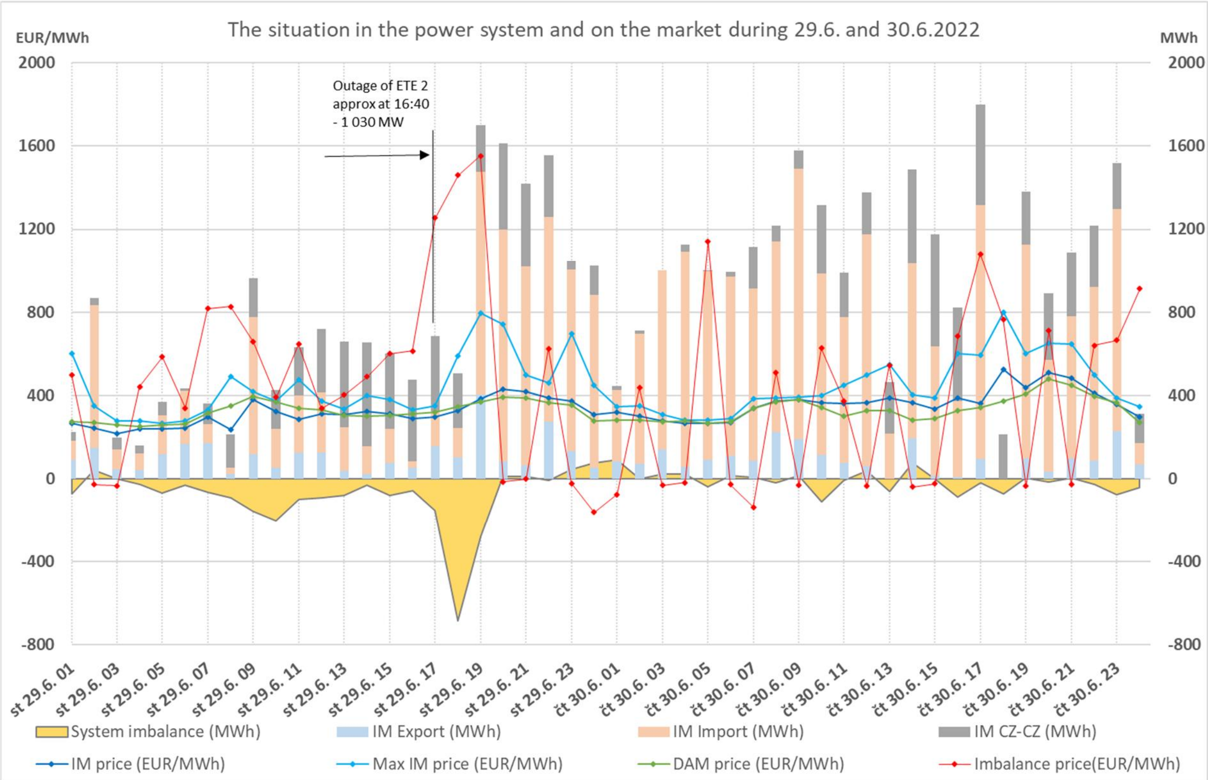

Figure 17: The situation in the power system and on the market on 29.- 30. 6.2022

The first tradable hour on the market was 19th delivery hour of June 29 where was bought 1.070 MWh of imported power (pink column), 226 MWh was traded locally (grey column) and 405 MWh was exported (blue column – traded before the outage), so the saldo of IM was 890 MWh that helps limited the system imbalance during this delivery hour.

For the 20th delivery hour, there was bought 1.116 MWh of imported power, and the exported power was only 84 MWh, so the System Imbalance was +10 MWh with price 14 EUR/MWh, compared with price of previous delivery hour that was 1.554 EUR/MWh, the positive impact of intraday trading is clear.

As there were enough cross-border capacities also during following delivery hours, there was traded more than 800 MWh of imported power in 12 out of 14 delivery hours. Sufficient liquidity of the market based on the availability of the cross-border capacities also enable to maintain the average weighted price on IM market (dark blue line) very close to day-head price (green line), even the maximum price of individual trades raised up to double during the first hours after the outage (light blue line).

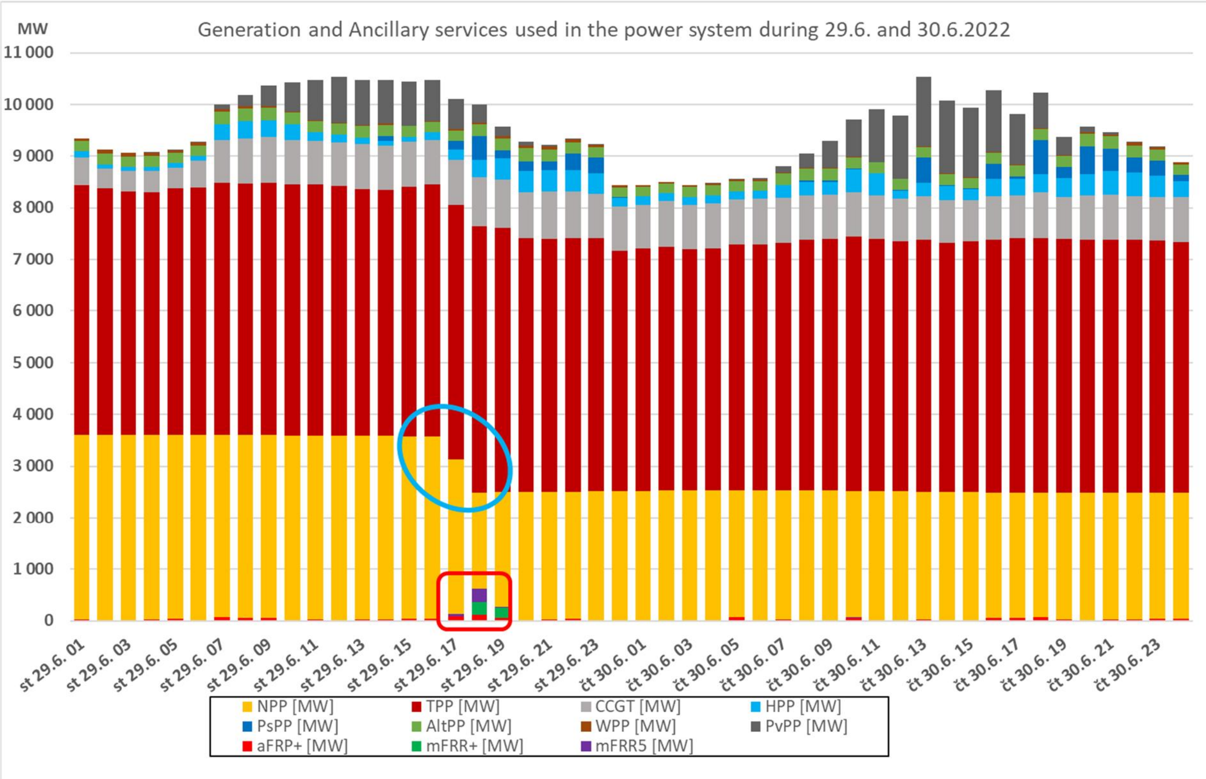

Figure 18: Generation and Ancillary services used in the power system on 29.- 30. 6.2022

7.2.4. Outage of biggest unit in the transmission system in June 2023

Figure 19 shows the situation in the power system around the outage of 1,030 MW unit at around 6:40 on Saturday 17.6.2023.

So, there was only two impacted delivery hours where the activation of AnS was necessary. There was activation of 92 MWh of Ancillary Services by TSO and with combination of the activation of other units (mainly Pumped-Storage Power Plant in the first two hours followed with activation of 880 MW CCPP), it results in the System Imbalance -499 MWh (see also Figure 20) in 7th delivery hour. During the 8th delivery hour was activated 8 MWh of AnS and System Imbalance was -212 MWh. Next delivery hours were not directly impacted by this outage in the sense of activation of Ancillary Services by TSO.

The imbalance price was in these hours 465 EUR/MWh and 290 EUR/MWh (red line).

The first tradable hour on the market was 9th delivery hour of June 17 where was bought 420 MWh of imported power (pink column), 48 MWh was traded locally (grey column) and 375 MWh was exported (blue column – traded before the outage), so the balance of IM was only 93 MWh that helps limited the system imbalance during this delivery hour. There was traded lower amount of imported power during next two hours, but since 12th delivery hour until end of the day, average amount of 1,060 MWh of imported power was traded.

As there are not high amounts of the local trades during the delivery day 17th June after the outage, we can declare that there were no problems with cross-border capacities.

This example shows that the intraday trading was not immediately used for solving the outage mainly because of activation of CCPP, but afterwards there was period of 24 consecutive hours when was possible to trade huge amounts of import power (average amount was 924 MWh).

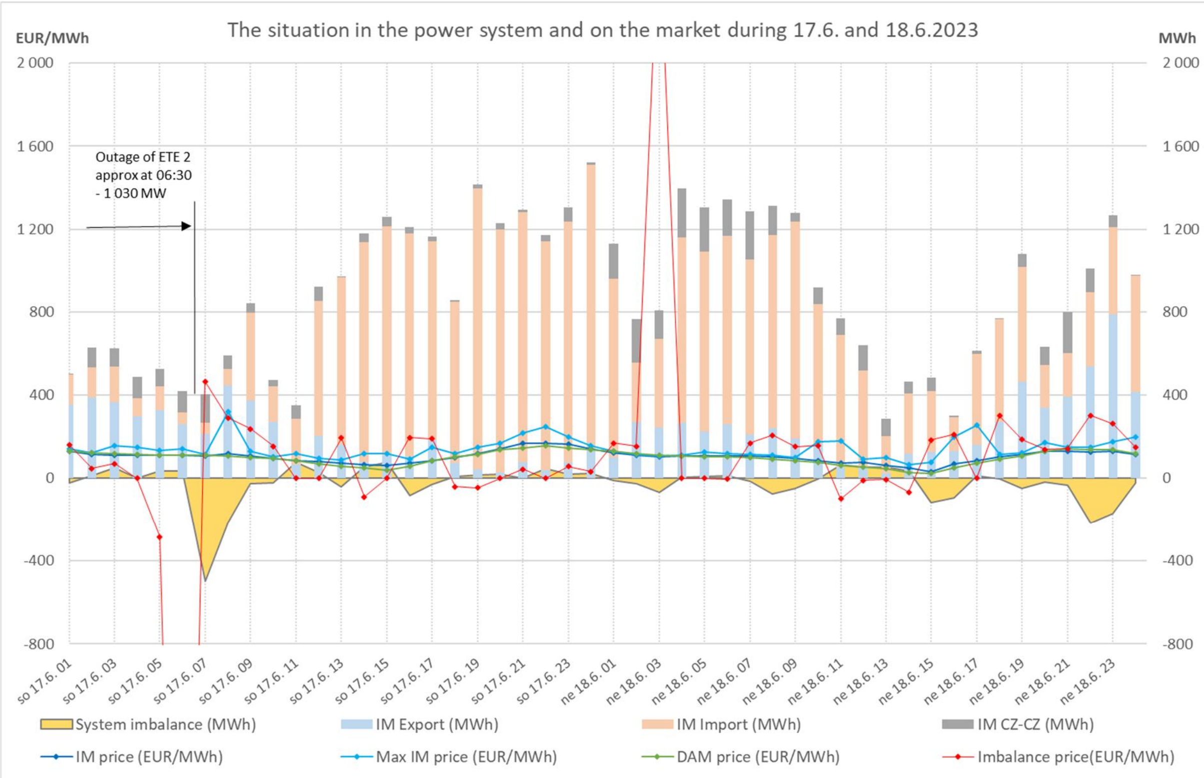

Figure 19: The situation in the power system and on the market on 17.-18.6.2023

For the 20th delivery hour, there was bought 1.116 MWh of imported power, and the exported power was only 84 MWh, so the System Imbalance was +10 MWh with price 14 EUR/MWh, compared with price of previous delivery hour that was 1.554 EUR/MWh, the positive impact of intraday trading is clear.

As there were enough cross-border capacities also during following delivery hours, there was traded more than 800 MWh of imported power in 12 out of 14 delivery hours. Sufficient liquidity of the market based on the availability of the cross-border capacities also enable to maintain the average weighted price on IM market (dark blue line) very close to day-head price (green line), even though the maximum price of individual trades raised up to double during the first hour after the outage (light blue line).

