



NATIONAL RESOURCE ADEQUACY ASSESSMENT 2025

Power System Planning & Analyzes

MEPSO

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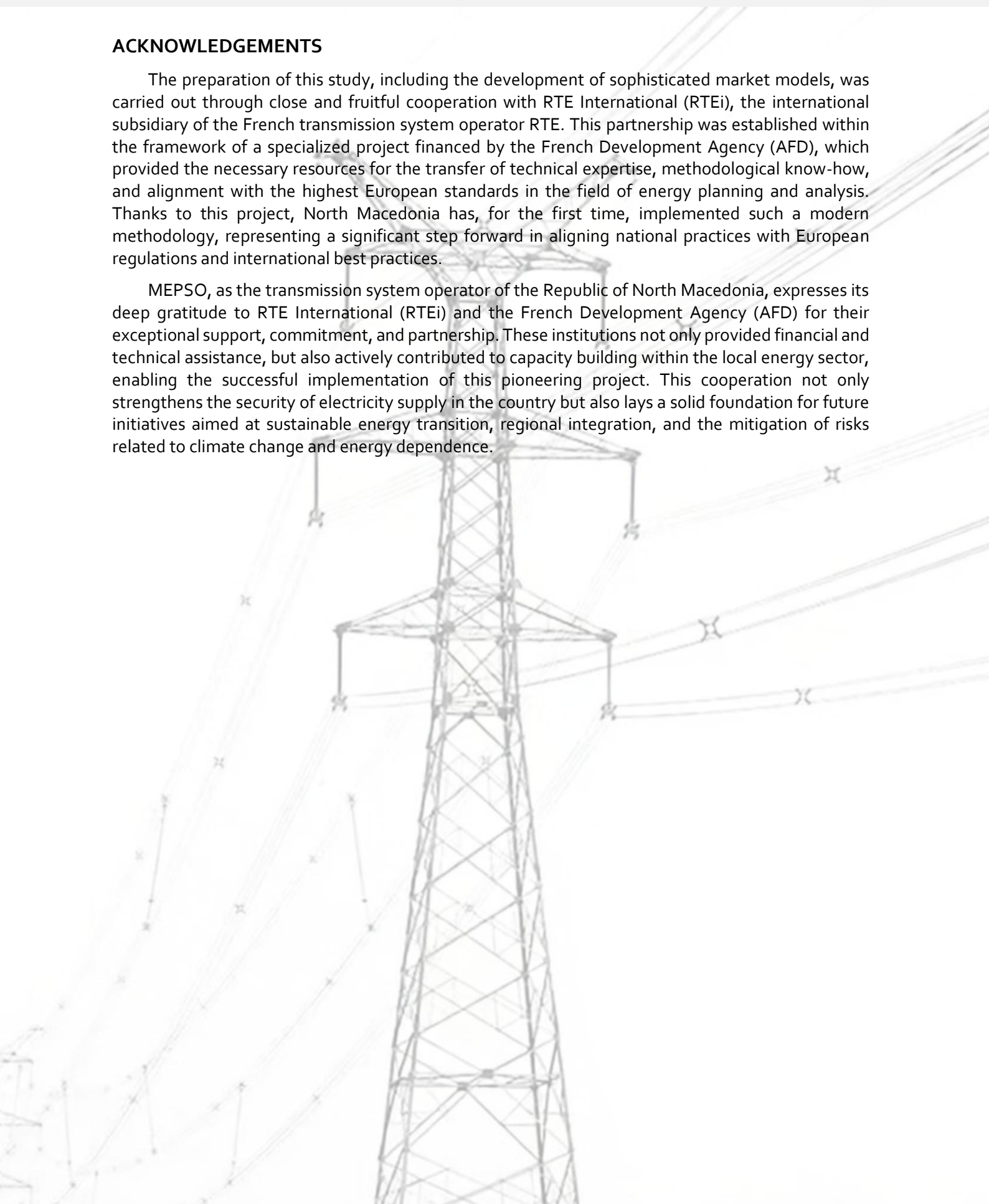
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MEPSO, as the transmission system operator of the Republic of North Macedonia, expresses its deep gratitude to RTE International (RTEi) and the French Development Agency (AFD) for their exceptional support, commitment, and partnership. These institutions not only provided financial and technical assistance, but also actively contributed to capacity building within the local energy sector, enabling the successful implementation of this pioneering project. This cooperation not only strengthens the security of electricity supply in the country but also lays a solid foundation for future initiatives aimed at sustainable energy transition, regional integration, and the mitigation of risks related to climate change and energy dependence.



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1. INTRODUCTION

According to the Energy Law [1], MEPSO, as the transmission system operator, is responsible for the operation, maintenance, development, interconnection with the transmission systems of neighboring countries, and for ensuring the long-term capability of the system to meet reasonable needs for the transmission of electricity.

Article 20 of the Energy Law stipulates that the transmission system operator prepares a resource adequacy assessment for the Republic of North Macedonia, which is approved by the Ministry and which also covers regional aspects, applying the methodology used for the European assessment.

Adequacy represents the ability of the power system to meet total electricity demand and capacity requirements at all times, taking into account available domestic generation capacities, cross-border exchange possibilities, and expected conditions of consumption and production.

“Absolute” adequacy of the power system cannot be achieved unless “infinite” investments are considered. Therefore, the essential objective is to ensure an optimal balance between cost-effectiveness and security of supply.

There are two approaches to assessing system adequacy:

- Deterministic approach,
- Probabilistic approach.

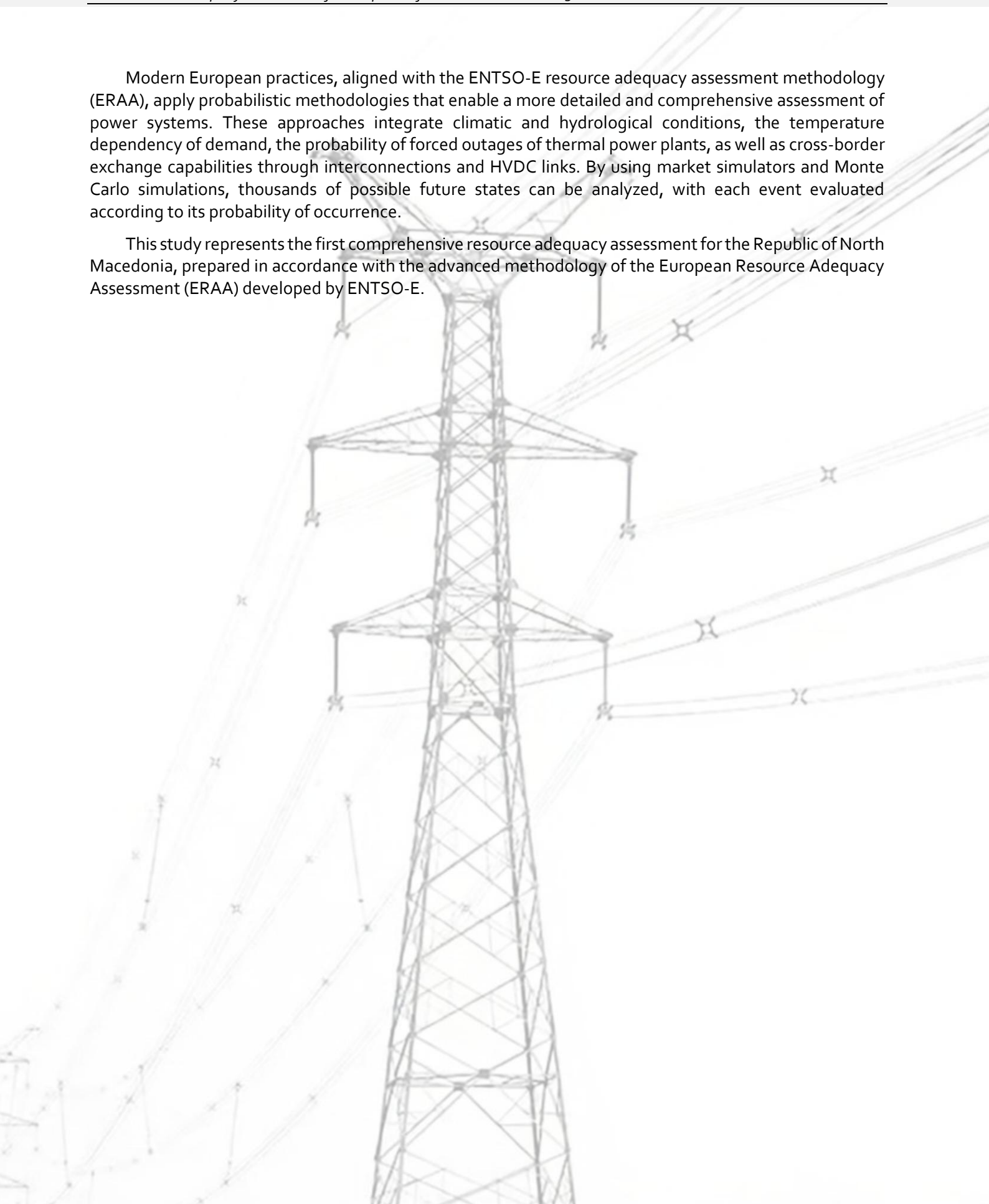
The deterministic approach to adequacy assessment essentially consists of calculating specific system states based on predefined scenarios. As a result, only a limited number of calculations can be performed for pre-defined specific system conditions. This method provides fast results and does not require significant computational capacity, but it does require extensive knowledge of the power system—the transmission system operator must identify and anticipate the most critical future system states, and adequacy calculations are then performed based on these assumptions. The main weakness of deterministic analyses lies in the fact that they do not account for the probabilistic nature of power system behavior. Due to the large-scale integration of renewable energy sources with intermittent characteristics, as well as market liberalization, the deterministic method is becoming an increasingly inaccurate and unreliable way for assessing system adequacy.

Traditionally, system adequacy in the region has been assessed using deterministic approaches that considered worst-case scenarios regardless of their probability. However, with the increasing share of variable renewable energy sources, the stochastic nature of generation, and the climate-driven variability of demand, the deterministic method is becoming less accurate and reliable. This necessitates a transition toward probabilistic methodologies aligned with the European Resource Adequacy Assessment (ERAA) and the evolving standards of ENTSO-E. Such approaches enable a more accurate and advanced assessment of supply shortage risks.

The Macedonian energy sector is undergoing a fundamental transformation. The planned gradual retirement of lignite-fired power plants, the accelerated integration of renewable energy sources (RES), and increased regional market integration present both significant opportunities and serious challenges for the future operation of the power system. With the transition toward a green generation mix, in which variable sources such as wind and solar progressively replace fossil-fuel plants, it is crucial to assess resource adequacy and the system’s ability to ensure secure supply. For North Macedonia, these challenges are even more pronounced due to import dependency, aging thermal fleet, and the planned decommissioning of lignite plants. Although interconnections create opportunities for regional balancing and strengthening adequacy, reliance on cross-border support must be carefully considered under potential stress conditions in the power systems of Southeast Europe. At the same time, ambitious national and regional energy transition targets will change system dynamics and require substantial investments in the transmission network, the development of storage capacities, and the provision of advanced system services.

Modern European practices, aligned with the ENTSO-E resource adequacy assessment methodology (ERAA), apply probabilistic methodologies that enable a more detailed and comprehensive assessment of power systems. These approaches integrate climatic and hydrological conditions, the temperature dependency of demand, the probability of forced outages of thermal power plants, as well as cross-border exchange capabilities through interconnections and HVDC links. By using market simulators and Monte Carlo simulations, thousands of possible future states can be analyzed, with each event evaluated according to its probability of occurrence.

This study represents the first comprehensive resource adequacy assessment for the Republic of North Macedonia, prepared in accordance with the advanced methodology of the European Resource Adequacy Assessment (ERAA) developed by ENTSO-E.



2. METHODOLOGY

The methodology applied in this study is based on the principles of the European Resource Adequacy Assessment (ERAA) [3], with adaptations to the specific characteristics of the Macedonian power system. The approach relies on probabilistic market modeling with high temporal (hourly) and spatial resolution, aiming to provide a quantitative assessment of resource adequacy under different future system conditions.

The input data is harmonized and based on demand and generation scenarios defined in the National Energy and Climate Plan (NECP) and the Pan-European Climate Database (PECD). This approach ensures consistency with European practices and enables realistic modeling of the weather dependency of demand, renewable energy generation, and hydrological inflows.

To analyze uncertainties, a Monte Carlo (MC) simulation framework with Unit Commitment and Economic Dispatch (UCED) is applied, capturing the variability of renewable resources, forced outages of units, and the availability of interconnections. This enables the simultaneous consideration of national and regional aspects of security of supply, including cross-border transmission capacities, interdependent shortage events, and structural risks within the interconnected European system.

Power system adequacy refers to the ability of the electricity system, under normal operating conditions, to continuously meet total demand and the energy needs of end users, taking into account planned outages and the probability of unplanned outages of generation units, storage facilities, and transmission elements.

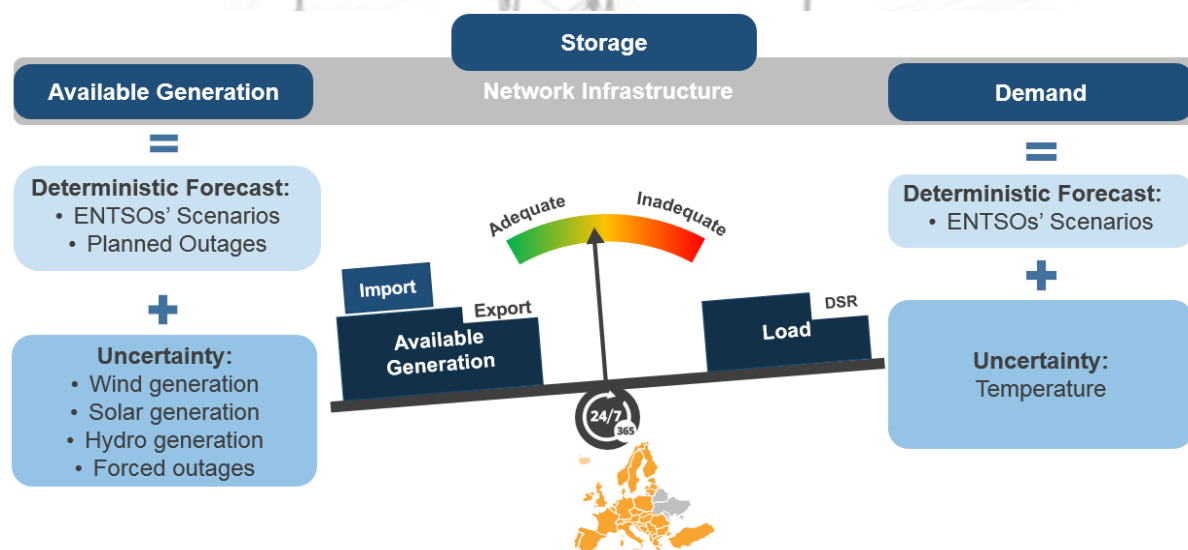


Figure 1. Resource Adequacy Assessment

In an interconnected system such as Macedonian power system, resource adequacy assessment cannot be limited solely to national borders, but must also include neighboring countries, as cross-border interconnections can significantly influence the systems ability to ensure secure supply. The objective of this assessment is to quantitatively evaluate security of supply across different future scenarios using probabilistic indicators.

Modern resource adequacy assessment methodologies incorporate uncertainties in demand, generation, and overall system conditions, enabling the analysis of a wide range of possible variations in key system variables. In this context, a Monte Carlo simulation framework with Unit Commitment and Economic Dispatch is applied, allowing for the modeling of renewable generation variability, forced and planned outages of generating units, and the availability of interconnections. This provides a realistic assessment of both national and regional adequacy risks.

In addition, an analysis of curtailed renewable energy (spilled energy) is performed for the medium-term planning horizon.

2.1. ADEQUACY INDICATORS

In probabilistic resource adequacy assessment studies, the typical adequacy metrics are expressed as expected values of indicators (e.g. EENS). The following indicators are used to assess the level of resource adequacy in accordance with the ERAA methodology adopted by ACER:

- **LOLE [h]:** The expected number of hours in which available resources are insufficient to meet demand, calculated across multiple Monte Carlo scenarios.
- **EENS [GWh]:** The expected amount of electrical energy that cannot be supplied due to insufficient resources..

A Reliability Standard (RS) is used for the quantitative evaluation of security of supply and integrates the key parameters: Value of Lost Load (VoLL), Cost of New Entry (CONE), and Loss of Load Expectation (LOLE)..

- **VoLL [€/MWh]** represents the economic value of unserved electricity for end consumers and defines the cost of unmet demand in market models..
- **CONE [€/MW/roA]** represents the investment cost of new generation capacity and links the economic viability of new investments with the need for security of supply.
- **LOLE [h/roA]** measures the expected number of hours in which available resources are insufficient to meet demand, serving as a direct indicator of system adequacy.