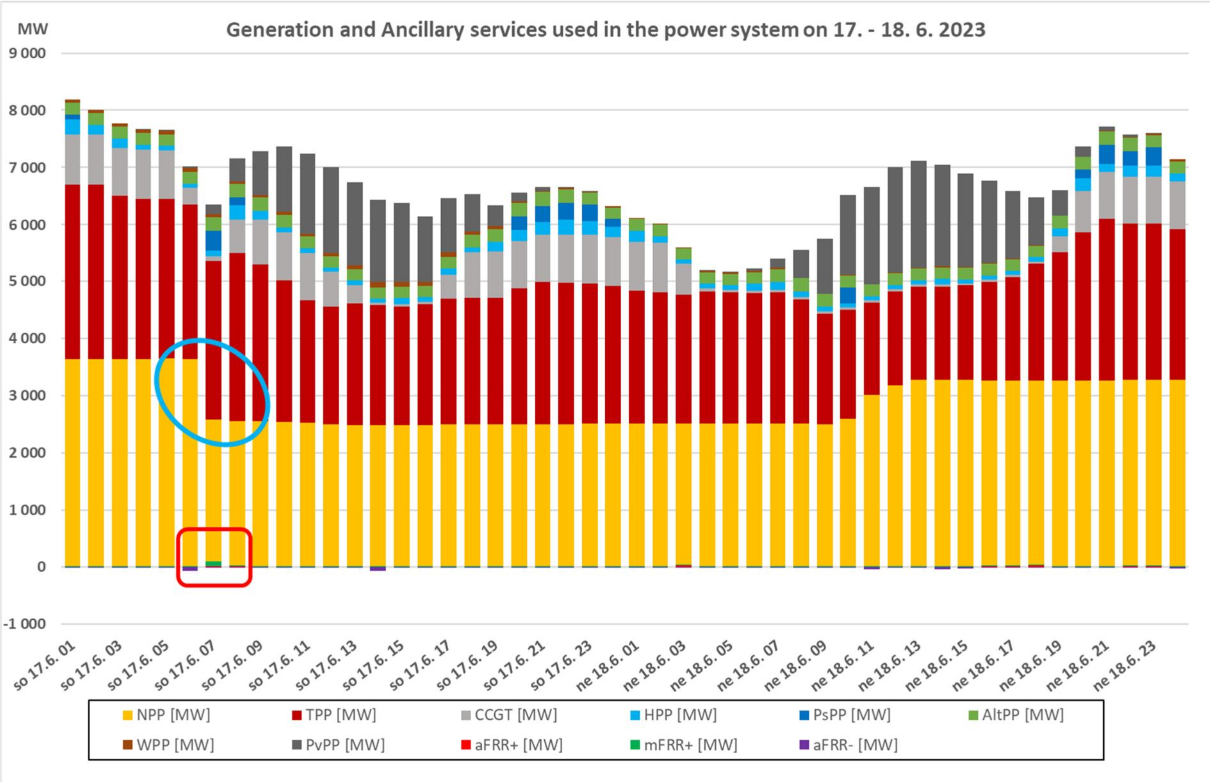

Figure 20: Generation and Ancillary services used in the power system on 17.-18.6.2023

7.2.5. Outage of biggest unit in the transmission system in August 2023

Figure 21 shows the situation in the power system around the outage of 1,030 MW unit at around 5:55 on Sunday 6.8.2023, but also Figure 22 shows that this was most probably planned outage, because before the outage there was 3 hours with reduced output of this power plant by approximately 400 MW.

So, there was only one impacted delivery hour where the activation of AnS was necessary. There was activation of 173 MWh of Ancillary Services by TSO and with combination of the activation of other units (mainly Hydro Power Plants and Coal Fired PPs), it results in the System Imbalance -472 MWh (see also Figure 22) in 6th delivery hour. During the 7th delivery hour was activated 11 MWh of AnS and System Imbalance was -119 MWh and in 8th delivery hour, total System Imbalance in this hour was +122 MWh. Next delivery hours were mostly with positive System Imbalance so with no impact of this outage in the sense of activation of Ancillary Services by TSO.

The imbalance price raised to 1.103 EUR/MWh in 5th delivery hour and decreased to 842 EUR/MWh in 6th delivery hour and to 650 EUR/MWh in 7th delivery hour (red line).

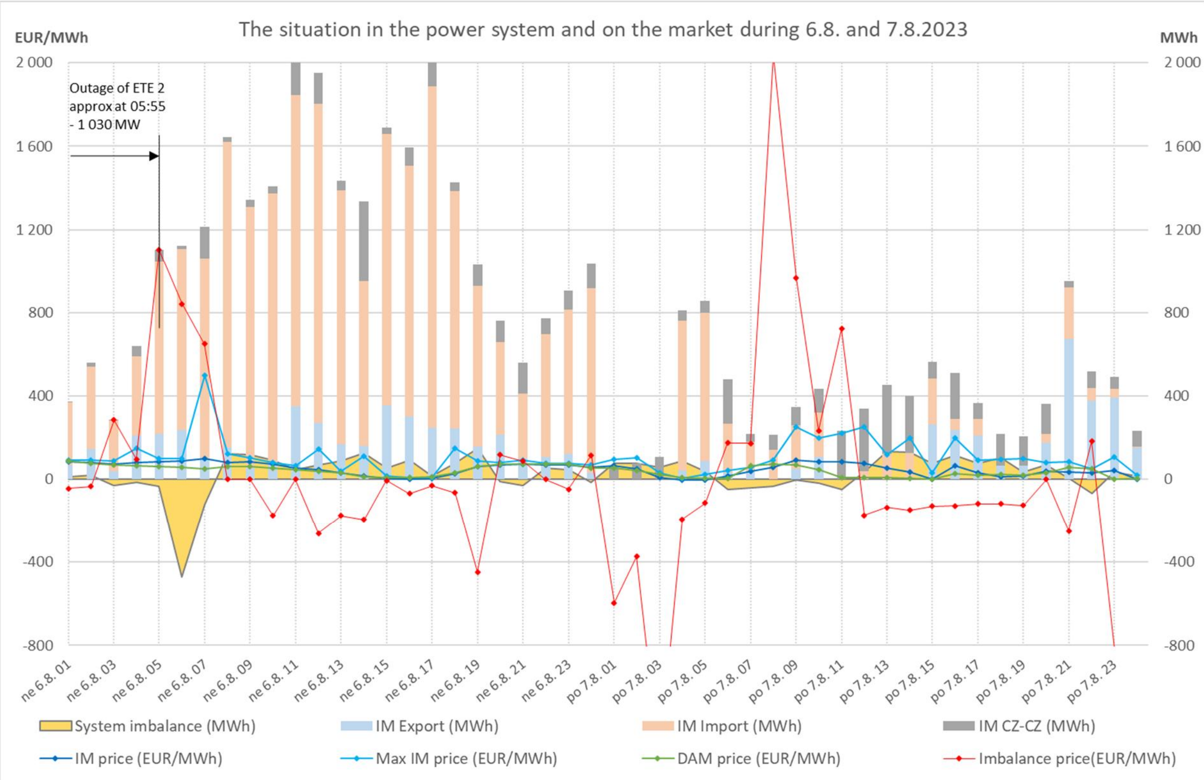

Figure 21: The situation in the power system and on the market on 6.-7.8.2023

The first tradable hour on the market was 8th delivery hour of August 6 where was bought 1.420 MWh of imported power (pink column), 21 MWh was traded locally (grey column) and 151 MWh was exported (blue column – traded before the outage), so the balance of IM was 1.290 MWh that helps limited the system imbalance during this delivery hour. But as was mentioned before that the issue with PP was known, there are higher numbers of import since 4th delivery hour.

As there were enough cross-border capacities also during delivery hours of August 6, the average traded volume was more than 1.000 MWh of imported power in 20 delivery hours, with peak value 1.640 MWh. Sufficient liquidity of the market based on the availability of the cross-border capacities also enable to maintain the average weighted price on IM market (dark blue line) very close to day-head price (green line), even though the maximum price of individual trades raised up to 5 times more during the 7th delivery hour (light blue line).

On the contrary, the first 3 hours of the day of delivery August 7 there was no cross-border trade at all.

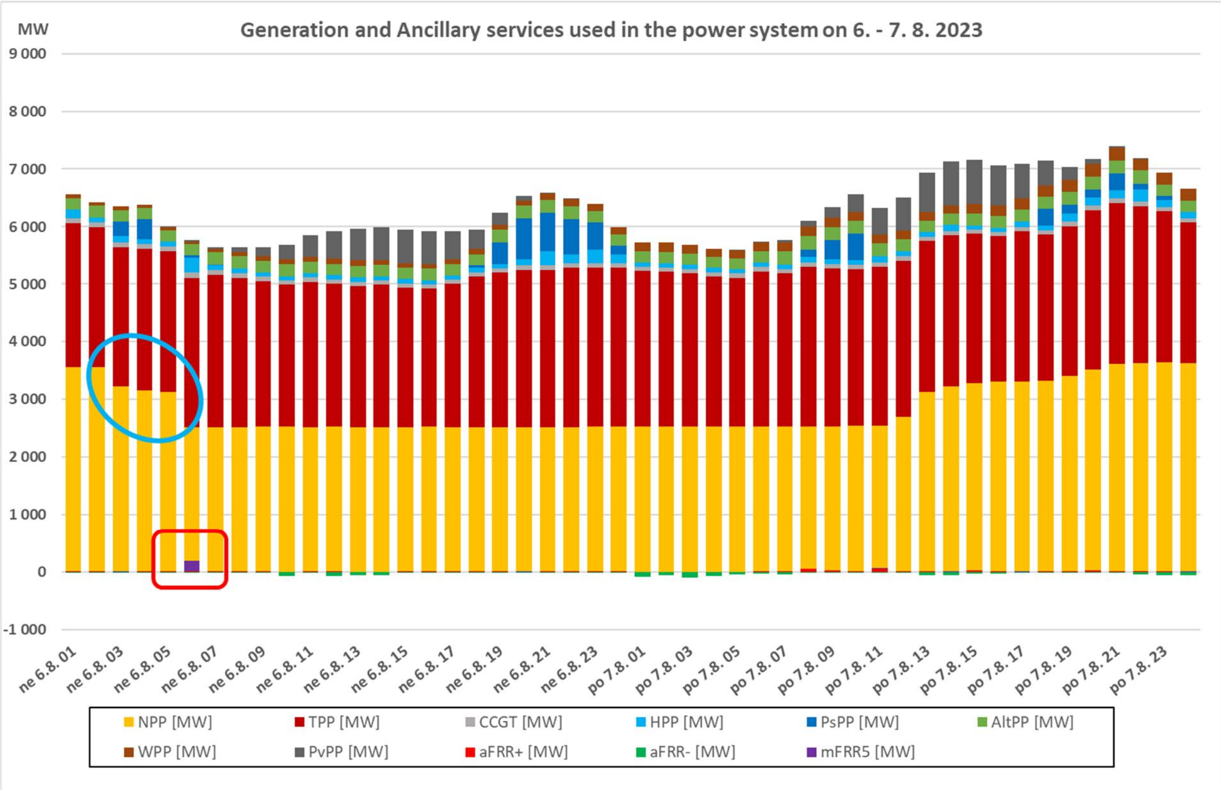

Figure 22: Generation and Ancillary services used in the power system on 6.-7.8.2023

7.2.6. Comparison of the different impacts of outages in different market situations

Figure 23 mainly shows the different price conditions on the energy markets in the individual years 2020 - 2023 during large unit outages. Along with this, we can also see a change in the prices of imbalances, which have an increasing tendency, unlike the market prices, where we can observe a calming down and a return to pre-crisis values from 2023 as it shown on Figure 24.

Another important state to compare is the impact of trading and the effect of the availability/unavailability of capacities on the return of the system imbalance in the hours when traders were not able to purchase the missing power.

Last but not least what to see there is the correlation of the system imbalance price with system imbalance. First two courses (from years 2020 and 2021) are calm and corresponding to each other, for the other three (from 2022 and two from 2023) only the initial state of the outage is more or less obvious and after that the price of the imbalance is no longer highly correlated with the system imbalance.

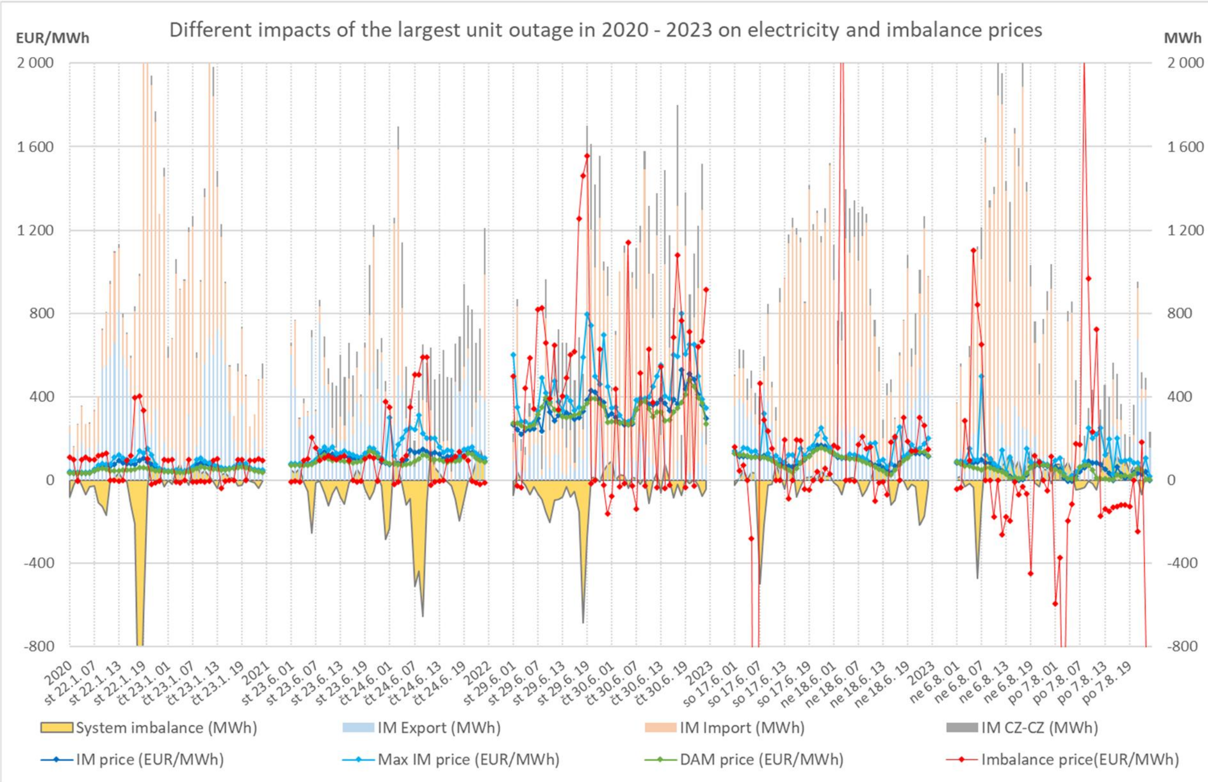

Figure 23: The situation in the power system and on the market during different outages of similar units