Up to this date, North Macedonia has not introduced a Reliability Standard in which the values of VoLL, CONE, and LOLE are formally defined. As a result, an economic viability assessment of options for the permanent or temporary closure of existing capacities and the construction of new electricity generation capacities (EVA) cannot be carried out. The dynamics of retiring the old thermal fleet and constructing new gas-fired power plants follow the Macedonian strategic energy framework.

After the calculation of adequacy indicators using the market simulator, the results are compared with European security-of-supply standards and with the assumed parameter values embedded in the market model.

The comparison between these assumed VoLL and LOLE values and the results obtained from the market simulations forms the basis for determining whether the national power system provides a level of security of supply aligned with European practice. Exceeding the reference thresholds of the adequacy indicators signals an increased risk to security of supply and indicates the need for additional generation capacity, increased flexibility, or expanded cross-border exchange capacities. Conversely, results significantly below the threshold indicate that security of supply is sustainable under the analyzed scenarios, while potentially also pointing to the existence of surplus capacity in the system.

2.2. CONVERGENCE

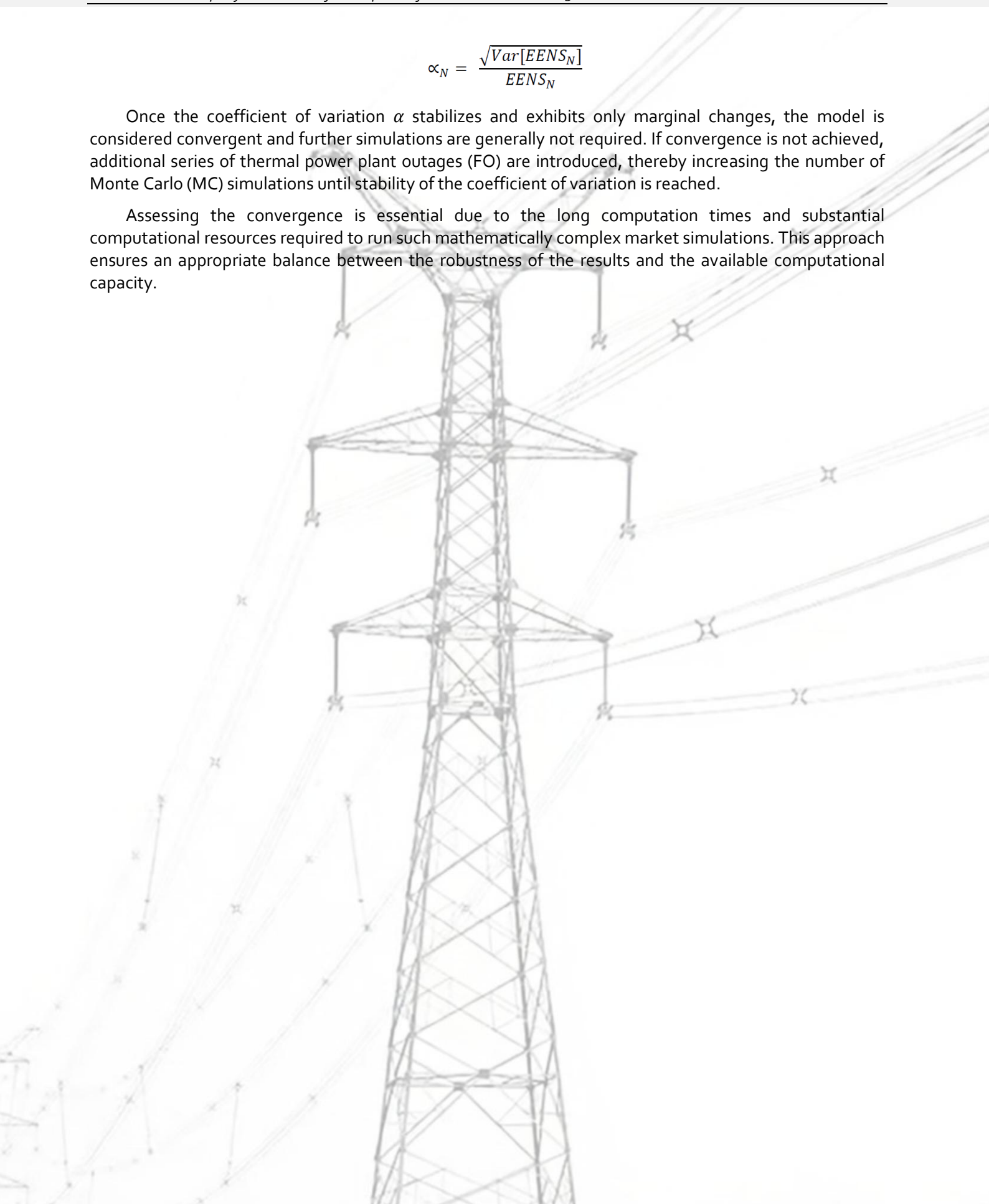
Monte Carlo (MC) simulations are defined as combinations of weather scenarios from the PECD (WS) and forced outages of thermal power plants (FO). Thermal plant outages can affect the results of individual MC years depending on demand and supply conditions. For example, an outage of a large thermal power plant may cause a significant adequacy risk during periods of high demand and low renewable generation, while the same outage may have a negligible impact under favorable system conditions.

To ensure statistically robust results, the impact of additional MC simulations is monitored using key indicators such as Energy Not Served (ENS). Convergence is assessed through the relative change of the coefficient of variation, α , calculated from ENS values across all executed MC simulations.

$$\alpha_N = \frac{\sqrt{\text{Var}[EENS_N]}}{EENS_N}$$

Once the coefficient of variation α stabilizes and exhibits only marginal changes, the model is considered convergent and further simulations are generally not required. If convergence is not achieved, additional series of thermal power plant outages (FO) are introduced, thereby increasing the number of Monte Carlo (MC) simulations until stability of the coefficient of variation is reached.

Assessing the convergence is essential due to the long computation times and substantial computational resources required to run such mathematically complex market simulations. This approach ensures an appropriate balance between the robustness of the results and the available computational capacity.



3. STATISTICAL DATA

Power systems are complex systems that integrate multiple components, as shown in Figure 2. This chapter presents the individual categories for the energy and capacity balance of the Macedonian power system.

- Transmission network:
 - Generation from thermal power plants (TPPs) connected to the transmission network,
 - Generation from hydropower plants (HPPs) connected to the transmission network,
 - Generation from renewable energy sources (RES: wind and solar) connected to the transmission network,
 - Consumption by direct consumers connected to the transmission network,
 - Losses in the transmission network,
 - Net consumption by distribution networks.
- Distribution network:
 - Net injected electricity from the transmission network,
 - Generation from power plants connected to the distribution network,
 - Consumption in the distribution system,
 - Losses in the distribution network.
- Интерконекции со соседни ЕЕС-и:
 - Import of electricity from neighboring power systems,
 - Export of electricity to neighboring power systems.

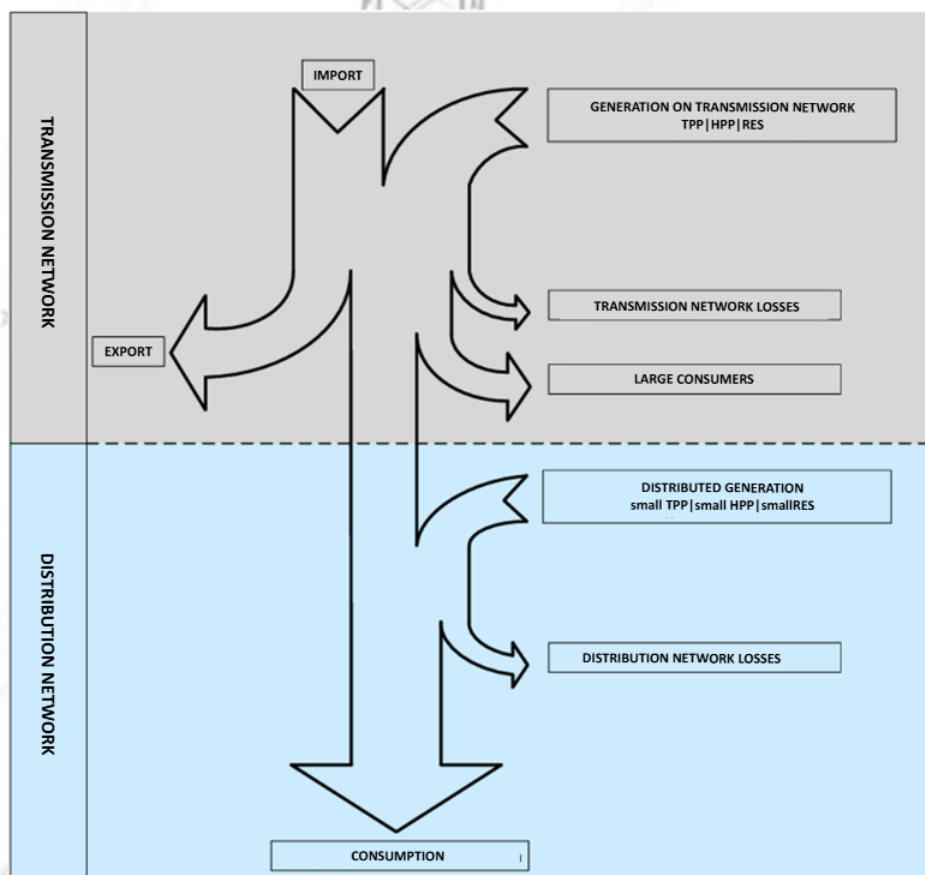


Figure 2. Components of the Macedonian Power System

3.1. HISTORICAL ELECTRICITY CONSUMPTION AND CHARACTERISTICS

This chapter presents statistical data related to electricity consumption in Macedonia, with a particular focus on historical trends and consumer characteristics over the past period. The analysis of these data provides insights into total consumption trends, seasonal and daily variations, as well as the distribution across sectors and consumer categories. This information forms the basis for forecasting future electricity demand and planning the appropriate development of the power system.

Figure 3 shows the total electricity consumption over the past ten years as measured at the transmission network. Total electricity consumption has been steadily declining since 2014. Due to decreased consumption on one hand, and network investments on the other, losses in the transmission and distribution networks have decreased from 1.06 TWh in 2014 to 0.972 TWh in 2024. Electricity consumption by large consumers directly connected on the transmission network has seen a significant reduction, from 1.98 TWh in 2014 to 0.65 TWh in 2024.

Electricity consumption among users connected to the distribution network grew during the period 2014–2021, reaching 5.67 TWh. However, in the period 2021–2024, a notable decline in consumption within the distribution network was observed, totaling 4.8 TWh in 2024, primarily due to distributed generation from small-scale photovoltaic (PV) installations.

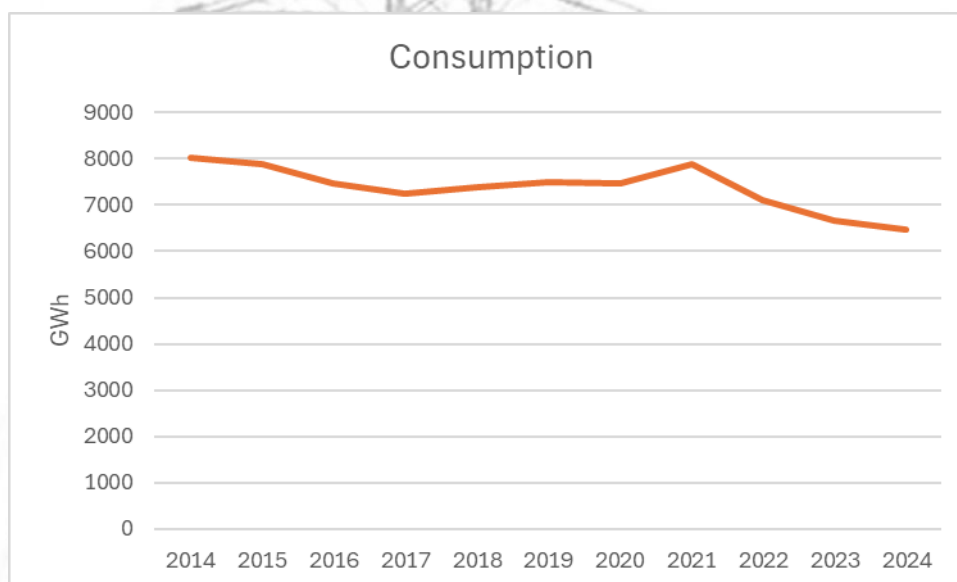


Figure 3. Total electricity consumption

Figure 4 shows the trend of losses in the transmission and distribution networks over the period 2014–2024. Total losses range between approximately 950–1050 GWh per year, with a noticeable decrease in recent years. The majority of losses occur in the distribution network, while the transmission network accounts for a relatively small share. However, following a slight increase in 2021, total losses have stabilized and shown a gradual decline, indicating an improvement in overall network efficiency.



Figure 4. Losses on transmission and distribution network

Figure 5 presents the total electricity consumption divided into:

- Distribution network consumption (households and small consumers), and
- Directly connected consumers (industry connected to the transmission network).

It can be observed that the share of distribution network consumption is increasing, while consumption by directly connected consumers is gradually declining, particularly after 2021. This trend indicates either a weakening of industrial activity or improved energy efficiency among large consumers, while demand within the distribution network remains stable.

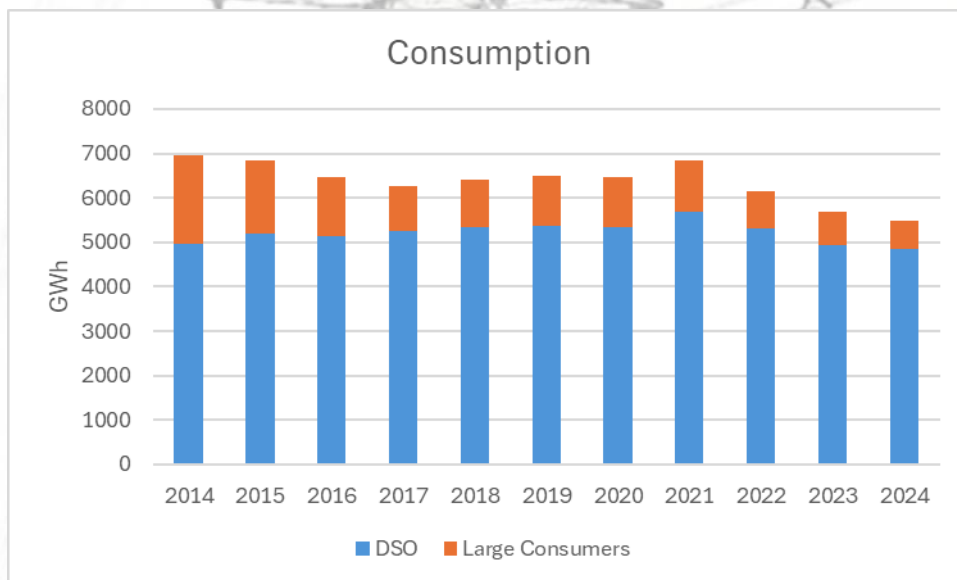


Figure 5. Total electricity consumption on transmission and distribution level

The total electricity consumption measured at the transmission network on a daily basis for the period 2021–2024 is shown in Figure 6.