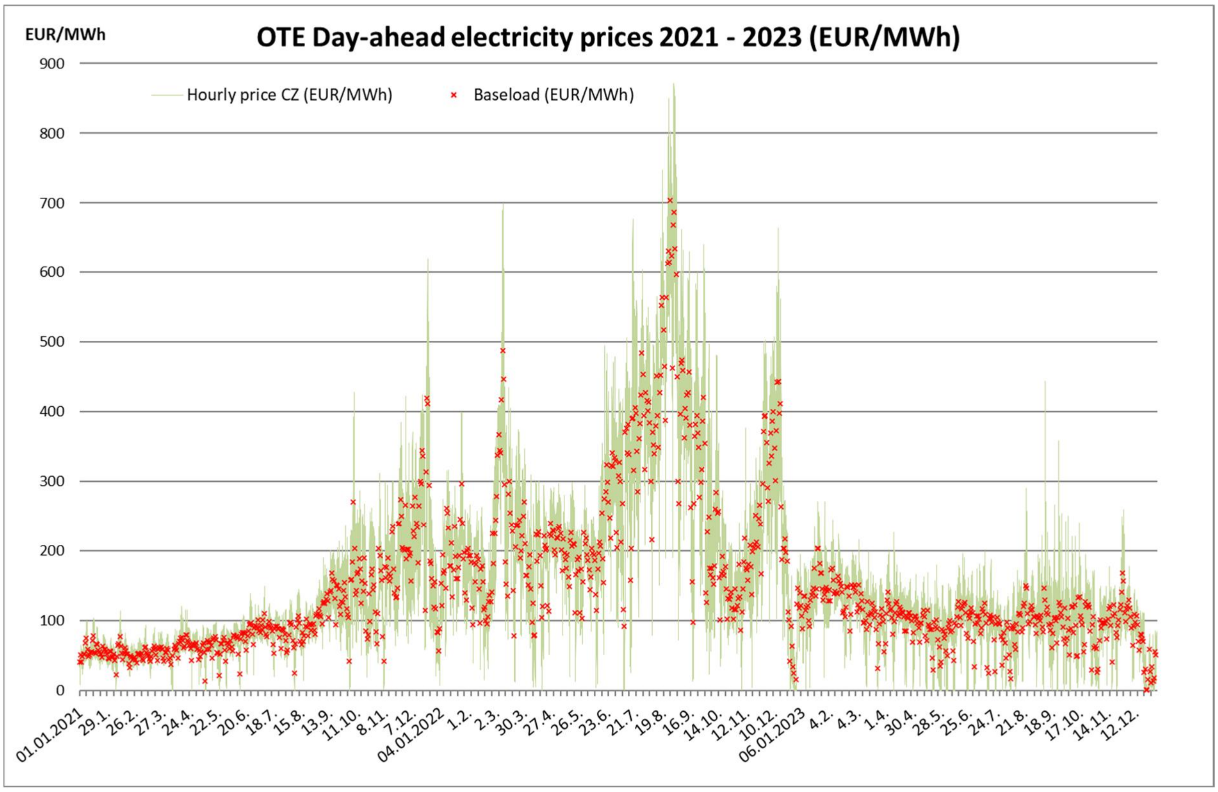

Figure 24: OTE Day-ahead electricity prices 2021 - 2023 (EUR/MWh)

7.2.7. Export of electricity to deficit areas

Another interesting operating situation that we would like to address is the development of trading on the intraday market in the Czech Republic due to low production from renewable sources in Germany, namely wind farms in northern Germany, accompanied by unplanned outages in foreign systems. This happened on 14/09/2020 – 16/09/2020 In Germany, they had a lack of power in the system, and the Czech Republic became an export country thanks to interconnected markets, which helped solve their power imbalance. It is therefore a situation opposite to that which was presented earlier, but from the point of view of the Czech Republic.

The forecast of low production from wind farms across Europe and the lower availability of conventional sources, including nuclear power plants in France, due to planned and unplanned shutdowns resulted in a sharp increase in electricity prices. Added to this was the fact that the production of electricity supplied by wind farms was still slightly lower than the morning forecasts of Monday 14/09/2020 showed, and at the same time, according to analysts, on 15/09 to several unplanned shutdowns of gas power plants in Western Europe.

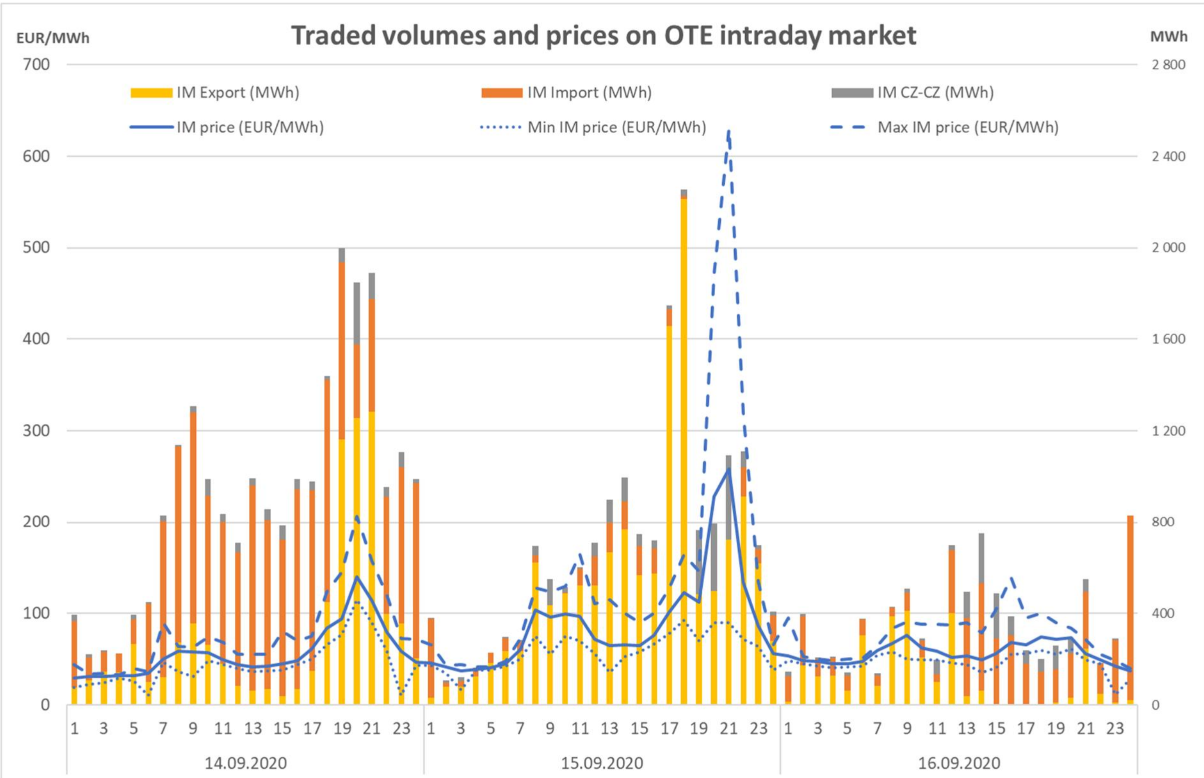

Figure 25: Development of prices and traded volumes of electricity at IDM with export/import distinction on 14/09/2020 - 16/09/2020

Figure 25 also shows that the highest prices were reached on 14/09/2020 - 16/09/2020, when the maximum prices on 15/09/2020 were at 470 EUR/MWh (8 p.m.), 630 EUR/MWh (9 p.m.)

and 320 EUR/MWh (10 p.m.). It is interesting that at 21:00, when the maximum price reached 630 EUR/MWh and the weighted average price for this hour was almost 260 EUR/MWh, 520 MWh out of the total 540 MWh was exported with a price above 150 EUR/MWh. These prices were thus the highest since the intraday electricity market was connected. The highest intraday price in Germany on 15/09/2020 was 3 999.99 EUR/MWh for the trading quarter hour between 18:45 and 19:00. This situation also influenced the price difference from DA and IDM of up to 535 EUR/MWh, precisely in the evening hours of 15/09/2020, not only in the Czech Republic, but also in Germany, where this difference was due to the operational situation in the system there is even higher. This chart also shows that essentially all day long, OTE market participants sold for export as long as capacity was available. At 6 p.m., 2 212 MWh were exported. Transmission capacities were used up for 19.00 – 21.00 hours (increased number of local trades – gray bars).

7.3. Price volatility on the local market and on the SIDC market

Another characteristic of the local market is considerable price volatility. Compared to the situation after joining the SIDC with sufficient capacities, especially towards the German market, the price volatility on IM is significantly lower and IM prices are more correlated with the prices on the day-ahead electricity market. The biggest deviation of the price on IDM is during Christmas, which is a very specific time from the consumption point of view.

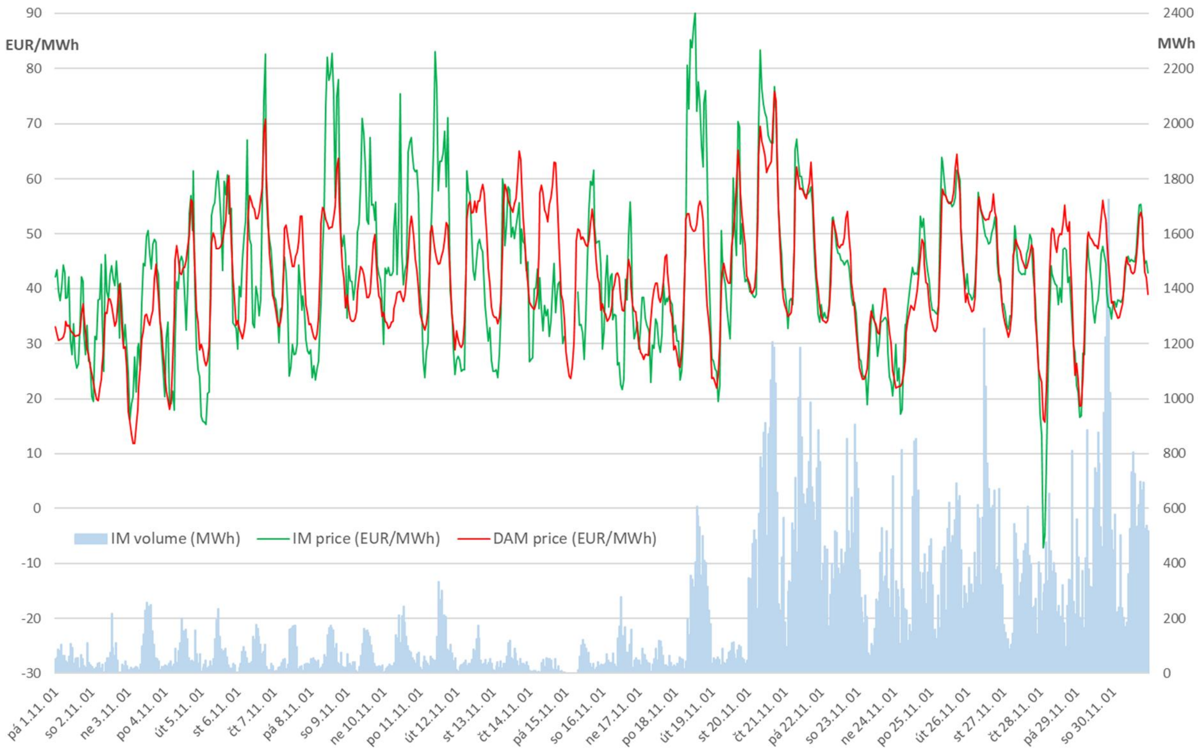

Figure 26: Impact of IM interconnections on price correlation in November 2019

Figure 27 shows the price and quantity patterns on the day before joining the SIDC (Saturday, 16 November 2019), where there are considerable differences between the minimum and maximum trading prices per hour. The maximum difference is at 8th delivery hour, namely 49 EUR/MWh, the minimum difference is 6 EUR/MWh at 10th delivery hour and the average value is 25 EUR/MWh. In contrast, 5 days after joining the SIDC, on Sunday, 24 November 2019, a strong correlation of minimum and maximum prices with a weighted average price can be seen. The maximum difference is 13 EUR/MWh at 6th delivery hour, the minimum difference is 3 EUR/MWh at 10th delivery hour and at 24th delivery hour and the average difference value is 6 EUR/MWh. Such a significant correlation is also due to a sufficient number of cross-border capacities, especially to Germany, which encourages high market liquidity with a minimum immediate spread of supply and demand of tens of cents.

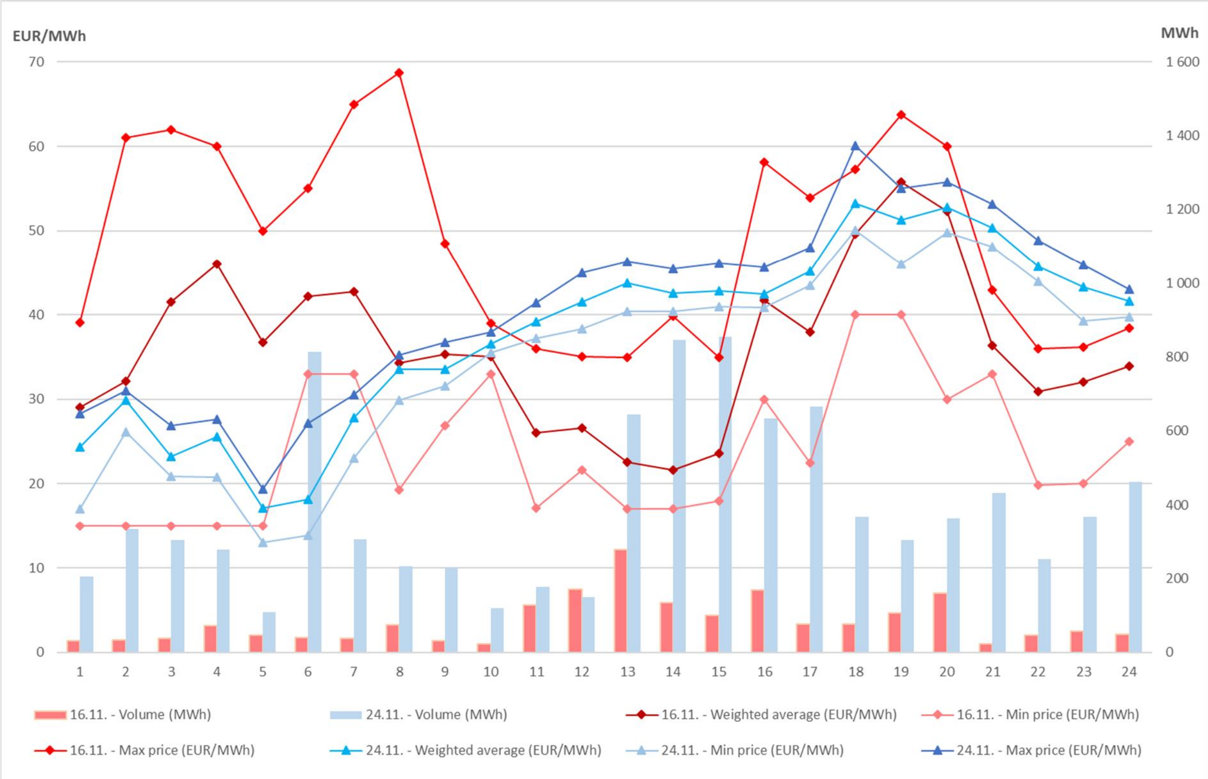

Figure 27: Influence of IM interconnection on prices and traded volumes (16. 11. a 24. 11.)

7.4. Influence of trading on TSO's operations and use of AnS

Topic discussed previously has also impact to TSO´s operations from balancing point of view, and mainly has impact to usage of Ancillary services.

There are expected values of used Ancillary Services in the deliver hour of the outage and in the next one, but in case that there is possibility to trade sufficient amounts of electricity on the intraday market where are sufficient cross border capacities, the usage of Ancillary services is limited to low values, or system imbalance could be changed to surplus and negative Ancillary services needs to be activated.

From the table below we can compare Ancillary services use during previously mentioned outages in the transmission system, also in relation of the outage size.

We can conclude two main points related to TSO´s operation.

Firstly, there is positive impact of intraday trading, if possible, in reducing of amount of activated Ancillary services.

Second one is negative, because TSOs are losing part of predictability in the system, mainly related to activation of International RE, as is possible to see in delivery hour 10 on 24/6, where negative aFRR (-98 MWh) has to be activated against International RE+ (150 MWh).

Figure 28: Total amount of MP imbalances and activated AnS in 2014 – 2023

But if we check the Figure 28 where the aggregated numbers of imbalances and activated AnS are shown, the direct impact of described IDM operation is not visible for more reasons.

- In 2020, Covid situation was unpredictable consumption in the system caused by the impact of government measures to mitigate the epidemic.
- In 2021, the first change in the system imbalance calculation which led to a doubling of the imbalance price compared to the prices usual in previous years[12], but there was also an increase in prices for DM from about June 2021, so some MPs chose the strategy of preferring to be in the imbalance, which was cheaper than electricity purchased at DM. And at the same time, it ceased to be profitable to speculate on a counter imbalance, because its price did not cover the increased costs. At the end of the year 2021, baseload prices rise over 300 EUR/MWh.

[12] Year Report on the Electricity and Gas Markets in the Czech Republic 2021, OTE, a.s.

- In 2022, another change in the system imbalance calculation, that led to another increase of the imbalance price[13] and also to higher level of unpredictability of the counter-imbalance price, that could be negative, that led to further limiting of MPs of MPs activity in counter-balancing. In the year 2022, the peak baseload prices rise over 600 EUR/MWh.
- In 2023, the trend from 2022 continuous there, but the prices on DM was stabilized under 150 EUR/MWh.

The Figure 28 and Figure 29 shows descending trend of system imbalance and also sum of individual MPs imbalances, but also growing trend of activated AnS. This this mainly means the above-described trend of leaving from counter-balancing, that was self-regulatory process in the transmission system that limited the necessity of AnS activation by the TSO.

System imbalance in 2023 was the lowest from of the years under review, but the volume of activated AnS was nearly doubled related to years with similar system imbalance volume.

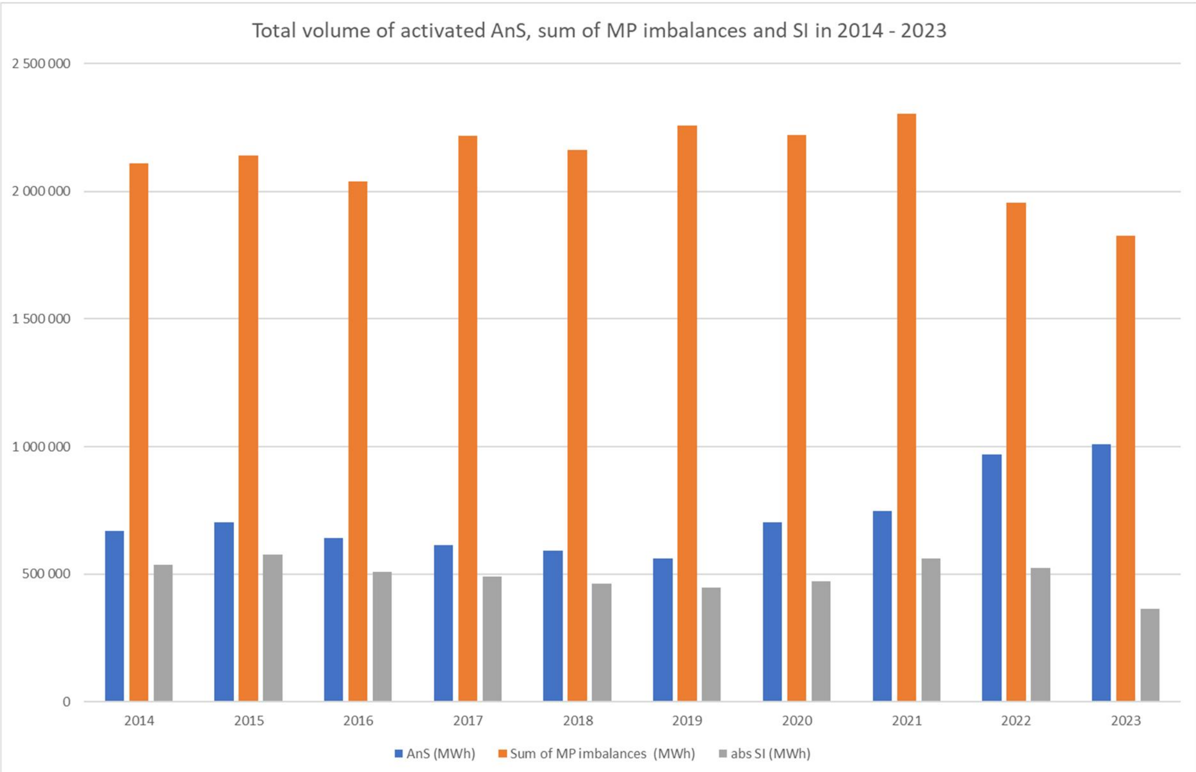

Figure 29: Total activated AnS, sum of MP imbalances and sum of abs SI in 2014 – 2023

If we look at these data from the point of view of their ratios as it is shown on Figure 30 we can see that ratio between sum of individual MPs imbalances and activated AnS is decreasing. But

[13] Year Report on the Electricity and Gas Markets in the Czech Republic 2022, OTE, a.s.

the ratio between sum of individual MPs imbalances and the volume of system imbalance as well as the ratio between the volume of system imbalance and activated AnS is significantly growing.

As was described in previous chapters, in the individual cases we can see that impact of the electricity market could have significant impact to reducing activation of AnS. But in the scale of the whole years and aggregated numbers over all market participants with more than 6 million of supply point in connection with significant changes in the system there is so far not visible positive impact to TSO operation.

The impact is visible only on decreasing imbalances of individual market participants and consequently also on the system imbalance.

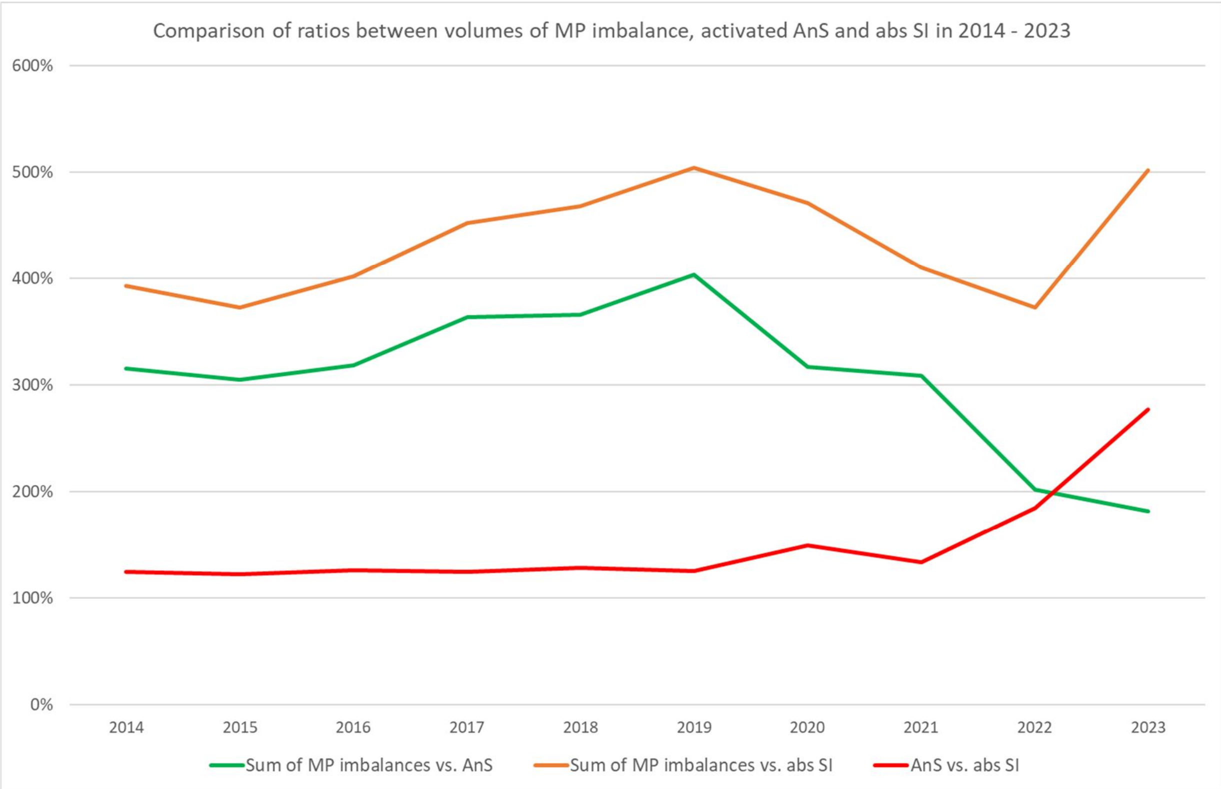

Figure 30: Ratios between volumes of MP imbalance, AnS and abs SI in 2014 - 2023

7.5. Influence of trading on the imbalance price and financial impact to Market participants

If we focus on the impact of the described outages on the price of the imbalance and the overall impact on other market participants, then on a theoretical level, each significant outage means an increase in the price of the imbalance, either by a linear coefficient corresponding to the size of the system imbalance, or by the price of activated support services to ensure performance balance.

The following graph shows the course of the impact of the resulting imbalances and used AnS and their impact on the imbalance and counter- imbalance prices.