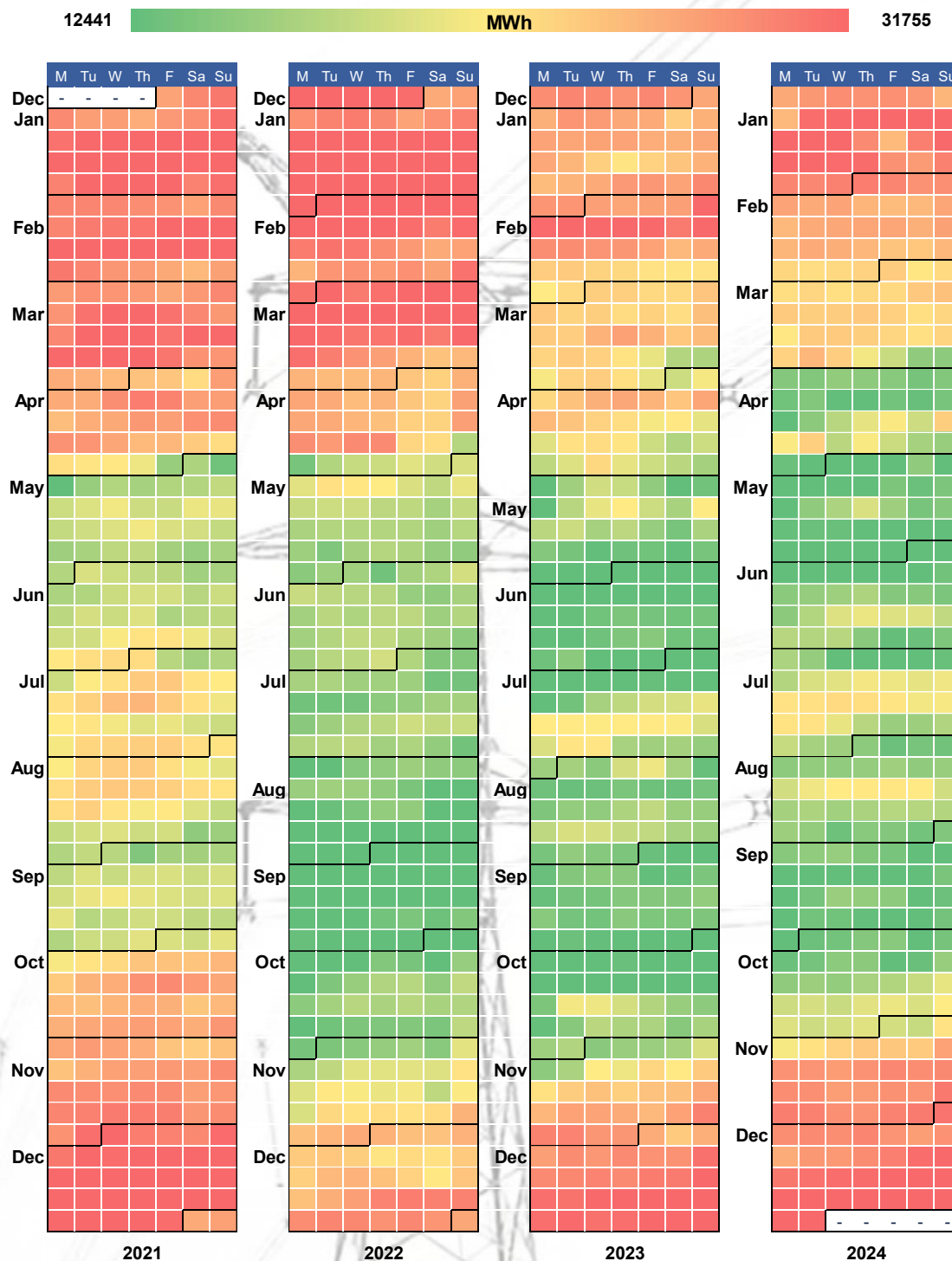


Figure 6. Daily electricity consumption

3.2. HISTORICAL ELECTRICITY PRODUCTION

During the period 2014–2024, electricity generation and consumption in the Republic of North Macedonia reflect the process of gradual energy transition. The analysis covers the main trends in domestic electricity generation, sectoral consumption, and changes in the structure of energy sources.

Over this ten-year period, a gradual decrease in total electricity consumption can be observed, alongside a stabilization of generation from thermal power plants, pronounced fluctuations in hydropower production, and a continuous growth of renewable energy sources, particularly after 2020.

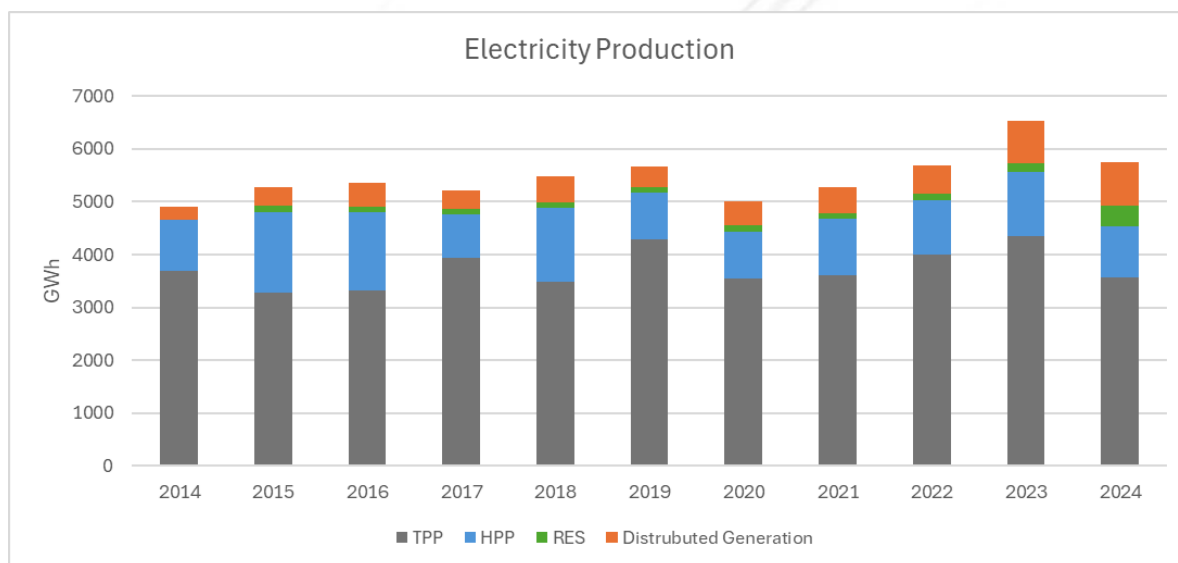


Figure 7. Electricity Production

Electricity generation from thermal power plants remains the dominant source, but with a declining trend, mainly due to reduced production at REK Bitola and the limited role of TPP Negotino. Although the combined-cycle gas power plant TE-TO demonstrates flexibility and reliability, overall generation from fossil fuels has decreased by more than 10% compared to the beginning of the period, indicating a gradual shift toward more sustainable energy sources.

Hydropower remains a key but highly variable component of electricity generation, strongly influenced by hydrological conditions and reservoir management. In favorable years, such as 2015 and 2023, hydropower plants contributed significantly higher production, while in dry years their share decreases by more than half.

At the same time, generation from renewable energy sources shows continuous growth, driven by the connection of new wind and solar power plants at transmission level, as well as the expansion of distributed generation (DG) from smaller photovoltaic systems and biogas plants.

Overall, the trend indicates a gradual reduction in dependence on coal and an increasing share of flexible and renewable energy sources, which is reshaping the country's energy mix and improving the level of energy sustainability. These changes, accompanied by improvements in energy efficiency and new investment initiatives, are placing North Macedonia on a path toward a stable and low-carbon energy future.

3.3. HISTORICAL ELECTRICITY EXCHANGES WITH NEIGHBOURING POWER SYSTEMS

Over the past decade, the energy balance of the Republic of North Macedonia indicates a gradual transition of the electricity system, characterized by a decline in total electricity consumption, an increasing share of renewable energy sources, and changing dynamics in cross-border electricity exchange.

During the period 2014–2024, a continuous decrease in consumption can be observed—from around 8,000 GWh to approximately 6,500 GWh. This trend is mainly driven by reduced industrial activity, improvements in energy efficiency, and the growing use of distributed photovoltaic systems, particularly after 2021.

Domestic electricity generation ranges between 5,000 and 6,500 GWh per year, showing a strong dependence on hydrological conditions and fuel supply and lignite quality. The increased integration of renewable energy sources in recent years has significantly reduced the need for electricity imports and enabled the country to achieve near energy independence in 2023.

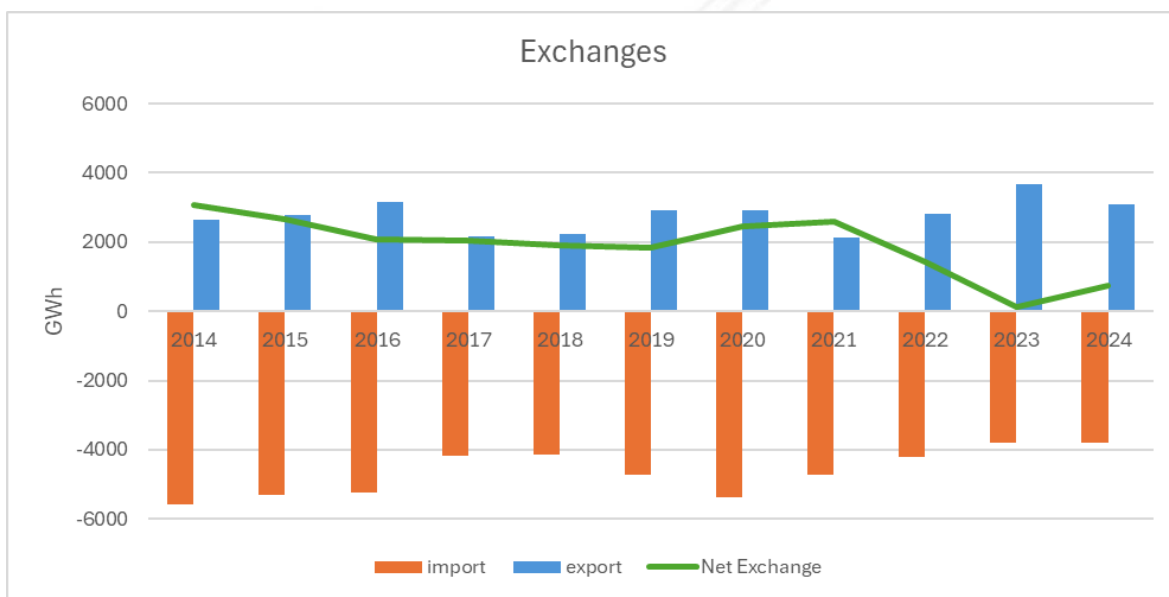


Figure 8. Import, export and net exchanges

Regarding cross-border electricity exchange, the volume of net exchanges with neighbouring power systems shows a gradual decline, from more than 3,000 GWh in 2014 to approximately 730 GWh in 2024. From 2022 onwards, net exchanges decreased significantly, in parallel with the decline in industrial electricity consumption and the growth of local generation from solar power plants. In 2023, a notable increase in electricity exports was recorded—exceeding 3,600 GWh—as a result of favourable conditions for renewable energy generation and reduced domestic demand. These trends confirm the increasing role of domestic renewable energy capacities in the national electricity system.

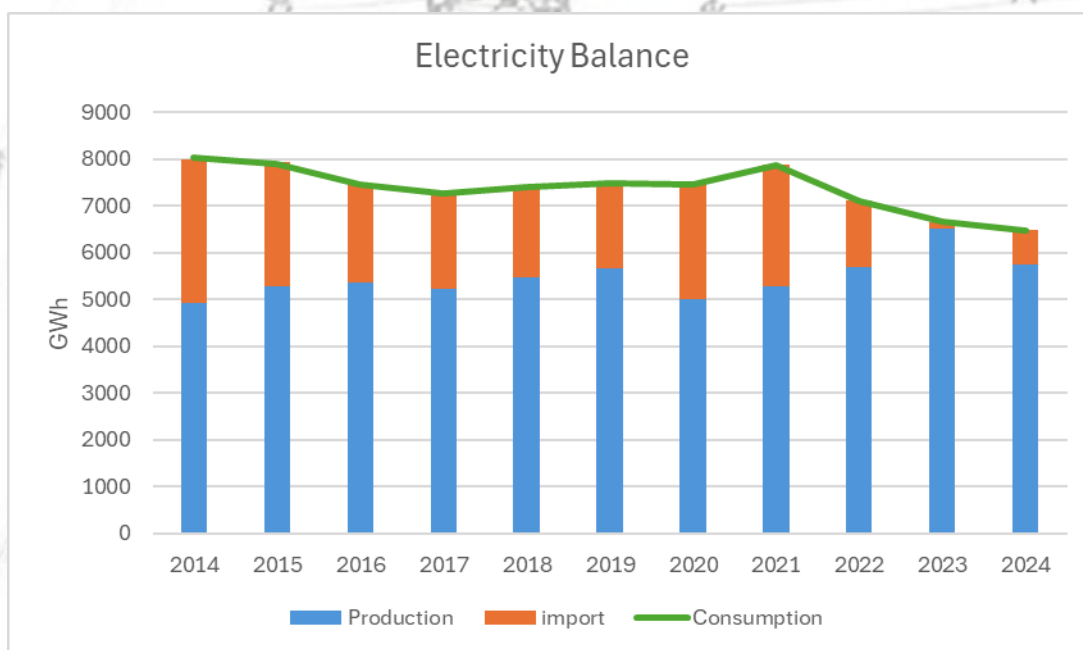


Figure 9. Electricity Balance



Figure 11: Geographical perimeter of the Market Model (u3b0p: ERAA)

This study explicitly models a total of 35 countries and the cross-border interconnections between the zones. Some countries are further divided into multiple zones in order to reflect their specific market structures and regulatory frameworks. Such granularity allows the model to more accurately capture regional differences in system characteristics, market behaviour, and transmission constraints.

4.3. PLANNING HORIZON

This study will analyse three planning horizons: short-term, medium-term, and long-term. The short-term planning horizon enables the assessment of immediate resource adequacy challenges, such as changes in electricity demand and the availability of generation capacities. The medium-term and long-term planning horizons allow for the analysis of longer-term trends, including the transition towards renewable energy sources, the reduction of carbon dioxide emissions, the economic viability of investments, and the integration of new technologies such as energy storage and smart grids. These planning horizons are aligned with the methodology of the European Resource Adequacy Assessment, which evaluates resource adequacy at the pan-European level.

5. SCENARIOS

For this national resource adequacy assessment of the Macedonian power system across different planning horizons, national scenarios have been defined to reflect possible future development pathways for generation capacities and electricity consumption. These scenarios are based on official strategic documents, including the National Energy Development Strategy until 2040, the National Energy and Climate Plan, the Ten-Year Network Development Plan, and the European Resource Adequacy Assessment by ENTSO-E.

Within the study, two generation scenarios (Scenario A and Scenario B) are considered. These scenarios differ in terms of the structure, scale, and pace of integration of new generation capacities, particularly regarding renewable energy sources and the transition away from fossil fuels. Both scenarios assume the gradual retirement of existing coal-fired thermal power plants, in line with national decarbonisation plans. However, they differ in the speed and extent of integration of solar, wind, and hydropower capacities, as well as in the development of gas-fired plants intended to provide system flexibility.

For electricity demand, one reference scenario has been defined, which is directly aligned with the European Resource Adequacy Assessment and the Ten-Year Network Development Plan of ENTSO-E. This approach ensures full harmonisation with the pan-European adequacy assessment methodology.

The combination of the two generation development scenarios with the reference demand scenario results in two simulation cases, which are analysed in ANTARES for all planning horizons. The key characteristics of each scenario are described in detail in the following sections.

5.1. GENERATION SCENARIOS

In this national resource adequacy assessment, two scenarios for the development of generation capacities have been defined for all planning horizons. These scenarios are based on different assumptions regarding the evolution of the generation mix, commissioning of new capacities, the level of integration of renewable energy sources, and the level of decarbonization. Each scenario represents an internally consistent development pathway for the electricity sector, aligned with national energy and climate objectives as well as relevant regional trends and policies.

5.1.1. SCENARIO A

Scenario A represents the reference development scenario for generation mix in the Macedonian electricity system, fully aligned with national policies and strategies. This scenario takes into account the current national plans for decarbonization, renewable energy integration, and system security, achieved through balanced investments in flexible capacities. It foresees the gradual retirement of coal-fired thermal power plants, their replacement with new gas-fired plants, and the parallel integration of solar and wind power plants.

The generation mix for Scenario A is presented in the following table and Figure 12.

Table 1. Installed Capacity – Scenario A

	Horizon [MW]		
	Short-term	Mid-term	Long-term
Lignite	300	150	0
Gas	509	759	959
Biomass/Biogas	31	61	71
Hydro	539	539	539
RoR	180	189	189
PSHPP	0	0	333
PV	1146	1316	1916
Wind	200	256	376
BESS	30	50	50

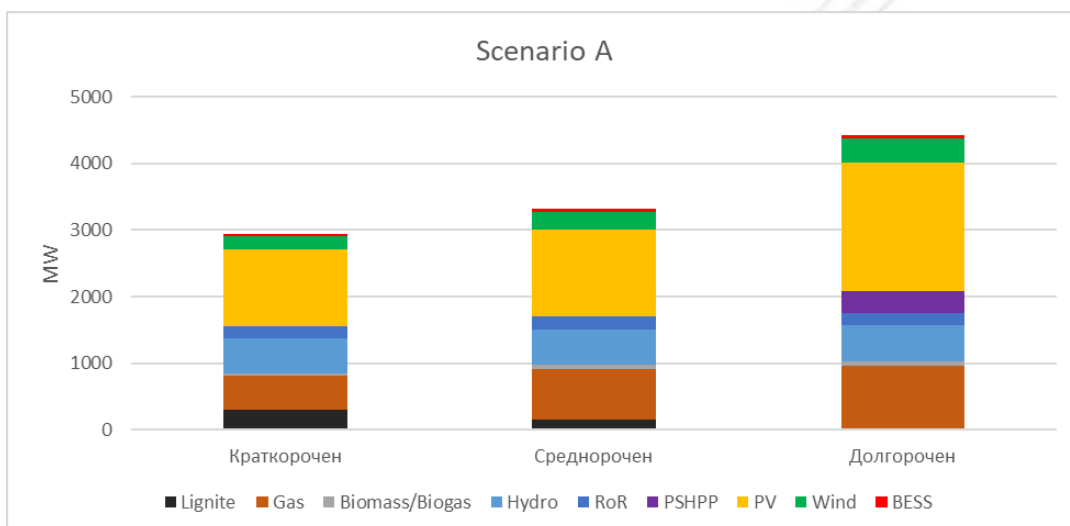


Figure 12. Generation Mix – Scenario A

5.1.2. SCENARIO B

Scenario B represents an ambitious development scenario for generation mix, with a strong focus on increased integration of renewable energy sources (RES). The development of conventional generation capacities in this scenario follows national policies and strategies but incorporates a significantly higher share of solar and wind power plants, complemented by battery energy storage systems.