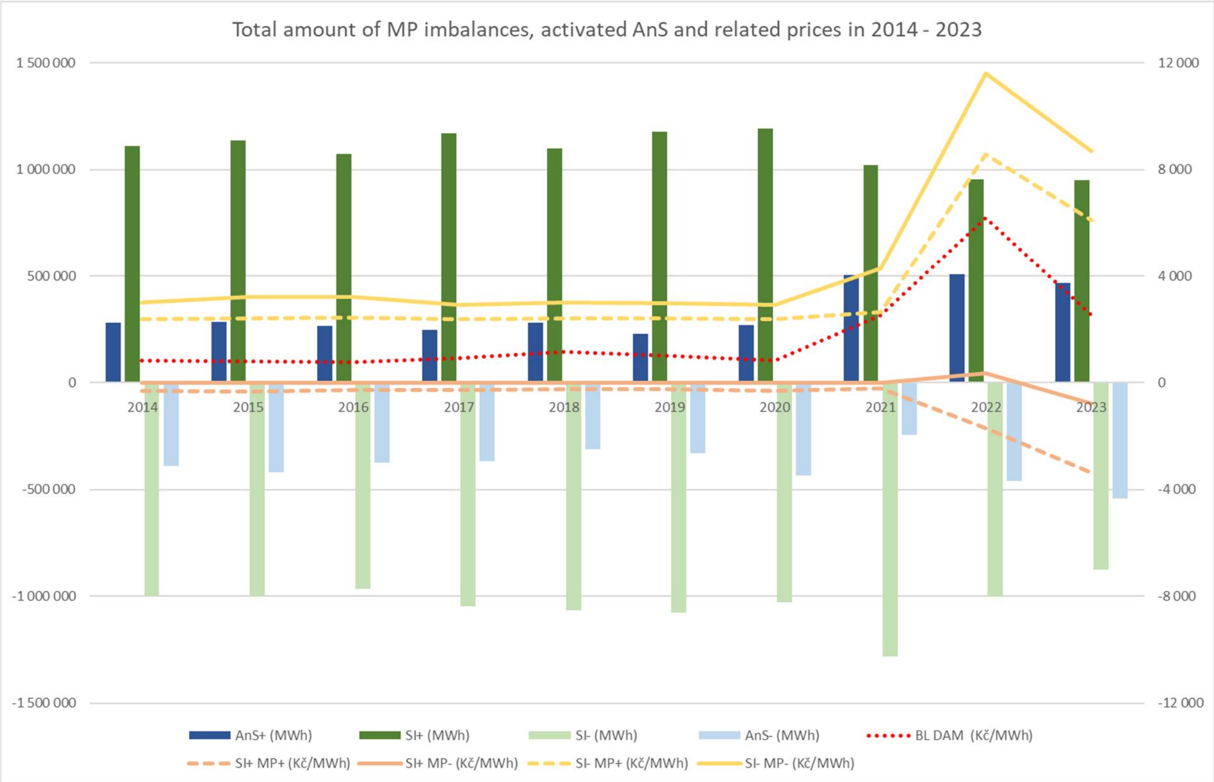

Figure 31: MP imbalances, activated AnS and related prices in 2014 - 2023

8. Case study

The basis for this case study will be the data from the outage on 29/06/2022, which is described in this work above, and when the following state within the system was as follows:

- Calculation of the system imbalance and activation of Ancillary services (AnS) took place in 60-minute granularity.
- Trading on the intraday electricity market (IDM) took place with 60-minute products, with the deadline for cross-border trading (ID GCT) being 60 minutes before the start of the delivery hour.

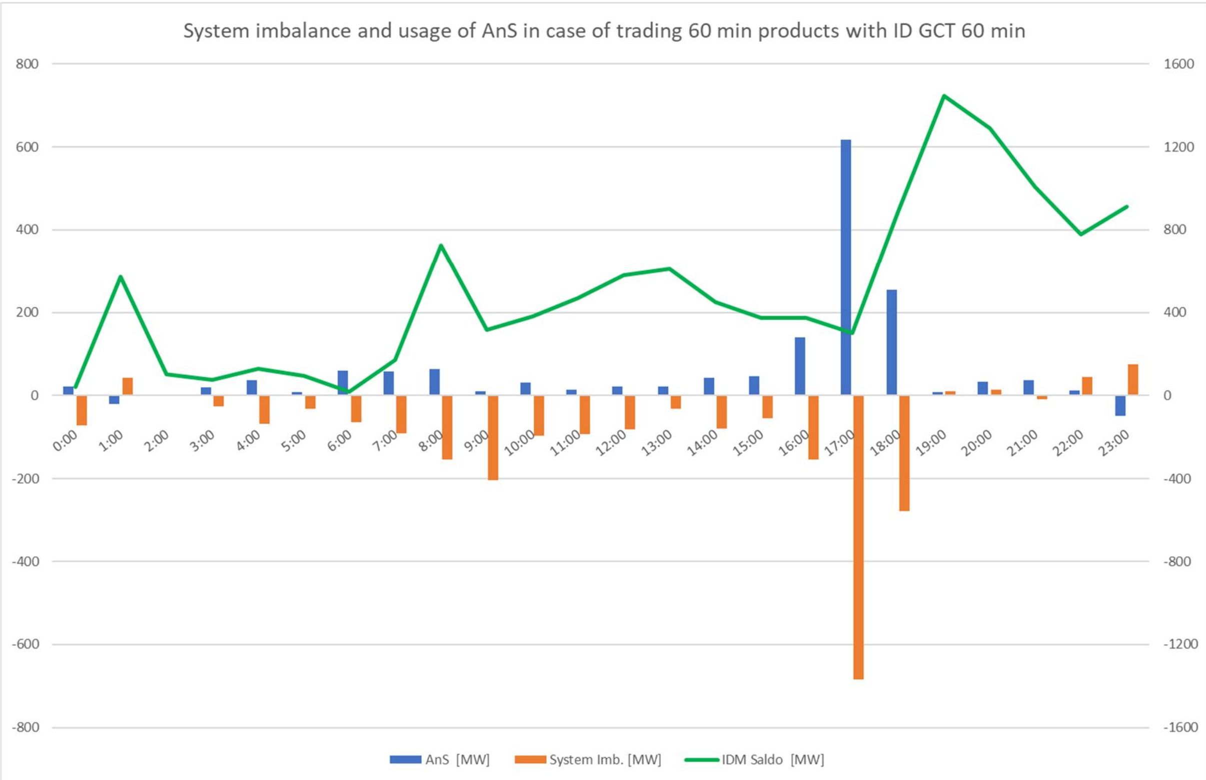

Figure 32: System imbalance and usage of AnS in case of trading 60 min products with ID GCT 60 min

As described in previous chapter 7.2.3, the outage of 1040 MW unit happened at 16:40, so as it is shown on the Figure 32, there are impacted 3 (three) delivery hours/imbalance intervals (16-17, 17-18 and 18-19).

The difference between the size of the unit (1040 MW) that was in fault and the size of the activated AnS (618 MW) during delivery hour 17-18 is given by the fact that the operator of this unit has at its disposal, among other, a fast-starting pumped-storage power plant with an installed capacity of 320 MW that was activated shortly after the outage.

There was no possibility to trade for the first two impacted delivery hours, but for the third one (18-19) such volume of electricity was traded that the need for activated AnS was reduced to half the value of the previous hour.

	AnS [MW]	System Imb. [MW]	Other influence [MW]	IDM Saldo [MW]		
15:00	46,1	-55,1	-9,0	372,3		
16:00	140,1	-153,4	-13,3	375,3	140,1	
17:00	618,1	-684,8	-66,7	303,1	618,1	
18:00	255,6	-278,5	-22,9	890,9	255,6	
19:00	7,9	10,1	18,1	1 446,4	1013,8 MWh	Ans

Figure 33: Usage of AnS in case of trading 60 min products with ID GCT 60 min

Figure 33 shows in yellow cells volume of activated AnS, total System Imbalance, other influence to SI a IDM Saldo (Import – Export + Local trades) related to mentioned outage. Total volume of activated AnS was 1 014 MWh with overall price 1 619 001 EUR.

There are prices of the activated AnS are accessible on the OTE website[14], so the activation of AnS in the delivery hour 16-17 cost a total of 193 332 EUR, which is converted to a unit price 1 380 EUR/MWh, in the hour 17-18 it was a totally 990 249 EUR, i.e. with 618 MWh of activated AnS it comes to 1 602 EUR/MWh. In the delivery hour 18-19, the activation of 256 MWh of AnS cost 435 420 EUR, so it is 1 704 EUR/MWh.

These unit prices will be used for following cases for valuation of activated AnS. This approach is not fully correct because the AnS are activated from the cheapest price to more expensive ones. So, in real state the price for activated AnS shall be lower, but as the prices are not public, but since the prices are not public, the average price approach used is sufficient for cost comparison.

[14] Source: https://www.ote-cr.cz/cs/statistika/odchylky-elektrina?version=2&date=2022-06-29

The following 4 states will be considered in this case study:

1. **30min_ID GCT 30min**
   - Calculation of system imbalance and activation of AnS would take place in 30-minute granularity,
   - Trading on the intraday electricity market took place with 30-minute products, with the deadline for cross-border trading (ID GCT) being 30 minutes before the start of the delivery hour.

2. **15 min_ID GCT 15 min**
   - Calculation of the system imbalance and activation of AnS would take place in 15-minute granularity,
   - Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 15 minutes before the start of the delivery hour.

3. **15 min_ID GCT 60 min**
   - Calculation of the system imbalance and activation of AnS would take place in 15-minute granularity,
   - Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 60 minutes before the start of the delivery hour.
   - This status is assumed to be active within the transmission system from 1 July 2024.[15]

4. **15 min_ID GCT 30 min**
   - Calculation of the system imbalance and activation of AnS would take place in 15-minute granularity,
   - Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 30 minutes before the start of the delivery hour.
   - This status is expected to be active within the transmission system from 1.1.2026 at the latest.[16]

[15] Based on relevant legislative requirements (Regulation of the European Parliament and of the Council (EU) 2019/943 and Decree No. 408/2015 Coll. on Electricity Market Rules)
[16] Based on REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union's electricity market design (= ‘‘EMDR‘‘), 19 December 2023

For the purposes of this case study, the AnS activation data on June 29, 2022, in 15-minute[17] and 30-minute resolution will be used.

The traded quantity on IDM will be considered with the same dynamics with which it was traded within the 60-minute products. The specified GCT ID influences which trading period can already be traded in response to an outage.

The interval from 16:00 to 19:00, when the imbalance in the system was caused by this outage, will be essential for assessing the effect of the length of the system imbalance calculation period, IDM products and activation of support services.

[17] Source: https://www.ceps.cz/cs/data#AktivaceSVRvCR

8.1. 30min_ID GCT 30min

The following state within the system is considered as follows:

- Calculation of system imbalance and activation of AnS would take place in 30-minute granularity,
- Trading on the intraday electricity market took place with 30-minute products, with the deadline for cross-border trading (ID GCT) being 30 minutes before the start of the delivery hour.

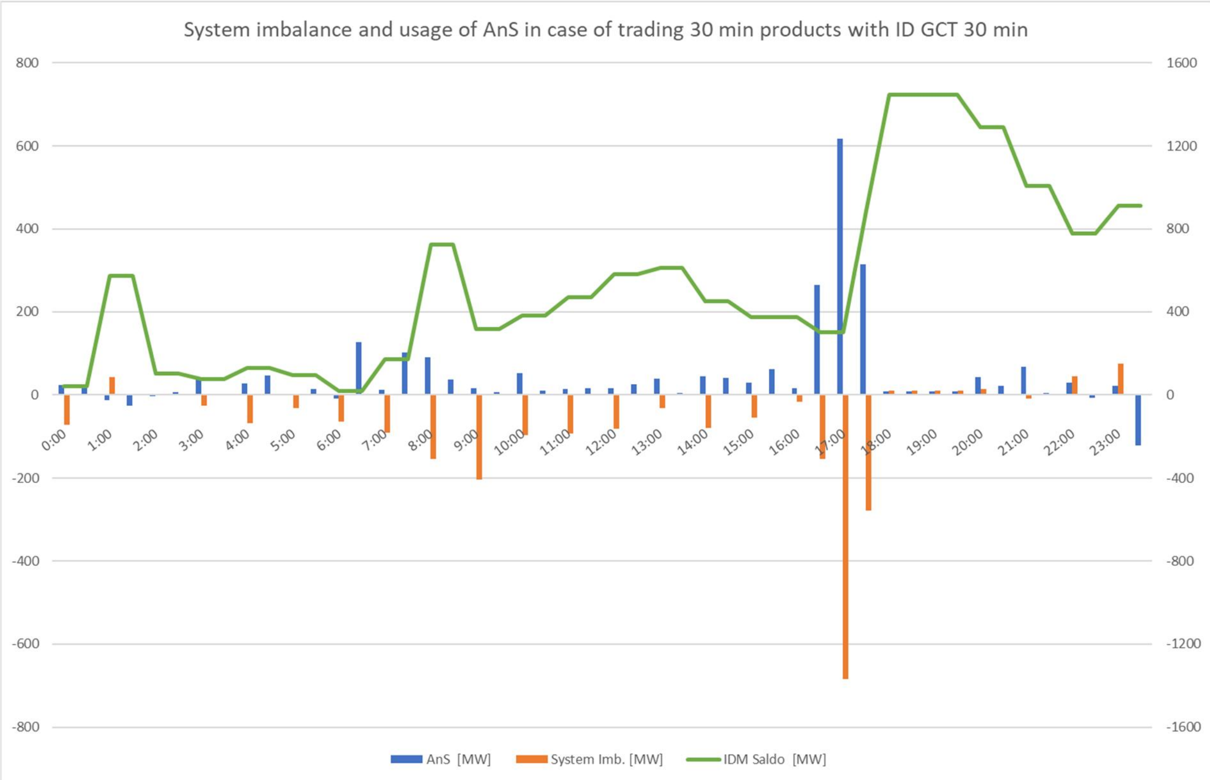

Figure 34: System imbalance and usage of AnS in case of trading 30 min products with ID GCT 30 min

Figure 34 shows similarly as it is shown on the Figure 32, that there are also impacted 3 (three) delivery/imbalance intervals (16:30-17:00, 17:00-17:30 and 17:30-18:00).

Now we can use unit prices calculated from hourly products for price of activation AnS in case oh half hour imbalance period as it is shown on Figure 35.

So, the activation of AnS in the imbalance periods between 16-17 cost 193 332 EUR (15,6 MW*0,5 h +264,5 MW*0,5 h = 140 MWh * 1 380 EUR/MWh), which is the same amount as in original case, because no difference could happen because the outage was in second half-hour.

Activation of the lower amount of AnS is expected in the second half-hour of the time interval 17-18 because of intraday trading, so the total volume of activated AnS is 465 MWh (616,7 MW*0,5 h + 313,0 MW*0,5). Then we use for the whole interval 17-18 calculated unit price 1 602 EUR/MWh and it gives us total activation price 744 681 EUR.