The generation mix for Scenario B is presented in the following table and Figure 13.

Table 2. Installed Capacity – Scenario B

	Horizon [MW]		
	Short-term	Mid-term	Long-term
Lignite	300	150	0
Gas	509	759	959
Biomass/Biogas	31	61	71
Hydro	539	539	539
RoR	180	189	189
PSHPP	0	0	333
PV	1300	1700	2550
Wind	309	448	803
BESS	50	100	300

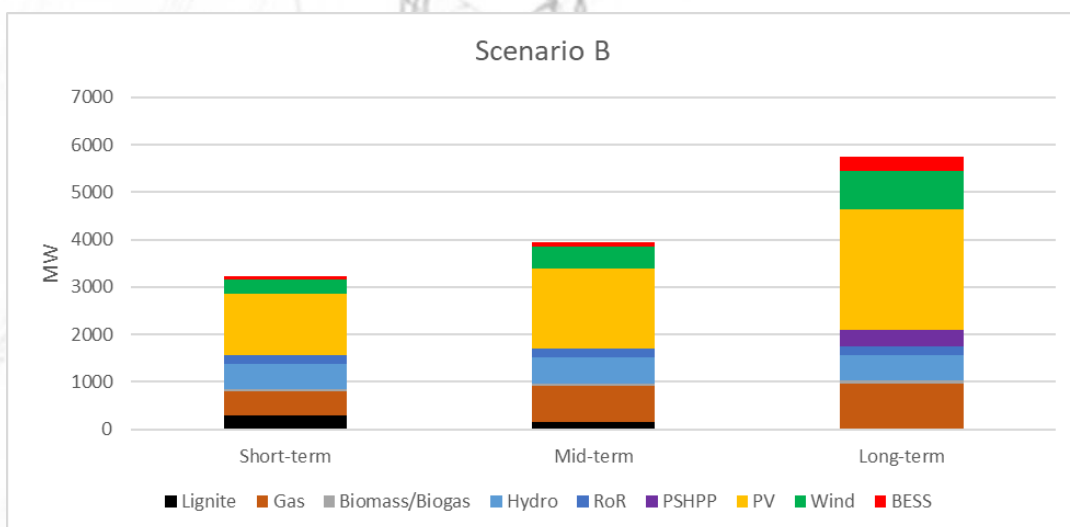


Figure 13 Generation Mix – Scenario B

5.2. DEMAND SCENARIO

This national resource adequacy assessment study uses a single consumption scenario, representing a reference development pathway for projecting electricity demand. This scenario is aligned with the methodology and assumptions applied in the ERAA 2025 study, ensuring consistency and comparability of results with ERAA. This approach provides a realistic basis for assessing supply security under different development conditions of generation capacities and market circumstances.

Electricity consumption is dependent on climatic parameters. In this study, consumption is modelled as a climate-dependent variable to reflect the impact of temperature and seasonal conditions on demand. To achieve this, the study includes a total of 36 different climatic years, with each year having its own hourly consumption profile. This approach allows for a realistic representation of demand variability and a more accurate assessment of security of supply under varying weather conditions.

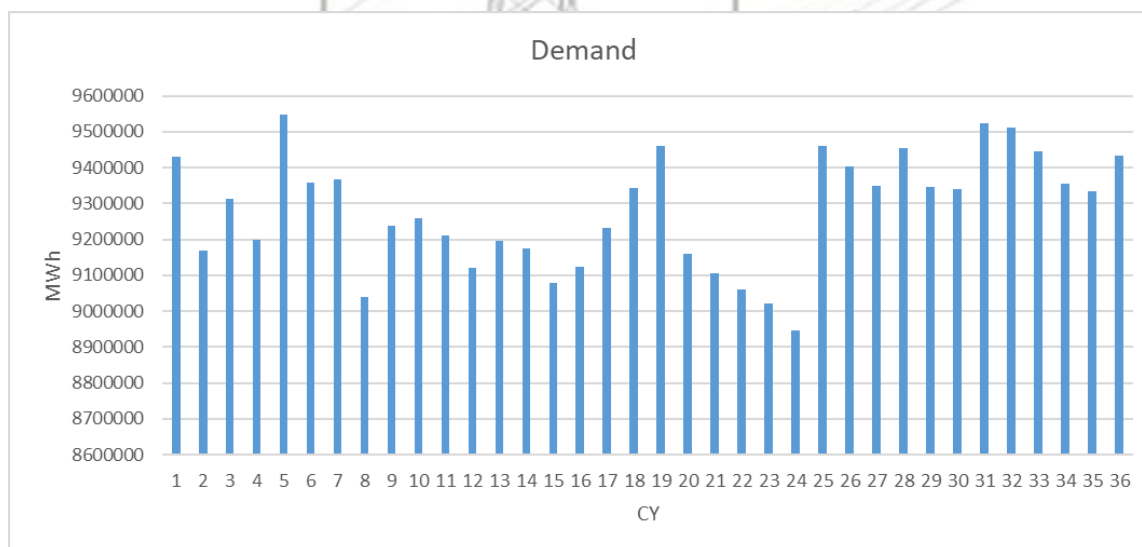


Figure 14. Total Electricity Consumption by CY – short-term horizon

This consumption represents the total electricity demand of the entire power system (including consumers connected to both the transmission and distribution networks), including electricity losses and without compensation from distributed generation.

The hourly electricity consumption profiles for several climatic years are shown in the following figure.

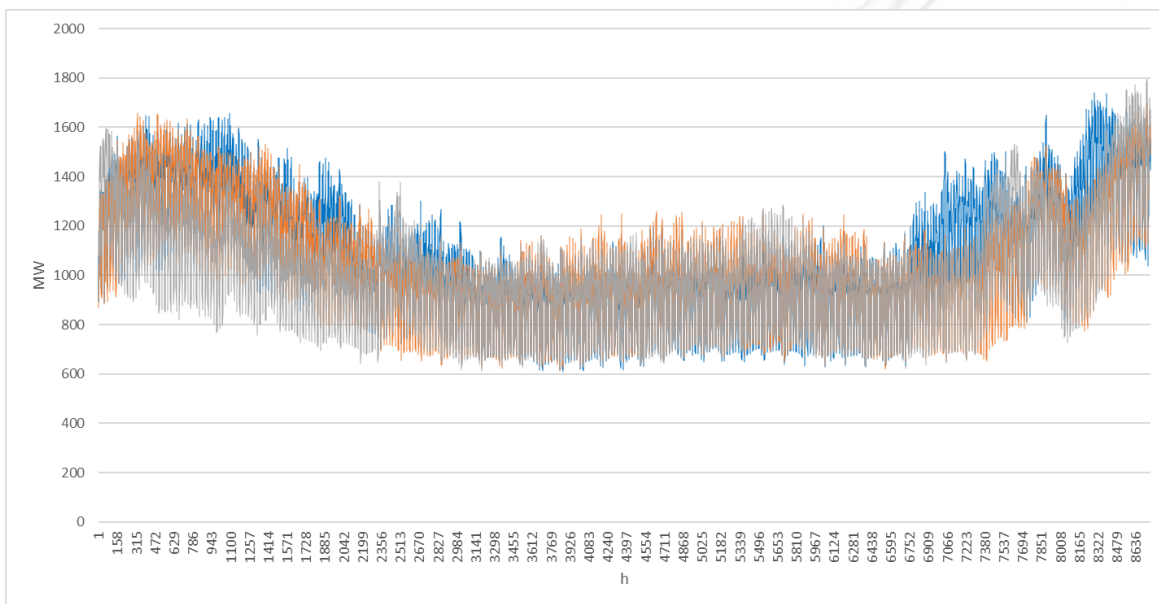


Figure 15. Total Electricity Consumption – Hourly resolution

For the short-term planning horizon, the minimum hourly electricity demand across all climatic years, occurring during spring periods, is approximately 600 MW, while the maximum hourly demand, typical for winter months, reaches around 1,840 MW.

For the medium-term planning horizon, the minimum hourly demand in spring periods is about 640 MW, and the maximum winter demand is approximately 1,930 MW.

For the long-term planning horizon, the minimum hourly demand during spring periods rises to around 700 MW, while the maximum winter demand reaches about 2,150 MW.

6. DATA

6.1. PECD – CLIMATE DATABASE

For the modelling of all climate-dependent parameters in this study, the Pan-European Climate Database (PECD) is used. PECD is a comprehensive dataset that provides climatic and energy-related variables for both historical and future periods with high spatial and temporal resolution. It includes data on key meteorological parameters such as temperature, wind speed, and solar radiation across the entire European continent.

PECD serves as the basis for modelling hourly profiles of electricity demand and renewable generation, ensuring a realistic representation of variations caused by climatic conditions. In this study, a total of 36 different climatic years are used.

Climate Data

Hourly resolution

- Air temperature at 2m (TA)
- Wind speed at 10m (WS10)
- Wind speed at 100m (WS100)
- Global horizontal irradiance (GHI)

Daily Resolution

- Total precipitation (TP)

Weekly resolution

Energy Data

Hourly resolution

- Onshore wind power generation (WON)
- Offshore wind power generation (WOF)
- Photovoltaic generation Φ_{EL} (SPV)
- Concentrated solar power generation (CSP)

Daily Resolution

Weekly resolution

- Reservoir hydropower generation (HRG)
- Reservoir hydro inflows (HRI)
- Run-of-river hydropower generation (HRO)
- Run-of-river inflows (HRR)
- Small storage hydropower generation (HPO)
- Small storage inflows (HPI)
- Pumped-storage hydropower inflows (HOL)

The following figures present the climate data for North Macedonia at an hourly resolution for a single climatic year.



Figure 16. Wind Speed (PECD)

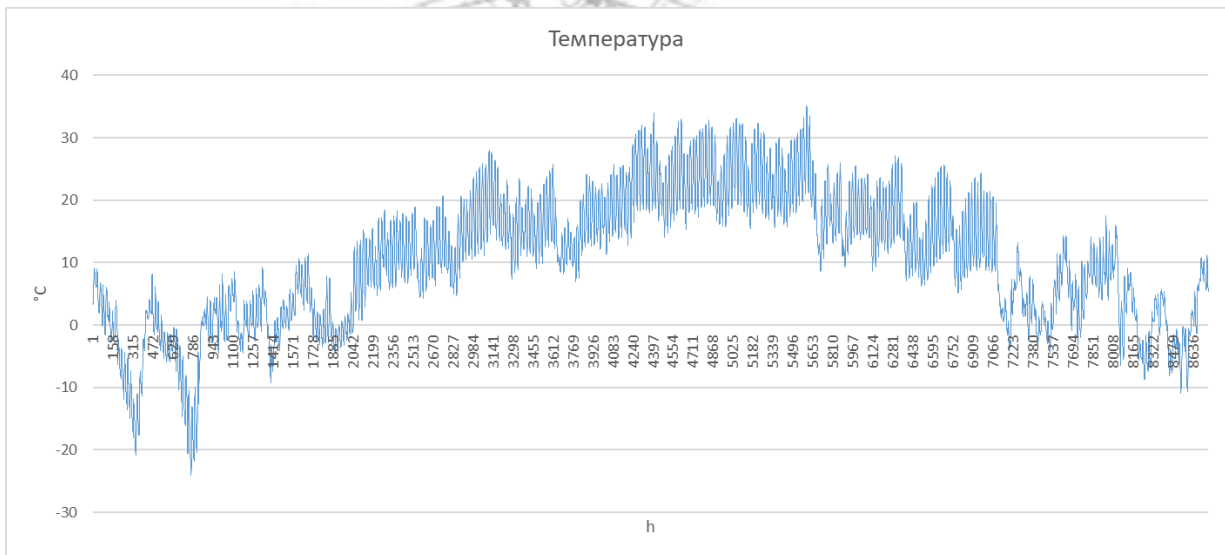


Figure 17. Temperature (PECD)

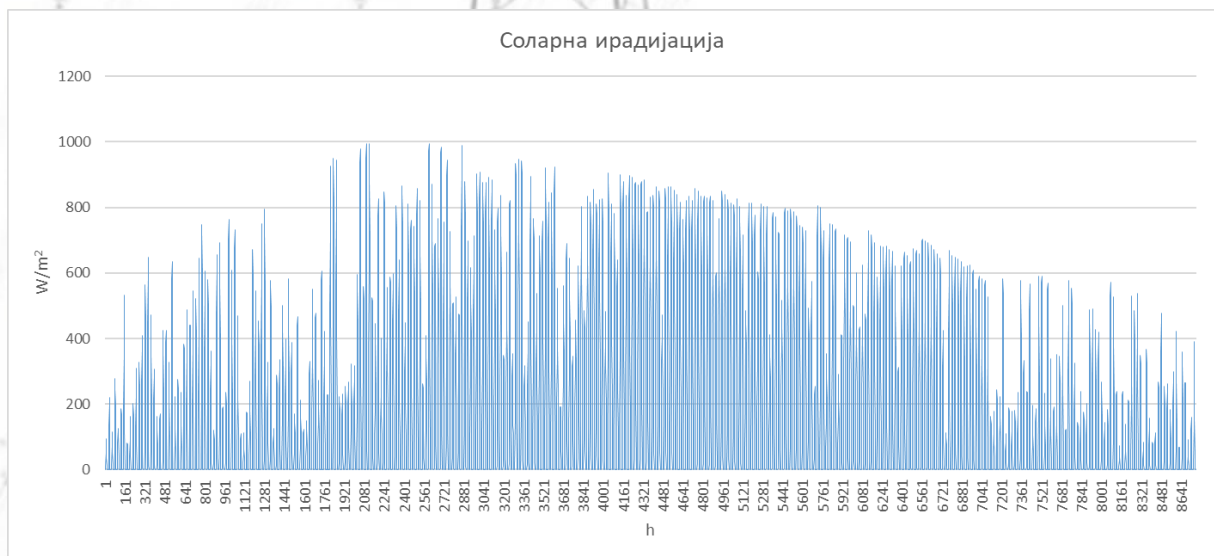


Figure 18. Solar Irradiation

6.2. PEMMDB – PAN-EUROPEAN MARKET MODELING DATABASE

The PEMMDB (Pan-European Market Modeling Data Base) is a key ENTSO-E tool for modelling the European market framework within ERAA. This database is used to simulate market dynamics, including generation capacities, electricity demand, transmission constraints, and cross-border capacities across 34 European countries. In this study, data from the latest updated PEMMDB, prepared for ERAA 25 and TYNDP 26 editions, will be used.

PEMMDB is based on the ENTSO-E National Trends (NT) scenario, which serves as a reference framework for assessing medium- and long-term energy sector trends. The NT scenario integrates existing and planned development measures, with a focus on the transition to renewable energy sources and decarbonisation. Within the context of the TYNDP (Ten-Year Network Development Plan) and ERAA, this scenario is used to simulate market conditions in line with actual national policies.

The NT scenario is directly derived from the National Energy and Climate Plans (NECPs) of EU member states. These plans, submitted by each country, define energy and climate targets, including measures for emissions reduction, renewable energy, and efficiency improvements. PEMMDB collects and harmonises these NECP data to create a coherent pan-European market model. Using this database ensures that ANTARES modelling is consistent with national priorities and European climate-neutrality goals.

The PEMMDB database has a modular structure and consists of multiple categories with files for each country:

- Generation capacities – thermal units: files containing technical and economic data for thermal generators
- Generation capacities – hydropower plants and reservoirs: files with technical and economic data
- Generation capacities – renewable energy sources (RES): files with technical and economic data
- Transmission capacities: files with technical data for interconnections
- Storage: files with technical and economic data for battery systems, demand-side response (DSR), hydrogen, etc.

Generation capacities, particularly thermal generators, are modelled with all their technical and economic parameters. Additionally, using the ANTARES simulator, 20 different time series were created to represent random outages. The availability of thermal generators is shown in the following figure.

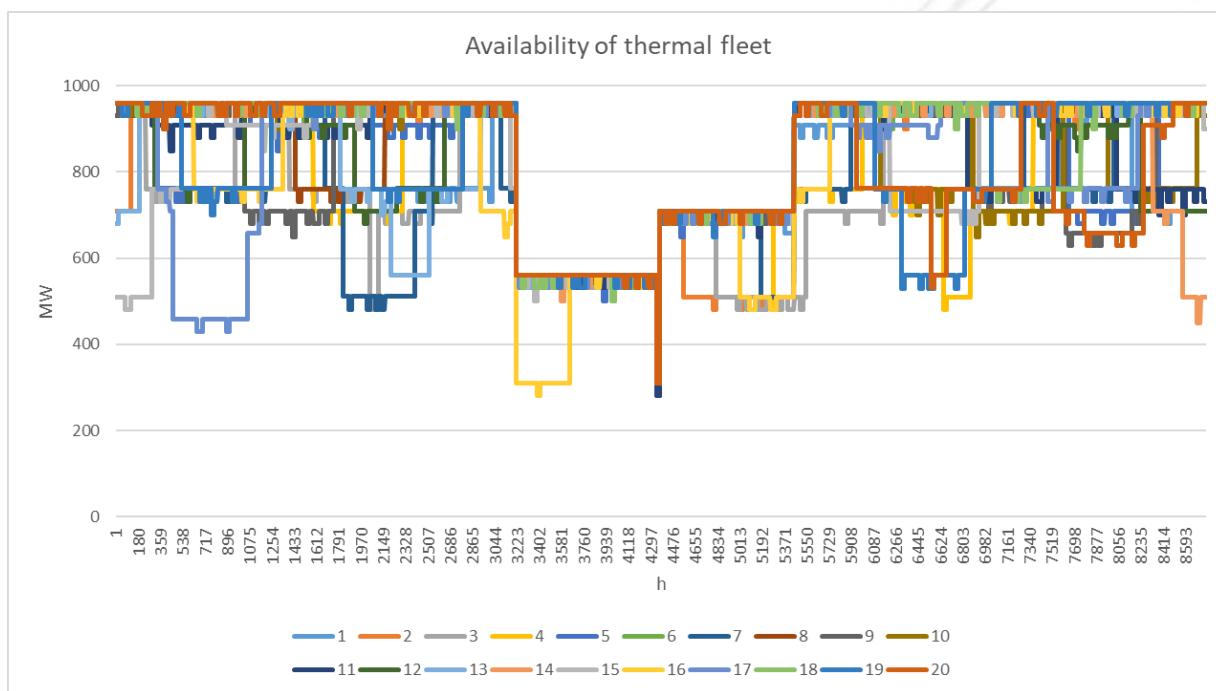


Figure 19. Availability of thermal fleet – long-term horizon

NTC (Net Transfer Capacity) represents the net transmission capacity between two market zones and is a key parameter in ANTARES for simulating cross-border electricity exchanges. In this study, NTC values are taken from PEMMDB. For each interconnection, hourly profiles are defined, taking into account planned outages and technical constraints.

The modelling of NTC is bidirectional – in each hour, the power flow can occur in either direction, optimized according to the marginal prices in the two zones.

The average interconnection capacities of North Macedonia with neighboring power systems are presented in the following table.

Table 3. Average cross-border (NTC) capacity

Direction		Horizon [MW]		
From:	To:	Short-term	Mid-term	Long-term
BG	MK	500	500	500
MK	BG	400	400	400
MK	GR	650	850	850
GR	MK	650	1100	1100
MK	AL	0	500	500
AL	MK	0	500	500
MK	RS	800	800	800
RS	MK	600	600	600

6.3. ASSUMPTIONS

For the purposes of market modelling, it is essential to define appropriate input assumptions that provide a realistic basis for simulating the operation of the electricity system. Among the most important of these are fuel and CO₂ prices, which have a direct impact on the marginal costs of generation units. These costs determine the position of each unit in the merit order, which dictates the sequence of dispatching power plants to meet electricity demand. In this way, the merit order is a key factor for the operational strategies of thermal power plants, their efficiency, and the market revenues achieved.

The table below presents selected fuel and CO₂ price values in accordance with ERAA.

Table 4. Fuel and CO₂ price

Параметар	Eur/ton		
	краткорочен	среднорочен	долгорочен
CO2	105	136	157
Hydrogen	22.18	23.47	21.69
Light oil	15.73	16.33	15.55
Heavy oil	12.9	13.39	12.76
Shale oil	2.16	2.16	2.65
Natural Gas	6.77	6.22	5.95
Hard coal	2.59	2.34	2.21
Lignite G1 (BG - MK - CZ)	1.63	1.63	1.63
Lignite G2 (SK - DE - RS - PL - ME - UKNI - BA - IE)	2.09	2.09	2.09
Lignite G3 (SL - RO - HU)	2.75	2.75	2.75
Lignite G4 (GR - TR)	3.6	3.6	3.6
Nuclear	1.95	1.95	1.95

In the absence of a Reliability Standard (RS) for North Macedonia, a value for the VoLL (Value of Lost Load) parameter must be assumed. VoLL represents the economic value of unserved electricity and is a key input for market simulations. In this study, a value of VoLL = 3,000 €/MWh is assumed for each modelled zone. Using different VoLL values across zones can lead to different economic valuations of unserved energy in the market model: zones with higher VoLL experience higher prices during energy shortages, which in turn attract more electricity imports, encourage new investments, and achieve higher reliability, whereas zones with lower VoLL tend to “accept” relatively more unserved energy at a lower economic cost.

The LOLE (Loss of Load Expectation) values for European countries with officially published Reliability Criteria (RS) are presented in the following table.

Table 5. Reliability Standard – EU Member States

Country	Indicator	Value
Belgium	LOLE (hours/annualy)	3,0
Cyprus	LOLE (hours/annualy)	15,0
Czech Republic	LOLE (hours/annualy)	6,7
Estonia	LOLE (hours/annualy)	8,0
Finland	LOLE (hours/annualy)	2,1
France	LOLE (hours/annualy)	2,0
Germany	LOLE (hours/annualy)	2,8
Greece	LOLE (hours/annualy)	3,0
Ireland	LOLE (hours/annualy)	3,0
Italy	LOLE (hours/annualy)	3,0
Luxembourg	LOLE (hours/annualy)	2,8
Netherlands	LOLE (hours/annualy)	4,0
North Ireland	LOLE (hours/annualy)	4,9
Poland	LOLE (hours/annualy)	3,0
Portugal	LOLE (hours/annualy)	5,0
Sweden	LOLE (hours/annualy)	1,0
Spain	LOLE (hours/annualy)	0.94-1.82

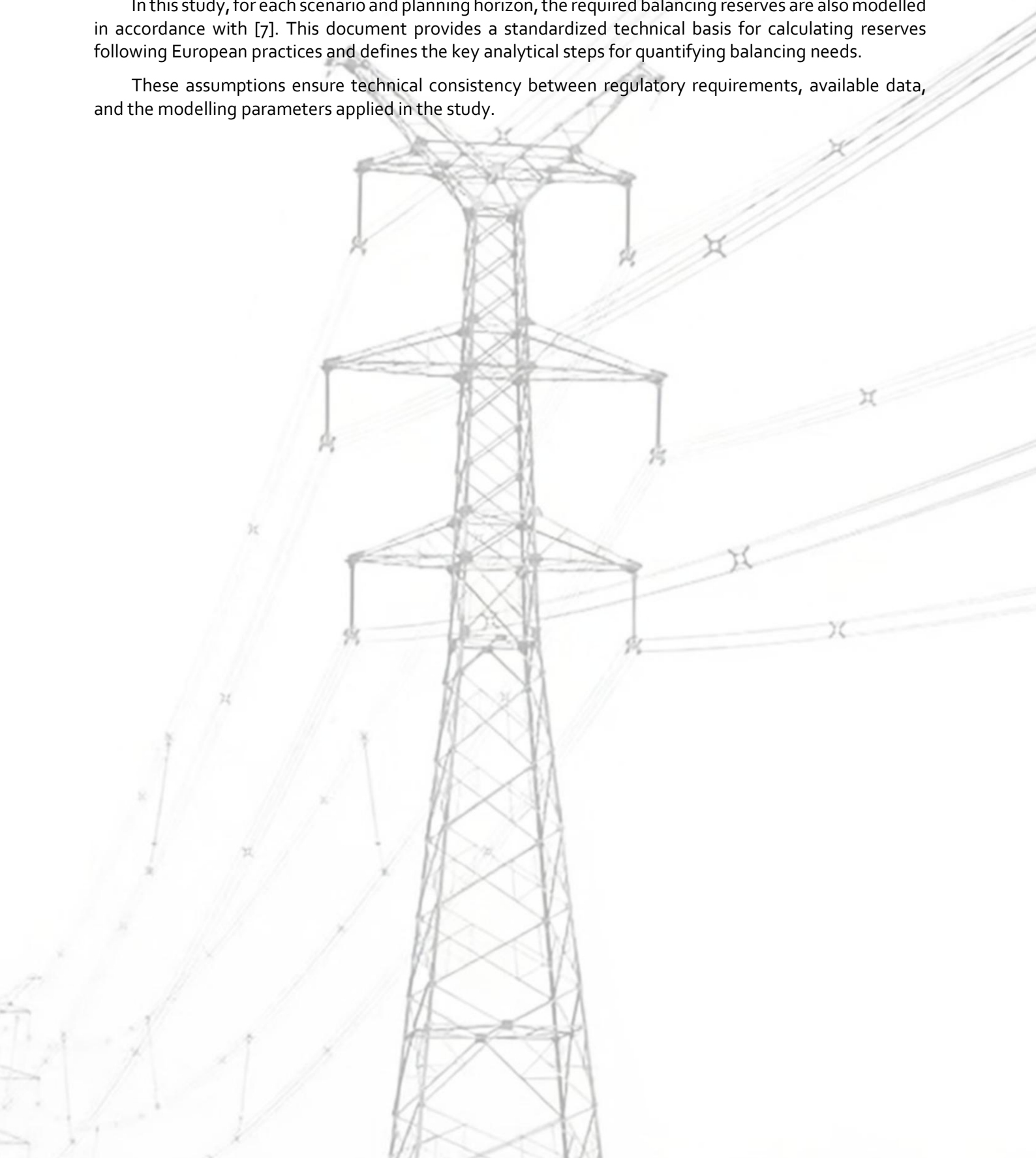
In the absence of an official Reliability Standard for North Macedonia, a value of LOLE ≤ 3 hours/year is assumed—derived as the median of the published RS values from EU member states. This LOLE value is used as a reference threshold. An value of LOLE of 3 hours corresponds to a system reliability of approximately 99.965%, meaning that electricity supply would be ensured for the vast majority of the time, with only a very limited expected deficit.

The assumptions in the models are defined based on data and methodological sources covering the requirements of the Energy Law, taking into account generation capacities, their installed power, and

connection status (connected plants and plants with a connection consent) [5]. Historical profiles of contracted and activated balancing reserves are based on data from the MEPSO operational database [6].

In this study, for each scenario and planning horizon, the required balancing reserves are also modelled in accordance with [7]. This document provides a standardized technical basis for calculating reserves following European practices and defines the key analytical steps for quantifying balancing needs.

These assumptions ensure technical consistency between regulatory requirements, available data, and the modelling parameters applied in the study.



The probabilistic dimension of the model is achieved through a Monte Carlo methodology, with 720 simulations per scenario and horizon. Each simulation combines one of the 36 climatic years with one of the 20 stochastic thermal plant outage series, creating a wide range of possible future system states—from extremely dry winter periods with outages at key plants to favourable years with high renewable generation. This approach enables a quantitative assessment of risk and the identification of critical combinations that could lead to electricity shortages. By using Monte Carlo simulations, the model produces robust results reflecting all possible extreme scenarios and risks.

The combinations of Monte Carlo simulations are illustrated in the following figure.

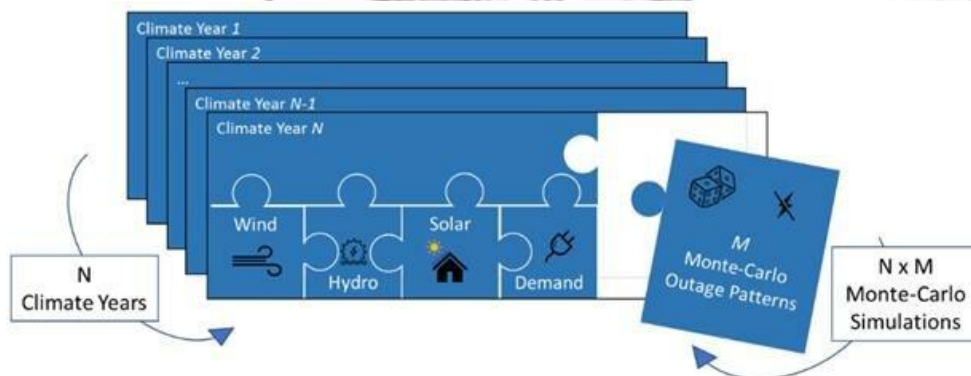


Figure 21. Monte-Carlo simulations principles

The simulations are based on hourly economic dispatch, where ANTARES determines each hour which power plants will operate based on marginal costs, technical constraints, and market signals. During periods of energy shortage, the VoLL (Value of Lost Load) is activated to simulate supply interruptions.

8. CONVERGENCE OF THE MODEL AND EENS PARAMETER

The convergence analysis of the model and the EENS parameter is a critical step in the probabilistic assessment of resource adequacy.

Evaluating convergence is necessary due to the long computation times and the high computational demand of such complex market simulations. This approach ensures a balance between result relevance and the computational capacity of the hardware.

A convergence analysis of the model and the EENS (Expected Energy Not Served) parameter was performed for a total of 720 Monte Carlo simulations. The results indicate that the model is convergent for all 720 simulations.

This analysis focuses on the stability of the key adequacy indicator – EENS – in the Monte Carlo simulations executed in ANTARES. The goal is to determine whether the average values of this indicator stabilize as the number of Monte Carlo simulations (MC years) increases, providing reliable results for short- and medium-term planning horizons.

The convergence analysis of the EENS parameter, following the ENTSO-E methodology, demonstrates that the model exhibits high stability. The average EENS value for all countries across all 720 Monte Carlo simulations is shown in the following figure.

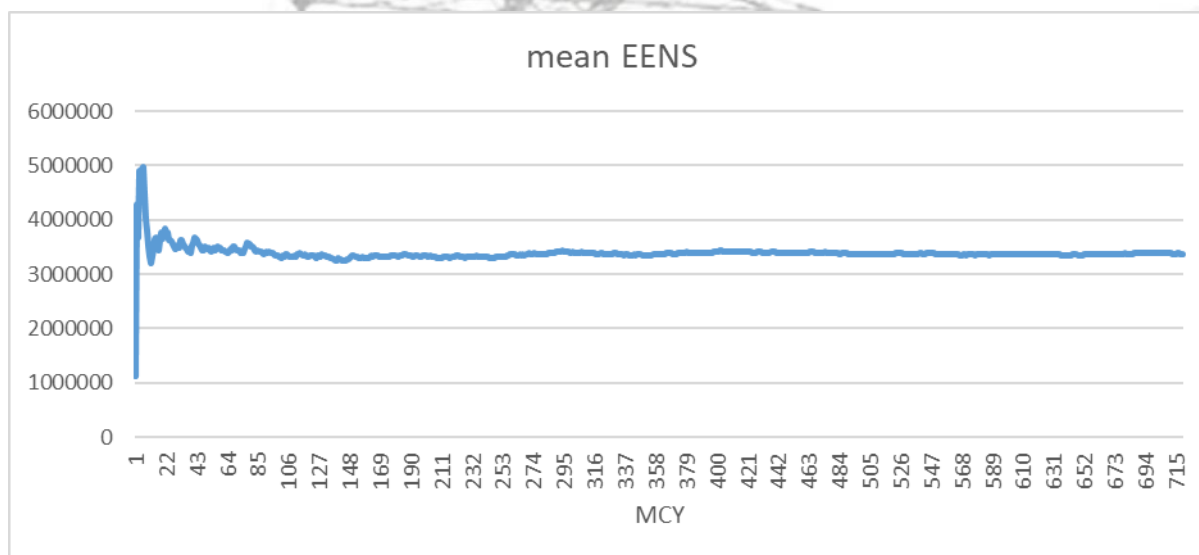


Figure 22. Mean value of EENS parameter

The coefficient of variation (α) indicates that the model achieves stability even with 540 Monte Carlo simulations. The obtained results for the stability of the α coefficient are highly consistent with the ERAA results.

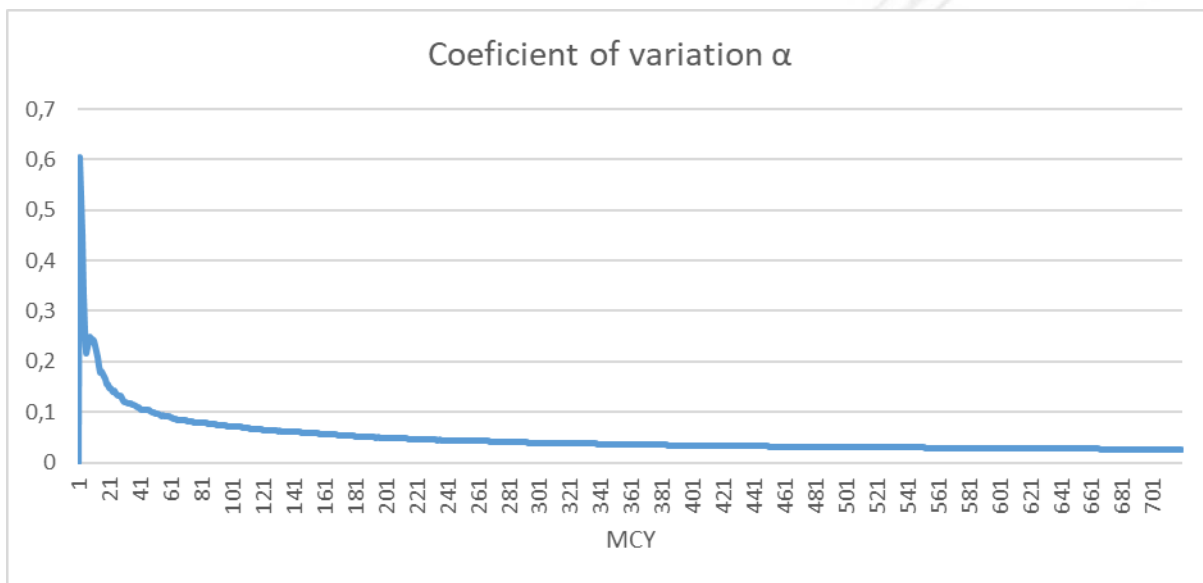


Figure 23. Coefficient of variation α



Figure 24. Relative change of Coefficient of variation α [%]

The results of the EENS convergence analysis demonstrate high stability across all analysed scenarios, with 720 Monte Carlo simulations providing a sufficient sample size to achieve statistical confidence. To further optimize computational capacity and simulation runtime, it is recommended to reduce the number of MC years to 540.