In the delivery hour 18-19, the activation of only 8 MWh of AnS at price 1 704 EUR/MWh cost 13 481 EUR.

	AnS [MW]	System Imb. [MW]	IDM Saldo [MW]		
15:00	29,9	-55,1	372,3		
15:30	62,3		372,3		
16:00	15,6	-15,4	375,3	7,8	
16:30	264,5	-153,4	303,1	132,3	
17:00	616,7	-684,8	303,1	308,3	
17:30	313,0	-278,5	890,9	156,5	
18:00	7,9	10,1	1 446,4	4,0	
18:30	7,9	10,1	1 446,4	4,0	
19:00	7,9	10,1	1 446,4	612,8 MWh	AnS

Figure 35: Usage of AnS in case of trading 30 min products with ID GCT 30 min

In case of 30-minutes System Imbalance interval with 30-minutes IDM products with 30 minutes GCT, total volume of activated AnS would be 631 MWh with overall price 951 495 EUR.

8.2. 15 min_ID GCT 15 min

The following state within the system is considered as follows:

- Calculation of system imbalance and activation of AnS would take place in 15-minute granularity,
- Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 15 minutes before the start of the delivery hour.
- The trading deadline for all contracts on IDM is 5 minutes before the delivery interval, however, the local market is not as liquid as the connected European market, moreover, if an outage occurs on the side of a major producer in the BZ, the liquidity will decrease even more.

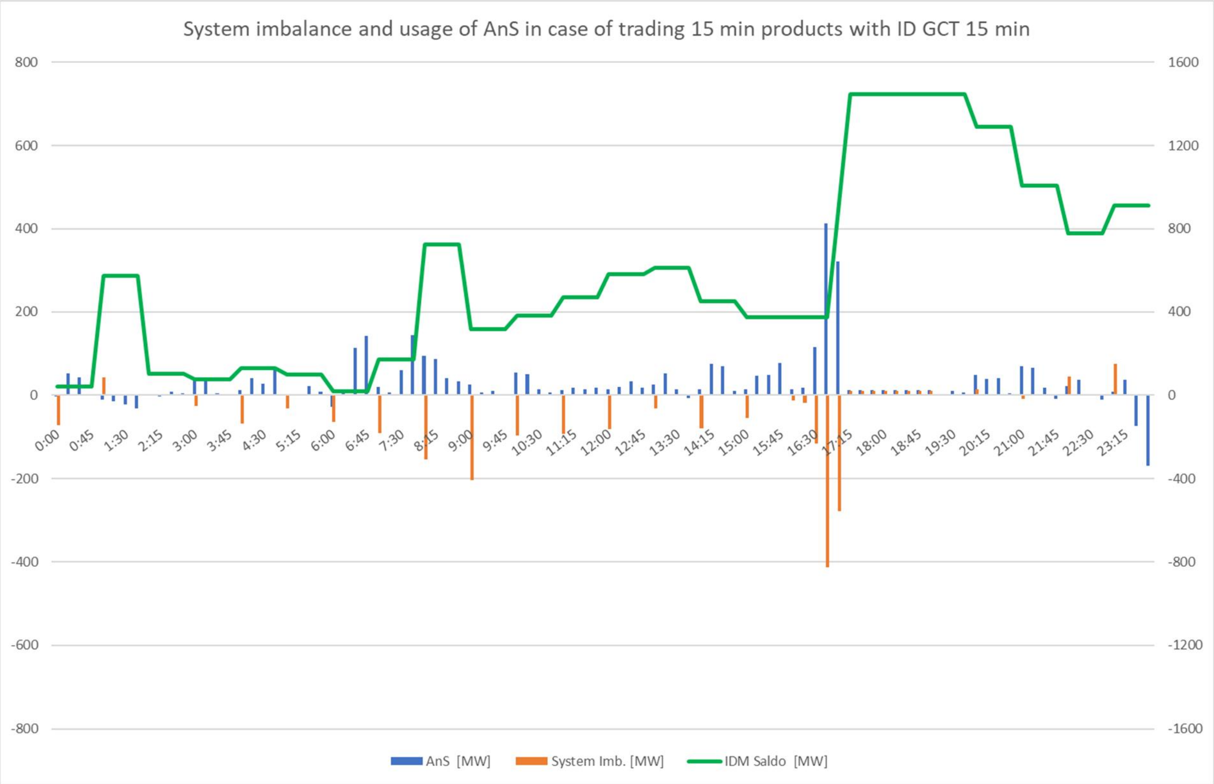

Figure 36: System imbalance and usage of AnS in case of trading 15 min products with ID GCT 15 min

Figure 36 shows similarly as previous ones, that there are impacted 3 (three) delivery/imbalance intervals (16:30-16:45, 16:45-17:00 and 17:00-17:15).

Now we can also use unit prices calculated from hourly products for price of activation AnS in case of 15 minutes imbalance period as it is shown on Figure 37.

So, the activation of AnS in the imbalance periods between 16-17 costs also 193 332 EUR (13,4 MW*0,25 h + 17,9 MW*0,25 h + 115,8 MW*0,25 h + 413,2 MW*0,25 h = 140 MWh * 1 380 EUR/MWh), because no difference could happen also in 15 minutes interval.

Activation of the lower amount of AnS is expected in the first 15 minutes interval of the time interval 17-18 because of intraday trading and following 3 ones are expected to be balanced by trading on IDM, so the total volume of activated AnS is 90 MWh (320,9 MW*0,25 h + 12,5 MW*0,25 + 12,5 MW*0,25 + 12,5 MW*0,25). So, we can use for the whole interval 17-18 calculated unit price 1 602 EUR/MWh, and it gives us total activation price 143 550 EUR.

In the delivery hour 18-19, the activation of only 13 MWh of AnS at price 1 704 EUR/MWh cost 21 315 EUR.

	AnS [MW]	System Imb. [MW]	IDM Saldo [MW]		
15:00	13,3	-55,1	372,3		
15:15	46,5		372,3		
15:30	47,6		372,3		
15:45	77,1		372,3		
16:00	13,4	-13,4	375,3	3,3	
16:15	17,9	-17,9	375,3	4,5	
16:30	115,8	-115,8	375,3	28,9	
16:45	413,2	-413,2	375,3	103,3	
17:00	320,9	-278,5	890,9	80,2	
17:15	12,5	10,1	1 446,4	3,1	
17:30	12,5	10,1	1446,4	3,1	
17:45	12,5	10,1	1446,4	3,1	
18:00	12,5	10,1	1 446,4	3,1	
18:15	12,5	10,1	1446,4	3,1	
18:30	12,5	10,1	1446,4	3,1	
18:45	12,5	10,1	1446,4	3,1	
19:00	12,5	10,1	1 446,4	242,2 MWh	AnS

Figure 37: Usage of AnS in case of trading 15 min products with ID GCT 15 min

In case of 15-minutes System Imbalance interval with 15-minutes IDM products with 15 minutes GCT, total volume of activated AnS would be 242 MWh with overall price 358 198 EUR.

8.3. 15 min_ID GCT 60 min

The following state within the system is considered as follows:

- Calculation of system imbalance and activation of AnS would take place in 15-minute granularity,
- Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 60 minutes before the start of the delivery hour.

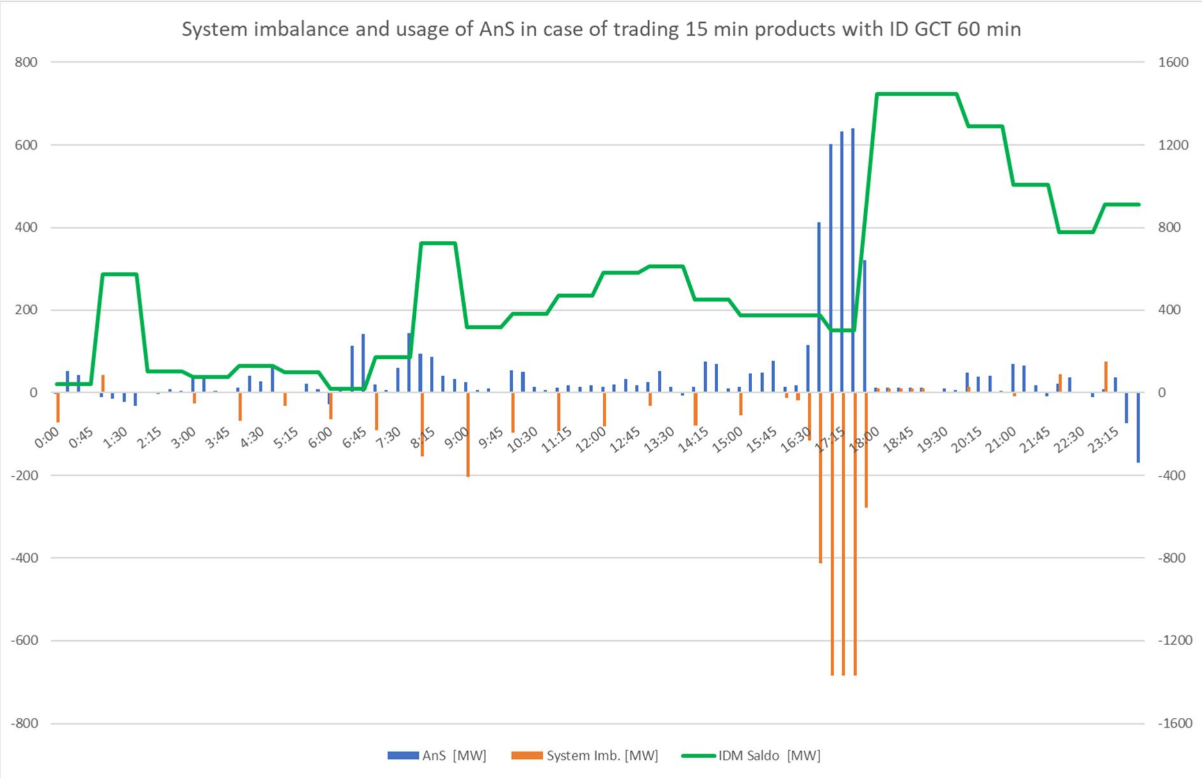

Figure 38: System imbalance and usage of AnS in case of trading 15 min products with ID GCT 60 min

Figure 38 shows that because of GCT 60 minutes that allows to trade as first delivery interval 17:45 – 18:00, so there are impacted 6 (six) delivery/imbalance intervals (16:30-16:45, 16:45-17:00, 17:00-17:15, 17:15-17:30, 17:30-17:45 and 17:45-18:00).

Now we use unit prices calculated from hourly products for price of activation AnS in case of 15 minutes imbalance period as it is shown on Figure 39.

So, costs of the activation of AnS in the imbalance periods between 16-17 are still 193 332 EUR (13,4 MW*0,25 h + 17,9 MW*0,25 h + 115,8 MW*0,25 h + 413,2 MW*0,25 h = 140 MWh * 1 380 EUR/MWh), because no difference could happen also in 15 minutes interval.

Activation of the lower amount of AnS is expected in the last 15 minutes interval of the time interval 17-18 because of intraday trading, so the total volume of activated AnS is 549 MWh (601,3 MW*0,25 h + 632,0 MW*0,25 + 639,8 MW*0,25 + 320,9 MW*0,25). So, we use for the whole interval 17-18 calculated unit price 1 602 EUR/MWh, and it gives us total activation price 878 726 EUR.

In the delivery hour 18-19, all intervals are expected to be balanced by trading on IDM, so the activation of only 13 MWh of AnS at price 1 704 EUR/MWh cost 21 315 EUR.

	AnS [MW]	System Imb. [MW]	IDM Saldo [MW]		
15:00	13,3	-55,1	372,3		
15:15	46,5		372,3		
15:30	47,6		372,3		
15:45	77,1		372,3		
16:00	13,4	-13,4	375,3	3,3	
16:15	17,9	-17,9	375,3	4,5	
16:30	115,8	-115,8	375,3	28,9	
16:45	413,2	-413,2	375,3	103,3	
17:00	601,3	-684,8	303,1	150,3	
17:15	632,0	-684,8	303,1	158,0	
17:30	639,8	-684,8	303,1	160,0	
17:45	320,9	-278,5	890,9	80,2	
18:00	12,5	10,1	1 446,4	3,1	
18:15	12,5	10,1	1446,4	3,1	
18:30	12,5	10,1	1446,4	3,1	
18:45	12,5	10,1	1446,4	3,1	
19:00	12,5	10,1	1 446,4	701,1 MWh	AnS

Figure 39: Usage of AnS in case of trading 15 min products with ID GCT 60 min

In case of 15-minutes System Imbalance interval with 15-minutes IDM products with 60 minutes GCT, total volume of activated AnS would be 701 MWh with overall price 1 093 373 EUR.

8.4. 15 min_ID GCT 30 min

The following state within the system is considered as follows:

- Calculation of system imbalance and activation of AnS would take place in 15-minute granularity,
- Trading on the intraday electricity market took place with 15-minute products, with the deadline for cross-border trading (ID GCT) being 30 minutes before the start of the delivery hour.