These findings confirm that the model is robust and that the EENS results are representative of the Macedonian system. This analysis not only supports the validity of the study but also provides a foundation for future iterations in the assessment of resource adequacy.

9. RESULTS OF NATIONAL RESOURCE ADEQUACY ASSESSMENT

Resource adequacy represents the ability of the electricity system to meet total electricity and capacity demand at all times, taking into account available domestic generation capacities, cross-border exchange capabilities, and expected demand and generation conditions.

This chapter presents the results of the probabilistic analysis, conducted with 720 Monte Carlo simulations per scenario and horizon, following the ERAA methodology of ENTSO-E. All simulations were performed using the ANTARES software.

In this study, two key indicators were used to assess resource adequacy:

- **LOLE [h]:** The expected number of hours in which resources are insufficient to meet demand, calculated across multiple Monte Carlo simulations.
- **EENS [GWh]:** The expected amount of electricity that cannot be delivered due to insufficient resources.

The results of the resource adequacy assessment for the Macedonian electricity system are presented in the following table.

Table 6. Results EENS and LOLE parameter - Macedonia

Scenario	Indicator	Horizon		
		Short-term	Mid-term	Long-term
A	EENS [GWh]	0	0	0,012
	LOLE [h]	0	0	0,04
B	EENS [GWh]	0	0	0,009
	LOLE [h]	0	0	0,01

The results indicate that the Macedonian electricity system is adequate for the analysed scenarios, meaning that electricity demand can be met across all planning horizons.

The key factor behind this security is a combination of three elements. First, excellent interconnection with neighboring systems – the total available cross-border capacity allows Macedonia to import or export nearly 150% of its peak load at any given moment. Second, a flexible generation mix – gas-fired plants (TE-TO and planned gas units) and reservoir hydro plants act as a “concrete shield” during critical winter hours when renewable generation is low. Third, regional market integration – any local deficit can be immediately covered by imports from neighboring systems before VoLL activation becomes necessary.

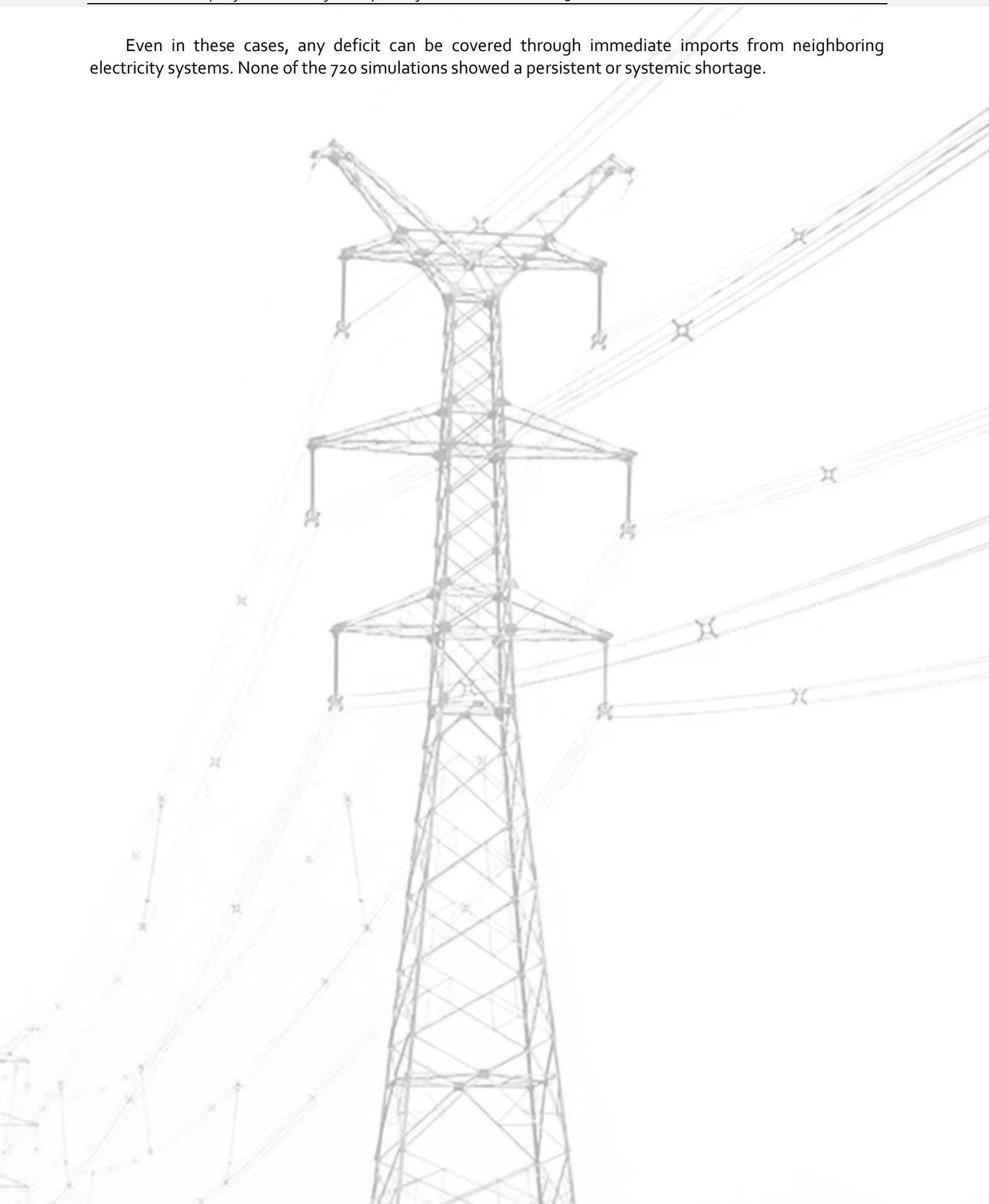
Interestingly, even in Scenario B – the ambitious scenario with increased renewable integration – LOLE remains below the assumed threshold of 3 hours per year. This demonstrates that large-scale integration of renewables does not compromise supply security in the Macedonian electricity system, thanks to the existing interconnections and the flexibility of hydro and gas capacities.

Comparison with European results is highly favorable for Macedonia. While some Western European countries show resource shortages in certain Monte Carlo simulations, the Macedonian system remains practically immune to the risk of shortages. This difference is not due to the size of domestic capacities, but rather the regional synergy – the Balkans function as a single, well-connected region that absorbs local shocks and benefits from relatively low demand compared to more developed countries.

A detailed analysis of critical hours shows that potential risk may occur only during extremely cold winter days with a combination of:

- very low temperatures ($-15\text{ }^{\circ}\text{C}$),
- drought conditions in hydrology, and
- forced outages of one or more gas-fired plants.

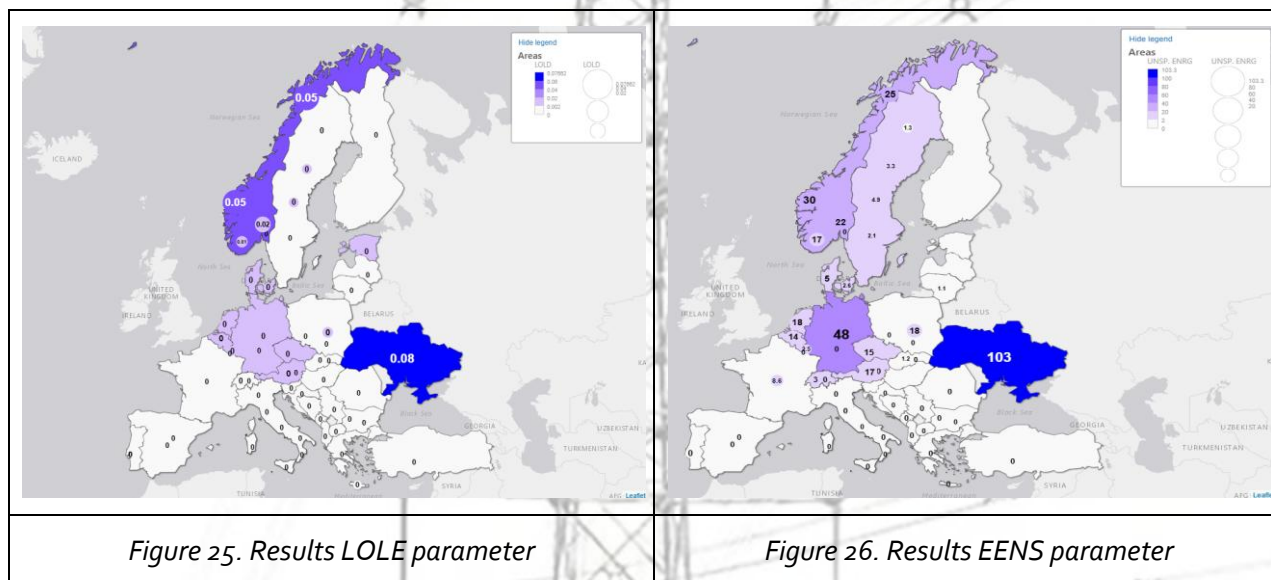
Even in these cases, any deficit can be covered through immediate imports from neighboring electricity systems. None of the 720 simulations showed a persistent or systemic shortage.



10. MID-TERM PLANNING HORIZON ANALYSES

The mid-term planning horizon represents a critical phase in the energy transition of the Republic of North Macedonia, during which the old lignite-fired power plants are expected to be fully retired, renewable energy generation will significantly increase, and the firsts large-scale battery storage systems will be deployed. This chapter focuses on Scenario A and analyses the ANTARES results for this horizon, with particular attention to the regional context and spilled energy from renewables.

Simulations for 2030 confirm that the Macedonian system remains fully adequate even in the mid-term horizon. LOLE is 0.00 hours across all 720 Monte Carlo simulations, while EENS is 0.00 GWh – a result indicating absolute security even under the most challenging combinations of dry winters, low renewable profiles, and forced outages of thermal units. This stability is not surprising, as in the mid-term, the total available capacity (domestic generation + NTC) exceeds 5,900 MW, compared to a maximum demand of 1,930 MW.



The results of the LOLE and EENS indicators for European electricity systems reveal a clear divide between the Balkans and Western Europe. Balkan countries – including North Macedonia, Serbia, Bulgaria, Romania, and Greece – show satisfactory adequacy levels, thanks to strong interconnections among them and relatively low electricity consumption per-capita. In contrast, developed Western European countries display positive LOLE values in certain Monte Carlo years, primarily due to higher demand and limited transmission capacity.

From the LOLE and EENS results, it can be concluded that the Balkan countries do not face adequacy issues. This is mainly due to cross-border transmission capacities and generally lower electricity consumption compared to Western European countries.

One of the most valuable insights is the analysis of spilled energy from renewable sources – a phenomenon that is becoming increasingly prominent across Europe.

The results for Scenario A in the mid-term planning horizon at the European level are shown in Figure 25.

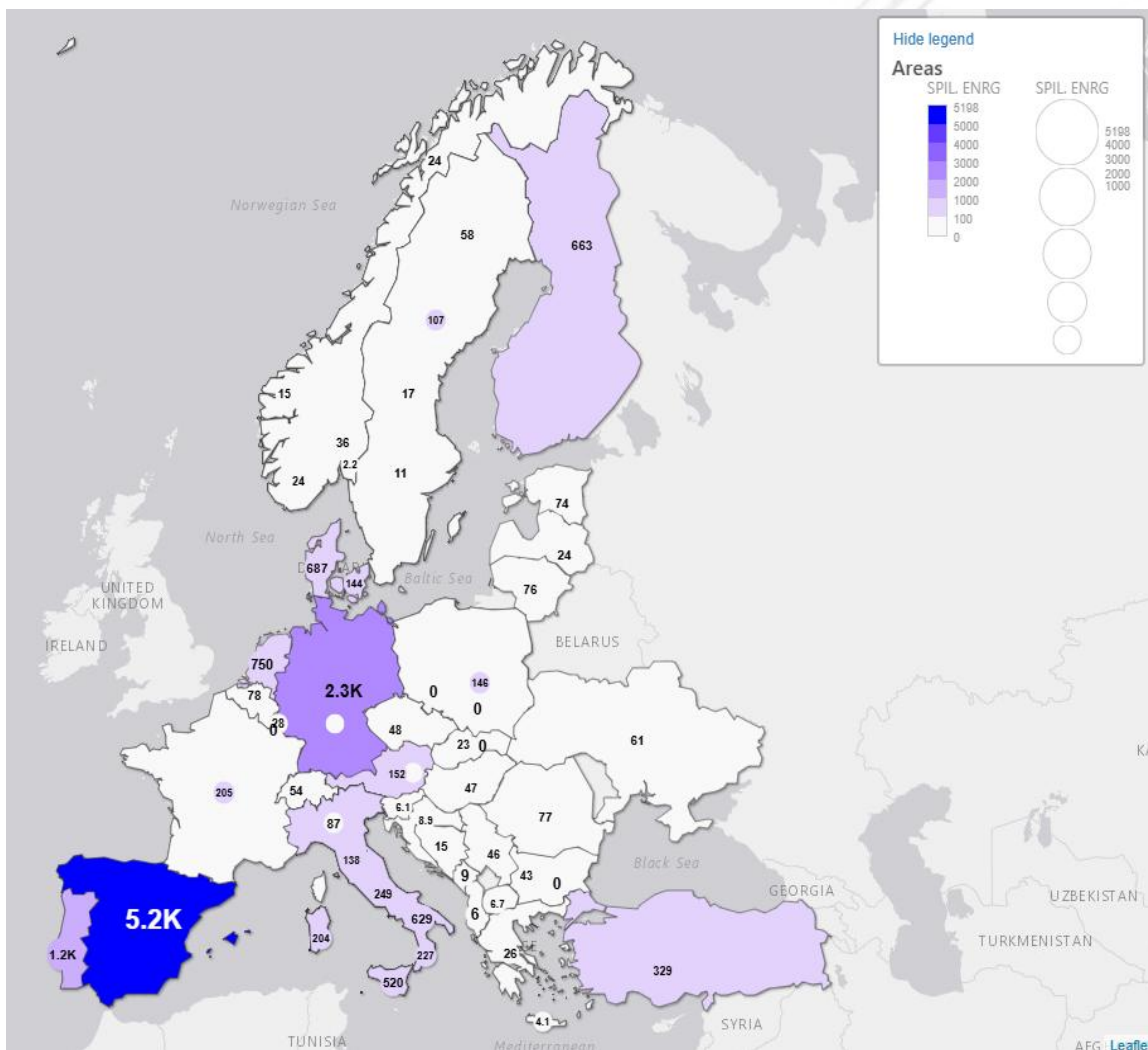


Figure 27. Spilled Energy

The analysis confirms that spilled energy from renewable sources occurs across Europe, particularly during periods of high solar and wind generation (days with intense solar irradiation and strong winds). This phenomenon is most pronounced in Western and Central Europe, where the high penetration of renewables clashes with transmission network constraints and low local demand during those hours. In North Macedonia, spilled renewable energy occurs mostly in the spring months, when electricity demand is at its lowest.

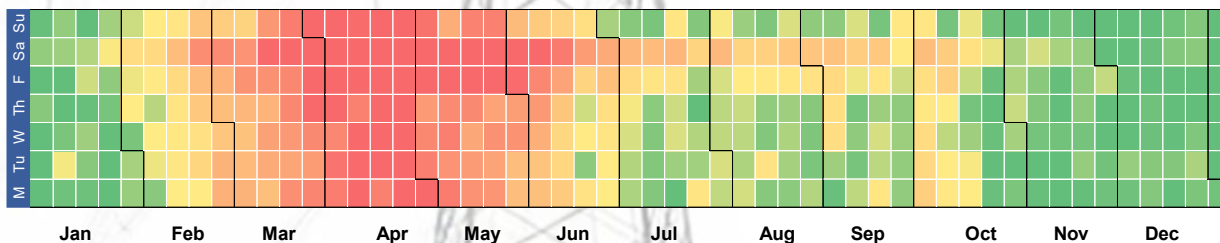


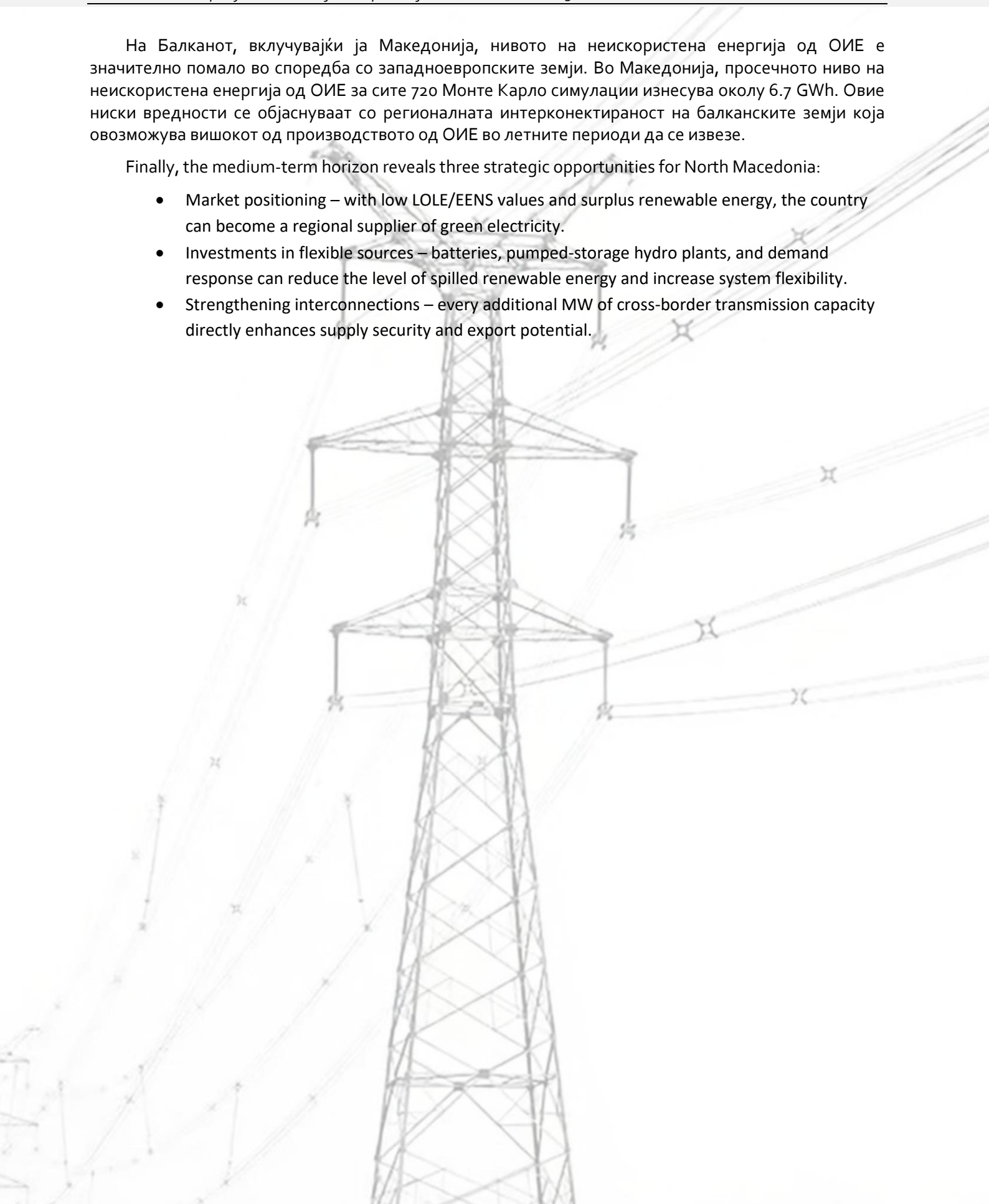
Figure 28. Distribution of Spilled Energy by Days

In the SEE region, including North Macedonia, the level of spilled renewable energy is significantly lower compared to Western European countries. In North Macedonia, the average spilled energy from renewables across all 720 Monte Carlo simulations is approximately 6.7 GWh. These low values are explained by the regional interconnections among Balkan countries, which allow surplus renewable generation during the summer months to be exported.

На Балканот, вклучувајќи ја Македонија, нивото на неискористена енергија од ОИЕ е значително помало во споредба со западноевропските земји. Во Македонија, просечното ниво на неискористена енергија од ОИЕ за сите 720 Монте Карло симулации изнесува околу 6.7 GWh. Овие ниски вредности се објаснуваат со регионалната интерконектираност на балканските земји која овозможува вишокот од производството од ОИЕ во летните периоди да се извезе.

Finally, the medium-term horizon reveals three strategic opportunities for North Macedonia:

- Market positioning – with low LOLE/EENS values and surplus renewable energy, the country can become a regional supplier of green electricity.
- Investments in flexible sources – batteries, pumped-storage hydro plants, and demand response can reduce the level of spilled renewable energy and increase system flexibility.
- Strengthening interconnections – every additional MW of cross-border transmission capacity directly enhances supply security and export potential.



11. CONCLUSION

This study represents the first comprehensive, probabilistic resource adequacy assessment of the electricity system of North Macedonia, carried out in line with the ENTSO-E European Resource Adequacy Assessment (ERAA) methodology. Through close collaboration with RTE International and financial support from the French Development Agency (AFD), MEPSO implemented, for the first time, the modern ANTARES market simulator with 720 Monte Carlo simulations per scenario, integrated into a pan-European model based on PEMMDB and PECD database.

The convergence analysis shows that the model is statistically robust, with the EENS parameter converging even after 540 simulations, achieving a coefficient of variation $\alpha < 0.05$.

The key conclusion is clear and fully aligned with ERAA results: the Macedonian electricity system is fully adequate across all planning horizons, regardless of the generation mix scenario. The LOLE and EENS indicators remain below the assumed reference threshold of 3 hours/year. These outcomes result from three structural advantages: excellent interconnection capacity, a flexible generation mix (gas + hydro), and regional market integration, which allows any local deficit to be covered immediately.

Even in Scenario B, which assumes increased renewable integration, the system remains fully secure in meeting domestic electricity demand. Spilled renewable energy occurs primarily in the summer months, when solar irradiation is highest and demand is relatively low; however, the level of spilled renewable energy is significantly lower compared to Western European countries.

The mid-term simulation results reveal an opportunity for North Macedonia to position itself as a regional green energy supplier, leveraging low LOLE/EENS and renewable surplus. At the same time, they highlight the need for investments in flexible sources—including batteries, pumped-storage hydro, and demand response—to minimize spilled energy, as well as strengthening interconnections with neighboring systems, where every additional MW of transmission capacity directly enhances supply security and export potential.

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Π 1. APPENDIX – ADDITIONS MANDATED BY THE ENERGY LAW

Π 1.1. WHOLESALE PRICES OF ELECTRICITY

The wholesale price from the ANTARES market simulations represents the marginal production cost of electricity. In electricity markets, the marginal price is defined as the cost of the last (marginal) unit of electricity needed to meet demand in a given time period (typically one hour), i.e., the price at which the last required megawatt-hour (MWh) of electricity is produced for that hour.

Within the ANTARES market simulator, the marginal price is obtained as the result of an optimization that minimizes the total system costs (fuel, variable O&M costs, start-up costs, import/export, penalties for unserved energy, etc.) under given technical and network constraints. Therefore, the marginal price determined by the model is a function of:

- Variable production costs of the marginal technology (fuel, CO₂, O&M);
- Availability and profile of renewable energy sources (vRES) – wind and solar power plants;
- Load level and profile;
- Network constraints and cross-border transmission capacities between zones;
- Availability of imports/exports and border prices in neighboring zones;
- Hydrological conditions;
- Value of Lost Load (VoLL).

The marginal price indicates which technology is “on the margin” during a given hour, i.e., which plant would increase (or decrease) its production in response to a marginal change in demand. If the system is constrained by network bottlenecks, the marginal price may vary across zones, reflecting the value of electricity in a specific area.

Based on the calculations in the ANTARES market simulator for all 720 Monte Carlo simulations, the hourly wholesale electricity prices for several Monte Carlo scenarios are presented in Figure 29.

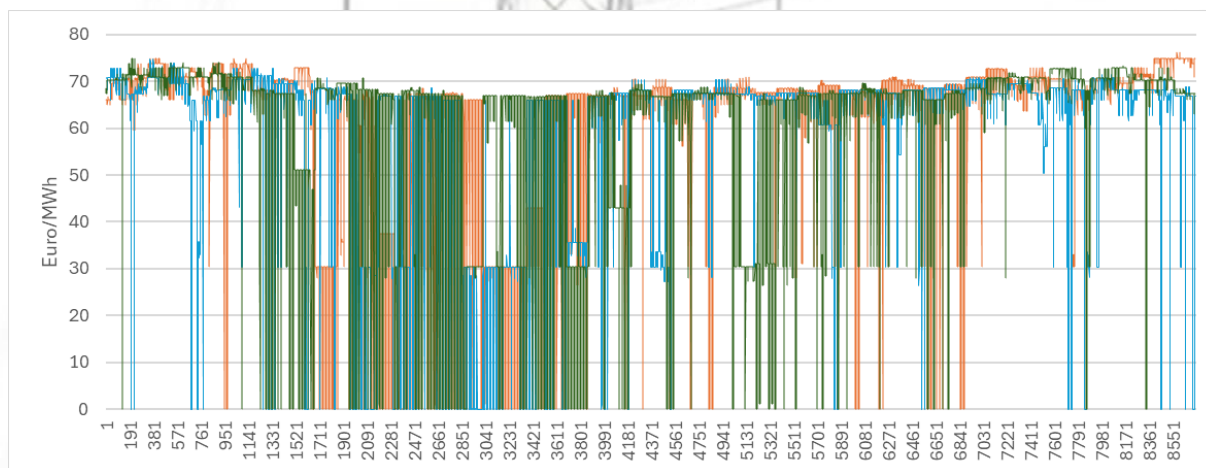


Figure 29. Average Wholesale Electricity Prices for Several Monte Carlo Simulations

The average hourly wholesale electricity price across all 720 Monte Carlo simulations is shown in Figure 30.

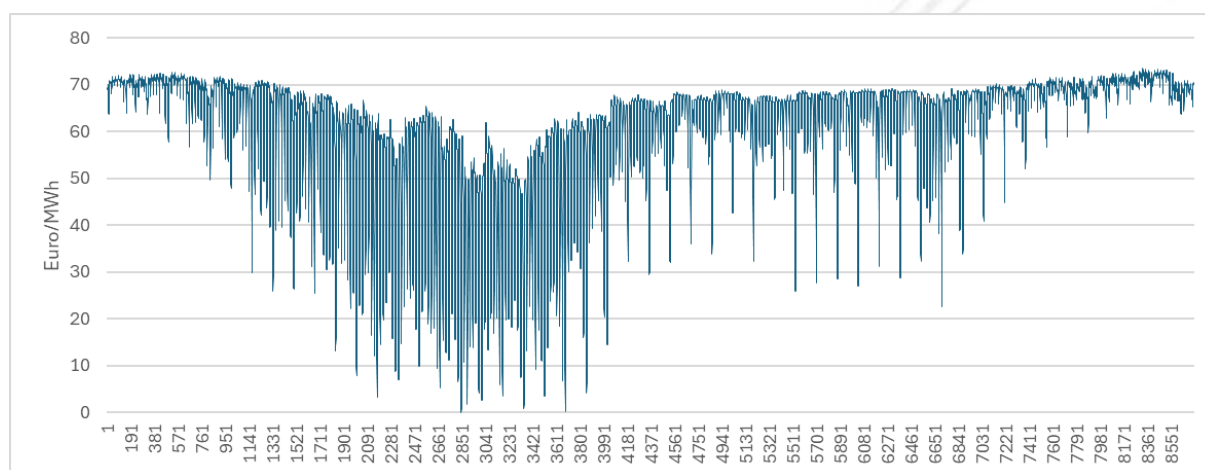


Figure 30. Average Wholesale Electricity Prices for All 720 Monte Carlo Simulations

П 1.2. LIST OF ELECTRICITY PRODUCTION PROJECTS WITH ISSUED CONSENT FOR CONNECTION TO THE TRANSMISSION NETWORK

Table 7 below presents the projects for which the Transmission System Operator has issued a grid connection approval for connection to the transmission network.

Table 7. List of Power Plants with Approved Transmission Network Connection

Проект	Номинална моќност производител [MW]
ФЕЦ Окта	12.0
ИГМ ТРЕЈД - Кровна	24.8
ВЕЦ Богданци	37.0
ВЕЦ Богословец	36.0
ВЕЦ Демир Капија - Дрен 2	44.0
ВЕЦ Штип	396.0
ФЕЦ Новаци	50.0
ФЕЦ Осломеј За	50.0
ФЕЦ Осломеј ЗБ	50.0
ФЕЦ Ерџелија	80.0

П 1.3. ECONOMIC VIABILITY ASSESSMENT OF EXISTING AND NEW ELECTRICITY GENERATION CAPACITIES

The Economic Viability Assessment of the possibilities for permanent or temporary closure of existing electricity generation capacities and the construction of new ones (Economic Viability Assessment – EVA) represents a methodology for assessing the economic sustainability of generation capacities within the electricity system. This methodology effectively serves as a bridge between technical adequacy and the economic reality of the market.

The EVA methodology analyses whether the revenues that power plants earn from electricity markets are sufficient to cover their costs and to ensure an adequate return on investment. In this way, EVA complements the classical adequacy assessment, as it not only evaluates whether the system is technically adequate, but also whether economic conditions exist for capacities to remain in operation or for new investments to materialize. The main objective of the EVA methodology is to bring the adequacy level as

close as possible to the acceptable level of risk of supply shortage through the permanent or temporary closure of existing capacities or the construction of new electricity generation capacities.

The Reliability Standard (RS) is used for the quantitative assessment of security of supply and integrates three key parameters: Value of Lost Load (VoLL), Cost of New Entry (CONE), and Loss of Load Expectation (LOLE).

- **VoLL [€/MWh]** represents the economic value of unserved electricity for end consumers and defines the price of unmet demand in market models.
- **CONE [€/MW/year]** represents the investment cost of new generation capacity and links the economic viability of new investments with the need for security of supply.
- **LOLE [h/year]** measures the expected number of hours during which available resources are insufficient to meet demand, representing a direct indicator of system adequacy.

A key prerequisite for applying the EVA methodology is the existence of a clearly defined Reliability Standard. This standard determines the acceptable level of risk of supply shortages. Without such a standard, there is no clear criterion to assess whether the potential closure of economically unviable capacities would represent a real risk to the system.

So far, North Macedonia has not established a Reliability Standard, which should define the values of VoLL, CONE, and LOLE. For this reason, the Economic Viability Assessment (EVA) of the possibilities for permanent or temporary closure of existing capacities and the construction of new electricity generation capacities cannot be applied.

Π 1.4. BALANCING RESERVES

Π 1.4.1. OVERVIEW OF HISTORICAL DATA ON CONTRACTED AND PROVIDED BALANCING RESERVES

The overview of historical data on contracted and actually provided balancing reserves aims to assess the effectiveness of the mechanisms for procuring system services, as well as the ability of the Transmission System Operator – AD MEPSO – to respond to the actual balancing needs of the power system. The analysis covers the volumes of contracted reserves (aFRR and mFRR, in both upward and downward directions), their temporal distribution (annual, monthly, and hourly), as well as a comparison with the actually provided quantities under real system operating conditions.

The annual contracted and provided balancing capacities for the year 2025 are presented in Figure 31 and Figure 32.