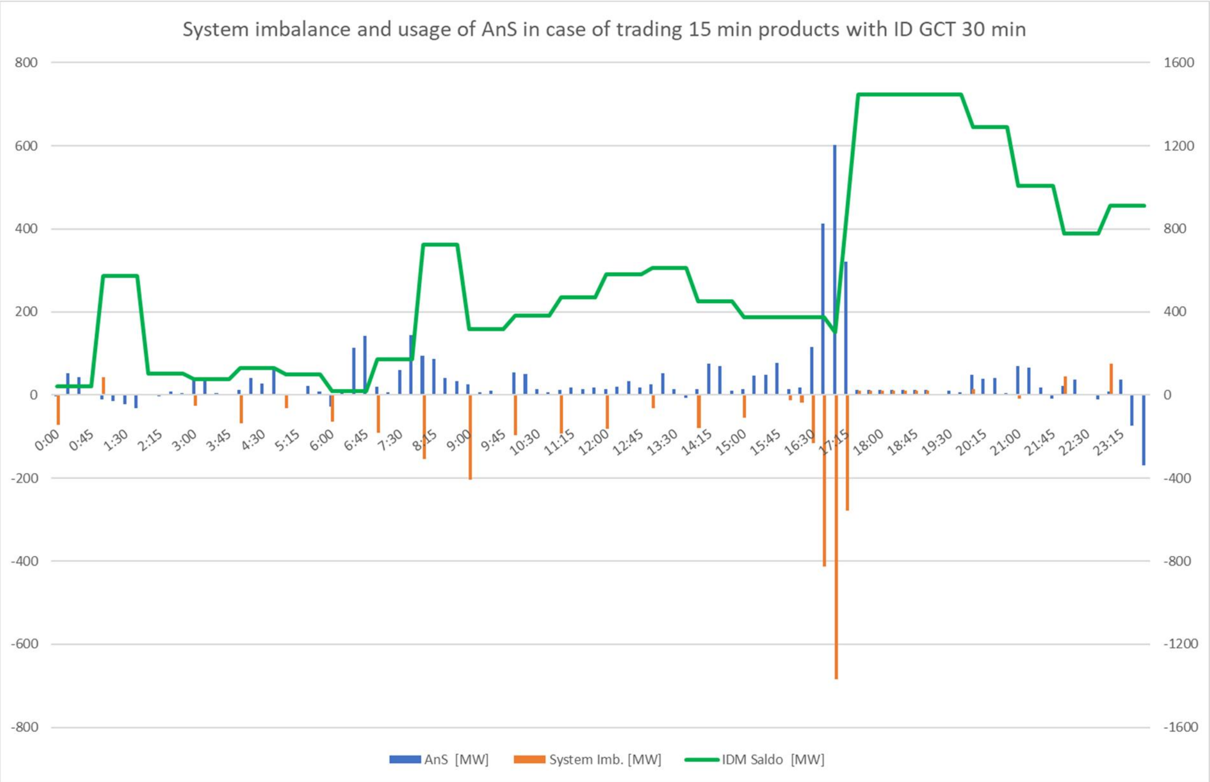

Figure 40: System imbalance and usage of AnS in case of trading 15 min products with ID GCT 30 min

Figure 40 shows that because of GCT 30 minutes that allows to trade as first delivery interval 17:15-17:30, so there are impacted 4 (four) delivery/imbalance intervals (16:30-16:45, 16:45-17:00, 17:00-17:15 and 17:15-17:30).

We use unit prices calculated from hourly products for price of activation AnS in case of 15 minutes imbalance period as it is shown on Figure 41.

So, the costs of the activation of AnS in the imbalance periods between 16-17 are still 193 332 EUR (13,4 MW*0,25 h + 17,9 MW*0,25 h + 115,8 MW*0,25 h + 413,2 MW*0,25 h = 140 MWh * 1 380 EUR/MWh), because no difference could happen also in 15 minutes interval.

Activation of the lower amount of AnS is expected in the second 15 minutes interval of the time interval 17-18 because of intraday trading and following 2 ones are expected to be balanced by trading on IDM, so the total volume of activated AnS is 237 MWh (601,3 MW*0,25 h + 320,9 MW*0,25 + 12,5 MW*0,25 + 12,5 MW*0,25). So, we use for the whole interval 17-18 calculated unit price 1 602 EUR/MWh, and it gives us total activation price 379 359 EUR.

In the delivery hour 18-19, all intervals are expected to be balanced by trading on IDM, so the activation of only 13 MWh of AnS at price 1 704 EUR/MWh cost 21 315 EUR.

	AnS [MW]	System Imb. [MW]	IDM Saldo [MW]		
15:00	13,3	-55,1	372,3		
15:15	46,5		372,3		
15:30	47,6		372,3		
15:45	77,1		372,3		
16:00	13,4	-13,4	375,3	3,3	
16:15	17,9	-17,9	375,3	4,5	
16:30	115,8	-115,8	375,3	28,9	
16:45	413,2	-413,2	375,3	103,3	
17:00	601,3	-684,8	303,1	150,3	
17:15	320,9	-278,5	890,9	80,2	
17:30	12,5	10,1	1 446,4	3,1	
17:45	12,5	10,1	1 446,4	3,1	
18:00	12,5	10,1	1 446,4	3,1	
18:15	12,5	10,1	1446,4	3,1	
18:30	12,5	10,1	1446,4	3,1	
18:45	12,5	10,1	1446,4	3,1	
19:00	12,5	10,1	1 446,4	389,4 MWh	AnS

Figure 41: Usage of AnS in case of trading 15 min products with ID GCT 30 min

In case of 15-minutes System Imbalance interval with 15-minutes IDM products with 30 minutes GCT, total volume of activated AnS would be 389 MWh with overall price 594 007 EUR.

8.5. Conclusion of the Case study

If we compare the results of individual cases, from the point of view of minimizing the number of affected intervals - namely 3, when, in the ideal case, there is a possibility when the 3rd interval could already be balanced on the IDM, so it would be ideal if the length of the imbalance interval, trading interval and GCT was the same.

As the value of GCT increases, the number of intervals during which it is not possible to trade increases, which limits the possibility of MP to settle its position as soon as possible and increases the necessity of activating AnS.

As the interval shortens, the need for activated energy decreases, although in terms of power it is necessary to cover the outage in the same way as with longer intervals. This can have a negative impact on the use of units with lower dynamics - ideal from this point of view would be hydroelectric plants and gas or PPC units.

60 min_GCT60	16-17	17-18	18-19	Total		
AnS (MWh)	140	618	256	**1 014**	**MWh**	**100%**
AnS (EUR)	193 332	990 249	435 420	**1 619 001**	**EUR**	**100%**
AnS (EUR/MWh)	1 380	1 602	1 704			
30 min_GCT30						
AnS (MWh)	140	465	8	**613**	**MWh**	**60%**
AnS (EUR)	193 332	744 681	13 481	**951 495**	**EUR**	**59%**
15 min_GCT15						
AnS (MWh)	140	90	13	**242**	**MWh**	**24%**
AnS (EUR)	193 332	143 550	21 315	**358 198**	**EUR**	**22%**
15 min_GCT60						
AnS (MWh)	140	549	13	**701**	**MWh**	**69%**
AnS (EUR)	193 332	878 726	21 315	**1 093 373**	**EUR**	**68%**
15 min_GCT30						
AnS (MWh)	140	237	13	**389**	**MWh**	**38%**
AnS (EUR)	193 332	379 359	21 315	**594 007**	**EUR**	**37%**

Figure 42: Usage and total price of AnS in individual cases

Shortening all 3 parameters from 60 minutes to 30 minutes would reduce the activated energy from AnS by 40% and the price by at least 41%.

Shortening all 3 parameters from 60 minutes to 15 minutes would reduce the activated energy from AnS by 76% and the price by at least 78%. This turned out to be an ideal solution, however, such a setting is unattainable under the current situation on the TSO side within the SIDC.

For the situation that should occur within the transmission system from 1.7.2024, which is a shortening of the imbalance and trading interval to 15 minutes while keeping the GCT at 60 minutes, there would be a reduction of the activated energy from AnS by 31% and the price by at least 32%.

From 1.1.2026, when the GCT will be shortened to 30 minutes, the activated energy from AnS could be reduced by 62% and the price by at least 63%.

Although not the best result, it is still the second best and the result shows a significant decrease in the required energy from AnS, which does not need to be activated. At the same time, a decrease in the total price of activated AnS, even if there could be a high unit price for activation, will be a motivation for MPs to balance their imbalances within the IDM.

This is ideal state that could be limited in case that there are not sufficient cross border capacities, mainly with Germany.

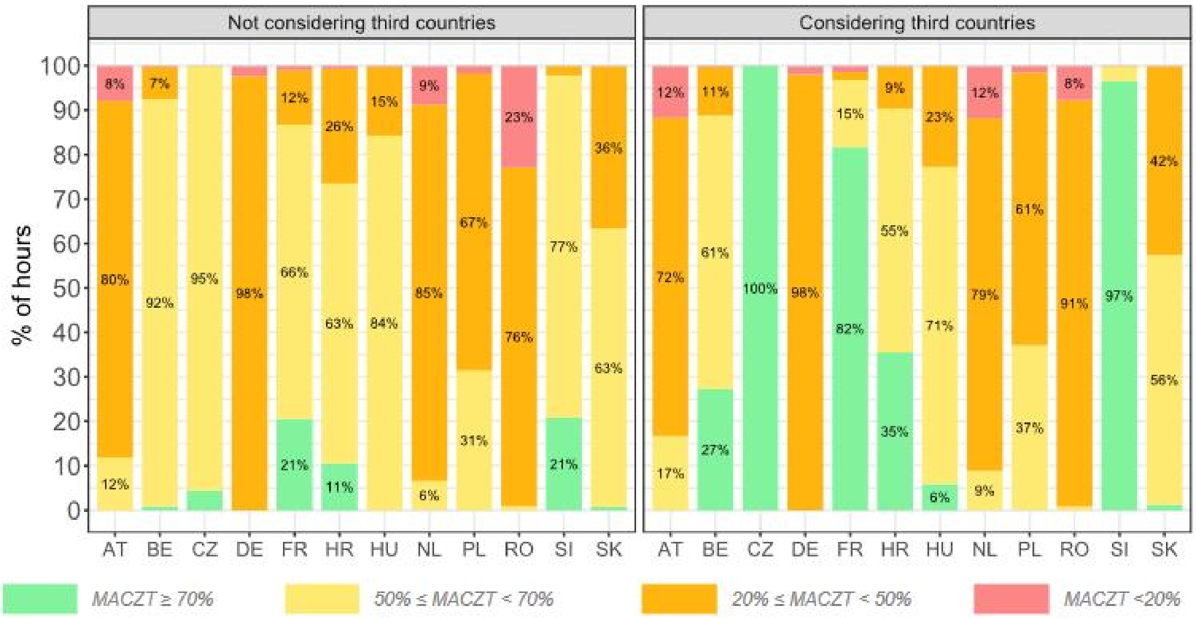

Figure 43: Percentage of hours when the minimum 70% target was reached in the CORE region (between 9. 6. 2022 and 31. 12. 2022[18]

[18] Source: Cross-zonal capacities and the 70% margin available for cross-zonal electricity trade (MACZT) 2023 Market Monitoring Report, ACER

But Clean Energy for All Europeans Package sets a minimum level of cross-zonal capacity - also called Margin Available for Cross-Zonal Trade (MACZT) – to be offered to the market by Transmission System Operators (TSOs), respecting operational security limits. This minimum 70% target took effect in 2020. The Electricity Regulation allows Member States to adopt transitional measures to gradually reach the minimum 70% target, by the end of 2025 at the latest.

9. Conclusions and Suggestions for Future Work

9.1. Conclusions

Nowadays, huge amount of small-scale power generating technologies, such as, photovoltaics, wind turbines, gas turbines and batteries, are gradually replacing conventional generating technologies in the electric power system. The decreasing of conventional fossil fuel/nuclear and increasing of energy demand forced society to consider and put emphasis on the utilization of environmentally friendly renewable sources.

This dissertation analyzes the effects of new possibilities of the energy market on the operation and control of the power system. It describes impacts of the different energy market situations to the system operation and during the evolution of the failure of big system powerplant. It analyzes the effects of different market settings and imbalance periods on the operation and control of the power system with regards to technical and economic signals, with respect to optimal market conditions. Worse cases with non-optimal market conditions are not considered in the case study but are described in this dissertation as real cases from the transmission system operation.

The result achieved from this dissertation can be summarized in the way that there was described numerous situations with different impacts of trading on the energy market to solve imbalance situations of market participant and his active participation on resolving this situation by himself, not to leave the whole effort on TSO. There was shown also cases, where market participants were not able to trade whole imbalances in all deliver hours and active balancing actions of TSO as necessary also few hours after the outage started. The Czech energy market is significantly losing the liquidity if there are no cross-border capacities, mainly to Germany. According to CACM regulation, this condition shall be fulfilled since 2026, when all TSOs in EU have to offer to the market as minimum 70% of the cross-zonal capacity. And as was shown previously, actual ratio of the German cross-zonal capacity available to the day-ahead market was in 98% of the year 2023 between 20 and 50%.

The optimal solution from the Case study is not reachable in the close future but the European legislation that regulates energy sector is directing energy markets to be able to handle with the second-best case. The first important step was harmonization of the imbalance settlement period to 15 minutes, and another is shortening of the deadline for cross-border trading (ID GCT) to 30 minutes.

9.2. Suggestions for Future Work

From the fact that the production from mainly non-controllable renewable sources is increasing due to among other things also electrical energy liberalization and a global (public and professional society) pressure on the use of environmentally friendly sources, there is a need in regards to TSO operation of the transmission networks to finding optimal methods of solving balancing of power system in cooperation with electricity market and its actual ability to solve the imbalance of individual market participants. This process shall be transparent and predictable for all involved parties. Taking this into consideration, this dissertation can be extended in the following issues:

To study and evaluate the energy market of AnS on TSOs side, with consideration of previous state, where at least some part of AnS was traded in long term contracts which gives TSO, and subsequently also the market participants, more certainty and transparency on the price formation of the imbalance price, which is currently largely dependent on the price of the activated AnS.

To study and evaluate possible prediction models that could use technical and economic signals from the energy market to improve model of AnS activation that could eliminate the extreme values of imbalance price and maintain the transparency and predictability of the price of the imbalance. When we would assume that as the volume of system imbalance will have significant impact to the price of the imbalance. But actual state shows, that this not the case, as a results of system imbalance on 20/03/2024 shows – for the 16th delivery hour the system imbalance was 0,355 MWh and imbalance price was 16 661,55 Kč and on the other hand, for 8th delivery hour the system imbalance was 81,663 MWh and imbalance price was 51,08 Kč and for 17th delivery hour the system imbalance was -87,046 MWh and imbalance price was 3 790,47 Kč.

10. Literatures

10.1. References

[1] Kundur, P.: *Power System Stability and Control*. New York: McGraw-Hill

[2] Operation Handbook, UCTE

[3] Acha, E., Agelidis, V.G., Anaya-Lara, O., Miller, T.J.E.: *Power Electronic Control in Electrical Systems*. Newnes Press, India, 2002

[4] Chemišinec I. et al.: *Obchod s elektřinou*, Conte, 2010

[5] Kolektiv autorů: *Trh s elektřinou*, Asociace energetických manažerů, 2016

[6] ACER Market Monitoring Report 2018 – Electricity Wholesale Markets Volume, 2019. Available online: https://www.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/ACER%20Market%20Monitoring%20Report%202018%20-%20Electricity%20Wholesale%20Markets%20Volume.pdf

[7] https://www.ote-cr.cz/cs/statistika/odchylky-elektrina?version=2&date=2024-04-29. (Accessed on 29 April 2024).

[8] www.europex.org,

[9] https://transparency.entsoe.eu/

[10] https://www.eex-transparency.com/power/

[11] REGULATION (EU) 2019/943 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 on the internal market for electricity. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R0943

[12] 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 Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019L0944

[13] *EU energy policy*. Available online: https://ec.europa.eu/energy/en/topics/energy-strategy/clean-energy-all-europeans

[14] Commission Regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32017R2195 (EBGL)

[15] Commission Regulation (EU) 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration. Available online: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32017R2196 (NC ER)

[16] Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32017R1485 (SO GL)

[17] COMMISSION REGULATION (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32017R2195

[18] Scharff, R., & Amelin, M. (2016). *Trading behaviour on the continuous intraday market Elbas. Energy Policy*, 88, 544–557. doi:10.1016/j.enpol.2015.10.045.

[19] Zalzar, S., Bompard, E., Purvins, A., & Masera, M. (2020). *The impacts of an integrated European adjustment market for electricity under high share of renewables*. Energy Policy, 136, 111055. doi:10.1016/j.enpol.2019.111055.

[20] Clò, S., & Fumagalli, E. (2019). The effect of price regulation on energy imbalances: A Difference in Differences design. Energy Economics, 81, 754–764. doi:10.1016/j.eneco.2019.05.008 10.1016/j.eneco.2019.05.008.

[21] Jackson. R, Onar. O, Kirkham. H, Fisher. E, Burkes. K, Starke. M, Mohammed. O, Weeks. G; *Opportunities for Energy Efficiency Improvements in the U.S. Electricity Transmission and Distribution System* , ORNL/TM-2015/5.

[22] Naval, N., & Yusta, J. M. (2021). *Virtual power plant models and electricity markets - A review. Renewable and Sustainable Energy Reviews,* 149, 111393. doi:10.1016/j.rser.2021.111393.

[23] Glantz, M., & Kissell, R. (2014). *Equity Derivatives. Multi-Asset Risk Modeling*, 189–215. doi:10.1016/b978-0-12-401690-3.00006-8.

[24] Gasparella, A., Koolen, D. and Zucker, A., The Merit Order and Price-Setting Dynamics in European Electricity Markets, European Commission, Petten, 2023, JRC134300 .

[25] International Bank for Reconstruction and Development / The World Bank, *Wholesale Electricity Market Design*, Washington, DC., 2022.

[26] Balardy, C. Auction and Continuous Market for Power: Organization and Microstructure. Ph.D. Thesis, Université Paris-Dauphine, Paris, France, 2021. [Google Scholar].

[27] MCSC. *MESC—Market Europe Stakeholder Committee*. 2022. Available online: https://eepublicdownloads.azureedge.net/clean-

documents/Network%20codes%20documents/MESC/2022%20MESC%20documents/220914_MESC_3.4_Update%20on%20MCSC.pdf (Accessed on 3 June 2024).

[28] CNMC; ERSE. *Request for Amendments of the Spanish and Portuguese Regulatory Authorities on Common Spanish and Portuguese TSOs and NEMO* Proposal for Complementary Intraday Regional Auctions in Accordance with Article 63 of Commission Regulation (EU) 2015/1222 of 24 July 2015 Establishing a Guideline on Capacity Allocation and Congestion Management. 2017. Available online: https://www.cnmc.es/sites/default/files/Request%20For%20Amendments.pdf (Accessed on 17 June 2024).

[29] https://www.epexspot.com/en/marketcoupling. (Accessed on 9 June 2024)

[30] https://www.iea.org/articles/czech-republic-electricity-security-policy. (Accessed on 18 June 2024).

[31] Stojanović, B.; Kostić, Z. *Convergence of Economic Performance in the European Union. In Researching Economic Development and Entrepreneurship in Transitional Economies*; Ateljević, J., Trivić, J., Eds.; KarlFranzens-Universität Graz: Graz, Austria, 2015; pp. 55–66. [Google Scholar].

[32] Alberizzi, Andrea & Grisi, Paolo & Zani, Alessandro. (2021). Analysis of the SIDC market on relationship between auctions and continuous trading. 1-5. 10.23919/AEIT53387.2021.9627048.

[33] https://www.ote-cr.cz/cs/statistika/odchylky-elektrina?version=2&date=2024-04-29. (Accessed on 29 April 2024).

[34] relevant legislative requirements (Regulation of the European Parliament and of the Council (EU) 2019/943 and Decree No. 408/2015 Coll. on Electricity Market Rules)

[35] REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations (EU) 2019/943 and (EU) 2019/942 as well as Directives (EU) 2018/2001 and (EU) 2019/944 to improve the Union’s electricity market design(= ‘‘EMDR‘‘), 19 December 2023 .

[36] https://www.ceps.cz/cs/data#AktivaceSVRvCR (Accessed on 12 May 2024).

[37] Cross-zonal capacities and the 70% margin available for cross-zonal electricity trade (MACZT) 2023 Market Monitoring Report, ACER

[38] Nicola De Blasio, The Colors of Hydrogen, Belfer Center for Science and International Affairs, July 2024

[39] Fandi, G. – Novák, J. – Chyský, J. - Šrom, J.: Review and modeling on hydrogen fuel cells electric vehicle (HFCEV), in comparison with battery electrical vehicle (BEV) using MATLAB environment. Case study: Postal car, *Energy Conversion and Management: X*, Volume 24, October 2024, 100684. ISSN 0196-8904

10.2. Author’s Publications

Publication in impact journals

- Fandi, G. – Novák, J. – Chyský, J. - Šrom, J.: Review and modeling on hydrogen fuel cells electric vehicle (HFCEV), in comparison with battery electrical vehicle (BEV) using MATLAB environment. Case study: Postal car, *Energy Conversion and Management: X*, Volume 24, October 2024, 100684. ISSN 0196-8904

  https://www.sciencedirect.com/science/article/pii/S2590174524001624

  Shares: 25 % (The authors have agreed that the author's shares are divided equally.)

Publication in periodicals

- Chemišinec, I. - Šrom, J.: Rok propojeného vnitrodenního trhu s elektřinou v ČR. *Energetika*. 2020, roč. 70, č. 6. ISSN 0375-8842

  Shares: 50 % (The authors have agreed that the author's shares are divided equally.)

- Šrom, J.: Mimořádné stavy v elektrizační soustavě a možnosti jejich předcházení prostřednictvím vnitrodenního trhu s elektřinou. *Energetika*. 2020, roč. 70, č. 3. ISSN 0375-8842

- Šrom, J.: Organizovaný vnitrodenní trh s plynem OTE. *Energetika*. 2019, roč. 69, č. 2. ISSN 0375-8842

- Šrom, J. – Stejskalová, A.: Evropský reporting obchodů s energiemi – od implementace k provozu. *Energetika*. 2017, roč. 67, č. 2. ISSN 0375-8842

  Shares: 50 % (The authors have agreed that the author's shares are divided equally.)

- Šrom, J.: Modernizace bloku pro poskytování primární regulace frekvence. *Energetika*. 2012, roč. 62, č. 4. ISSN 0375-8842

Publication in conference proceedings

- Šrom, J. - Müller, Z.: Emergency situations in the transmission grid and opportunities for their prevention through the intraday electricity market. In *Sborník 2020 21st International Scientific Conference on Electric Power Engineering (EPE),* Prague, 2020. ISBN 978-1-7281-9479-0.

  Shares: 50 % (The authors have agreed that the author's shares are divided equally.)

- Mareček, P. - Šrom, J. - Švec, J. - Müller, Z.: Impact of distributed sources on the currents in distribution networks. In *Sborník ČK CIRED 2011* [CD-ROM]. Tábor: Český komitét CIRED, 2011, p. 1-13. ISBN 978-80-905014-0-9.

  Shares: 25 % (The authors have agreed that the author's shares are divided equally.)

- Šrom, J.: *Evaluation of Dynamic Equivalents in the Distribution Network Models*. In POSTER 2010 - Proceedings of the 14th International Conference on Electrical Engineering [CD-ROM]. Praha: ČVUT v Praze, FEL, 2010, p. 1-5. ISBN 978-80-01-04544-2.

- Müller, M. - Müller, Z. - Kasembe, A. - Sýkora, T. - Švec, J. – Šrom, J. – Tlustý, J.: *Phasor Measurement Units in Power System Monitoring.* In Sborník konference ELEN 2010 [CD-ROM]. Prague: CTU, Faculty of Electrical Engineering, Department of Electroenergetics, 2010, p. 1-5. ISBN 978-80-254-8089-2.

  Shares: 14.3 % (The authors have agreed that the author's shares are divided equally.)

Publications related to the topic of the dissertation

Fandi, G. – Novák, J. – Chyský, J. - Šrom, J.: Review and modeling on hydrogen fuel cells electric vehicle (HFCEV), in comparison with battery electrical vehicle (BEV) using MATLAB environment. Case study: Postal car, *Energy Conversion and Management: X*, Volume 24, October 2024, 100684. ISSN 0196-8904

- Investigation, Validation, Supervision

In the paper was examined simulation for the difference in operation of Battery Electric Vehicle (BEV) and Hydrogen Fuel Cell Electric Vehicle (HFCEV) used as Postal car that resulted more in favor of BEV - travelled distance that the electric vehicle that runs on fuel cells without refueling turns out to be shorter (approximately 90 km for BEV and 65 km for HFCEV).

So, based on the results of the simulation, so far better BEV for the operation but worst from the transmission system operation as the solar generation cannot be used for charging of this type of EV.

On the other hand, the advantage of using HFCEVs for the transmission system is in the variability of the hydrogen generation in the time and possibility of storing the hydrogen for longer periods until it is needed.

Šrom, J.: Mimořádné stavy v elektrizační soustavě a možnosti jejich předcházení prostřednictvím vnitrodenního trhu s elektřinou. *Energetika*. 2020, roč. 70, č. 3. ISSN 0375-8842

- Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation

The intraday electricity market is increasing its importance within the electricity market. The article introduces real examples of the contribution of the intraday electricity market for the prevention and solution of emergency situations in the electricity system.

Chemišinec, I. - Šrom, J.: Rok propojeného vnitrodenního trhu s elektřinou v ČR. *Energetika*. 2020, roč. 70, č. 6. ISSN 0375-8842

- Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation

On November 19, 2020, one year passed since the day when the Czech intraday electricity market was organized market connected to the pan-European intraday electricity market. The purpose of this article was to remind one year of this operation. Looking back, we stated that there were positive effects that this connection brought for the Czech and European markets.

Šrom, J. - Müller, Z.: Emergency situations in the transmission grid and opportunities for their prevention through the intraday electricity market. In *Sborník 2020 21st International Scientific Conference on Electric Power Engineering (EPE),* Prague, 2020. ISBN 978-1-7281-9479-0.

- Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation

The article emphasizes the positive contribution of the integration of the intraday electricity market in the implementation of the single intraday electricity market in Europe. There are shown real examples from the operation of the transmission system during the outage of biggest unit in the system and reaction of the market participants on intraday market to eliminate financial damages.

11. Abbreviation

Abbreviation	Definition
4MMC	4M Market Coupling
ACER	Agency for the Cooperation of Energy Regulators
AnS	Ancillary Services
ATC	Available Transmission Capacity
CACM	Capacity Allocation and Congestion Management Guideline
CEE	Central-East Europe
CEP	Clean EnergyPackage
DA	Day-ahead
EC	European Commission
EU	European Union
FBMC	Flow Based Market Coupling
GCT	Gate Closure Time
ID	Intraday
IDM	Intraday Market
IEM	Internal Energy Market
LF	Loop Flow
MP	Market Participant
MRC	Multi-Regional Coupling
MS	Member State
MTU	Market Time Unit
NRA	National Regulatory Authority
NTC	Net Transfer Capacity
RES	Renewable Energy Sources
SDAC	Single Day-Ahead Coupling
SEM	Single Energy Market
SI	System Imbalance
SIDC	Single Intraday Coupling
SO	System Operation

TSO	Transmission System Operator
UAF	Unscheduled Allocated Flow
UF	Unscheduled Flow