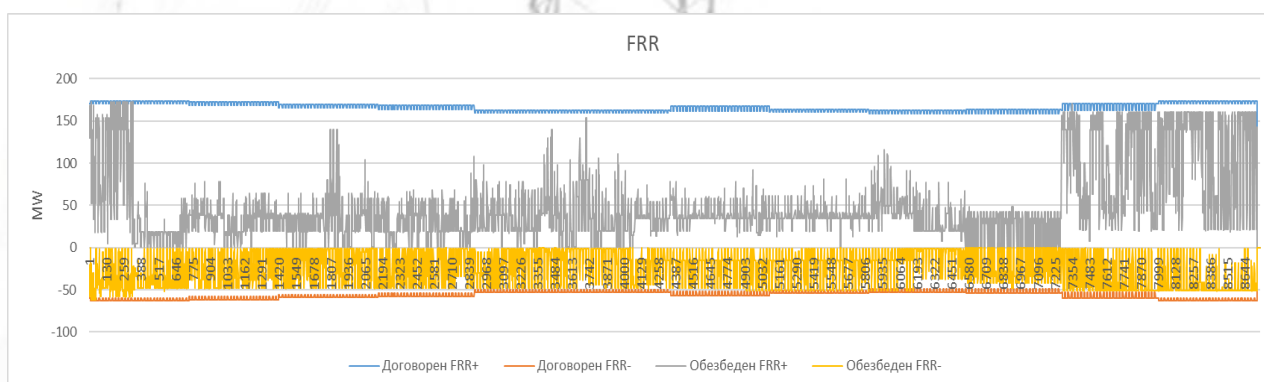


Figure 31. Contracted and provided balancing reserves FRR+ and FRR- - 2025

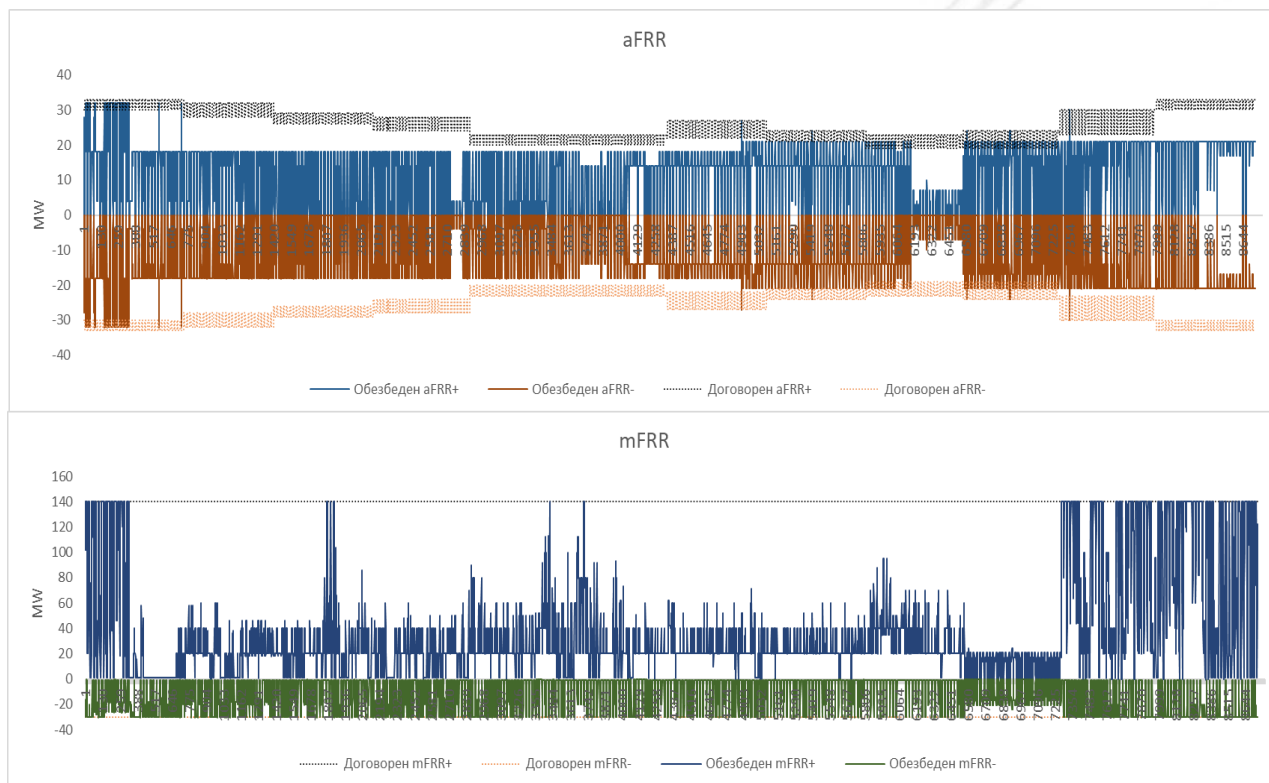
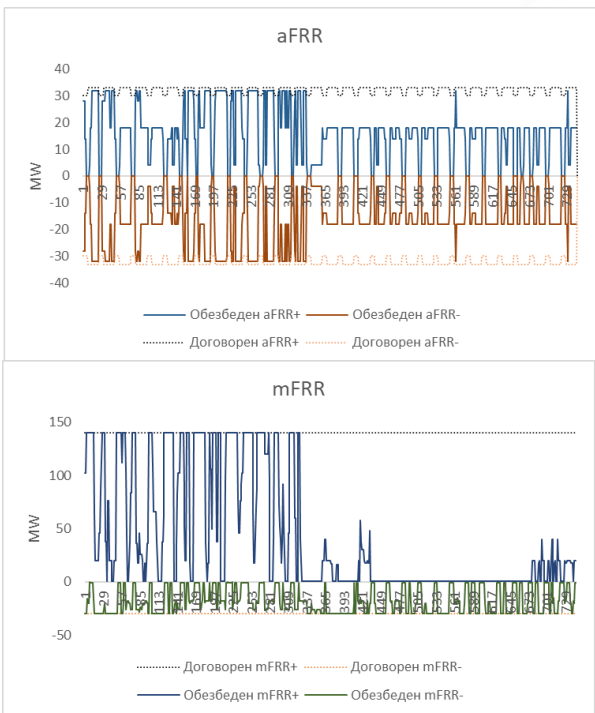


Figure 32. Contracted and provided balancing reserves aFRR and mFRR - 2025

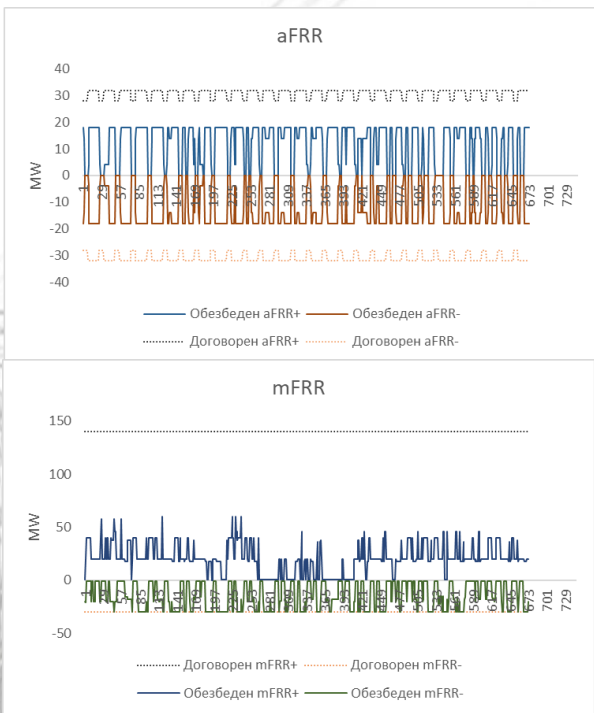
Table 8. Contracted and provided balancing capacity and activated balancing energy – 2025

Преглед на aFRR балансен капацитет и aFRR балансна енергија за 2025	јануари	февруари	март	април	мај	јуни	јули	август	септември	октомври	ноември	декември	вкупно 2025
Договорен aFRR балансен капацитет нагоре (MW)	23,880	21,460	20,925	19,320	16,461	15,930	19,003	17,205	15,720	16,771	20,130	23,901	230,706
Договорен aFRR балансен капацитет надолу (MW)	23,880	21,460	20,925	19,320	16,461	15,930	19,003	17,205	15,720	16,771	20,130	23,901	230,706
Обезбеден aFRR балансен капацитет нагоре (MW)	11,650	7,700	6,056	6,110	5,720	5,604	9,750	9,430	4,207	8,010	10,419	13,115	97,771
Обезбеден aFRR балансен капацитет надолу (MW)	11,650	7,700	6,056	6,110	5,720	5,604	9,750	9,430	4,207	8,010	10,419	13,115	97,771
Активирана aFRR балансна енергија нагоре (MWh)	3,745	2,388	1,345	2,397	1,849	1,628	3,938	2,010	970	3,069	2,621	4,922	30,881
Активирана aFRR балансна енергија надолу (MWh)	3,472	2,177	2,183	1,344	1,266	1,358	1,811	3,090	1,374	1,463	2,630	2,684	24,852

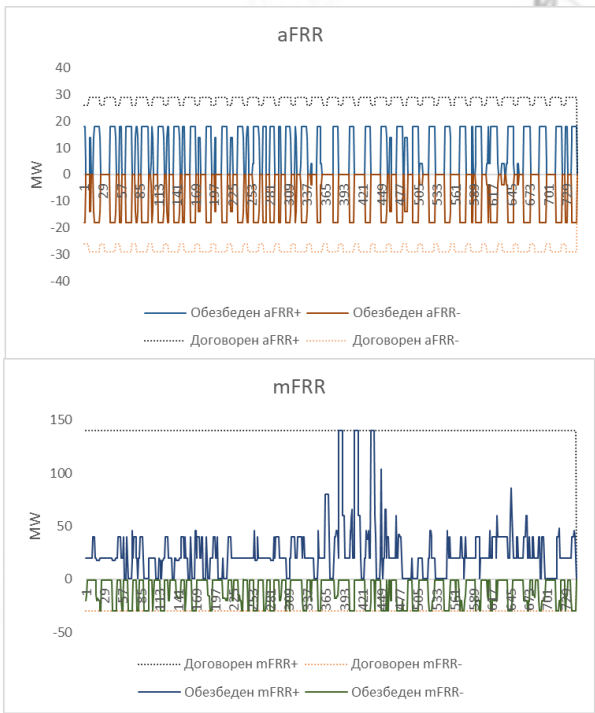
Преглед на mFRR балансен капацитет и mFRR балансна енергија за 2025	јануари	февруари	март	април	мај	јуни	јули	август	септември	октомври	ноември	декември	вкупно 2025
Договорен mFRR балансен капацитет нагоре (MW)	104,160	97,440	104,160	100,800	104,160	100,800	104,160	104,160	100,800	104,160	100,800	104,160	1,229,760
Договорен mFRR балансен капацитет надолу (MW)	22,320	20,880	22,320	21,600	22,320	21,600	22,320	22,320	21,600	22,320	21,600	22,320	263,520
Обезбеден mFRR балансен капацитет нагоре (MW)	31,004	13,945	18,493	12,910	21,065	19,946	18,590	17,780	22,842	50,913	58,828	66,194	352,510
Обезбеден mFRR балансен капацитет надолу (MW)	13,332	9,575	8,314	10,259	9,151	7,123	7,321	5,246	4,558	10,245	12,962	17,141	115,227
Активирана mFRR балансна енергија нагоре (MWh)	4,044	2,740	2,623	3,096	3,654	2,855	4,910	1,791	3,228	10,094	4,176	8,721	51,931
Активирана mFRR балансна енергија надолу (MWh)	13,592	12,952	6,532	4,486	4,008	2,515	4,886	5,112	2,909	5,128	10,651	11,063	83,834



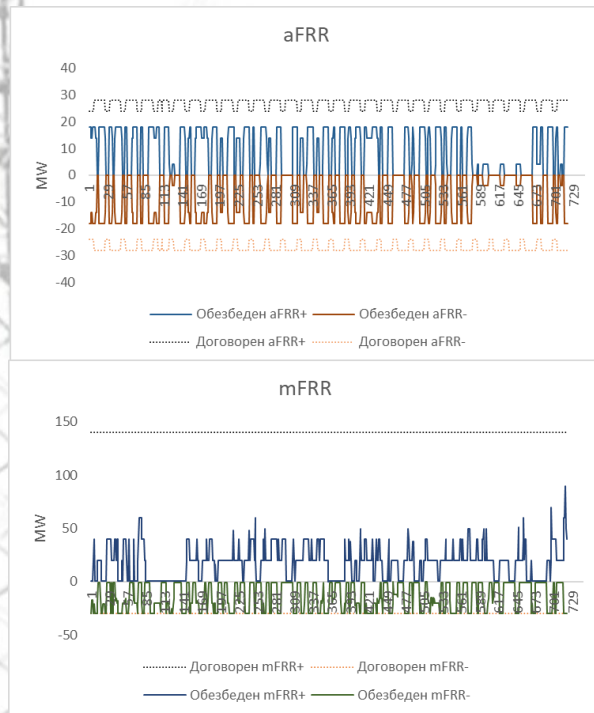
January 2025



February 2025



March 2025



April 2025

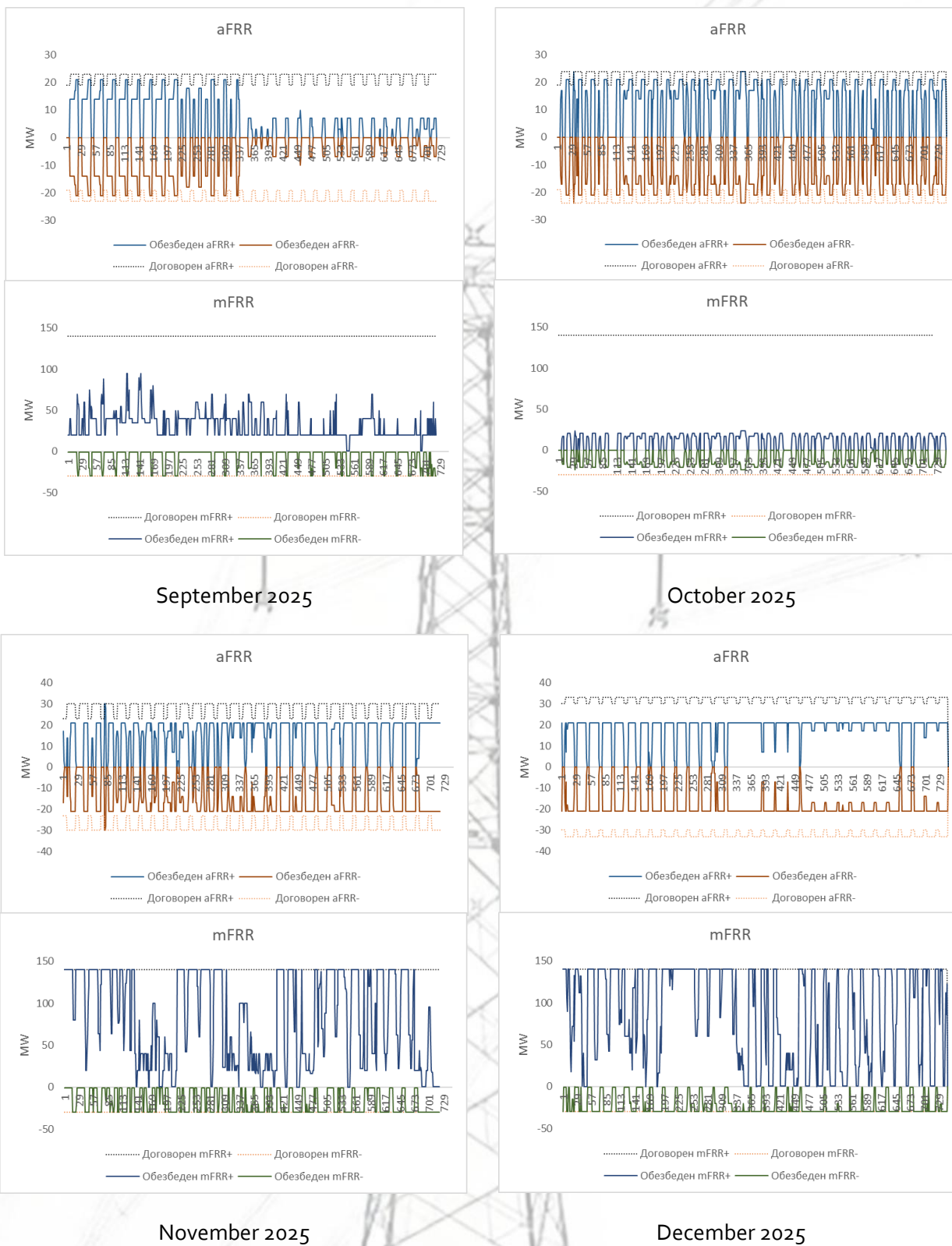


Figure 33. Contracted and provided balancing reserves aFRR и mFRR by months – 2025

The comparison between contracted and actually provided balancing reserves provides insight into the operational performance and the degree of compliance with obligations by the service providers. On the other hand, the volume of activated balancing energy provides additional information on the utilization of reserves, the functioning of the balancing mechanism, and the management of the system under real

operating conditions. Furthermore, it enables an assessment of the utilization of procured capacities and the identification of potential deviations between planned and actual needs, with the aim of improving planning processes and operational system management.

П 1.4.2. Methodology for Assessing Available and Required System Balancing Reserves

The methodology for assessing balancing reserves is based on a quantitative evaluation of expected imbalances in the power system, applying statistical and scenario-based modeling of generation and consumption. The analysis includes historical time series of load, generation from renewable energy sources, as well as outages of conventional units, with the aim of identifying and separating the sources of imbalances by physical origin (load, RES, outages).

The assessment of required reserves (aFRR and mFRR) is carried out by determining the required capacity that ensures coverage of imbalances with a defined level of reliability (99th percentile of the distribution), taking into account the correlations between the variability of generation and consumption.

In this context, MEPSO has developed a study [7] on the dimensioning of balancing reserves for the power system, with the aim of determining the required aFRR and mFRR. The study was prepared with the support of the consulting company EKC Belgrade, in accordance with the relevant European regulatory framework.

П 1.4.3. Assessment of Required Reserves, Available Reserves, and Potential Reserve Shortages for Balancing under High RES Integration

The study on the assessment of required system balancing reserves [7] provides a detailed quantitative analysis of the needs for secondary (aFRR) and tertiary reserves (mFRR), with a clear distinction between upward and downward components, for different levels of RES integration in the system and varying forecast errors.

The results are shown in Figure 34.

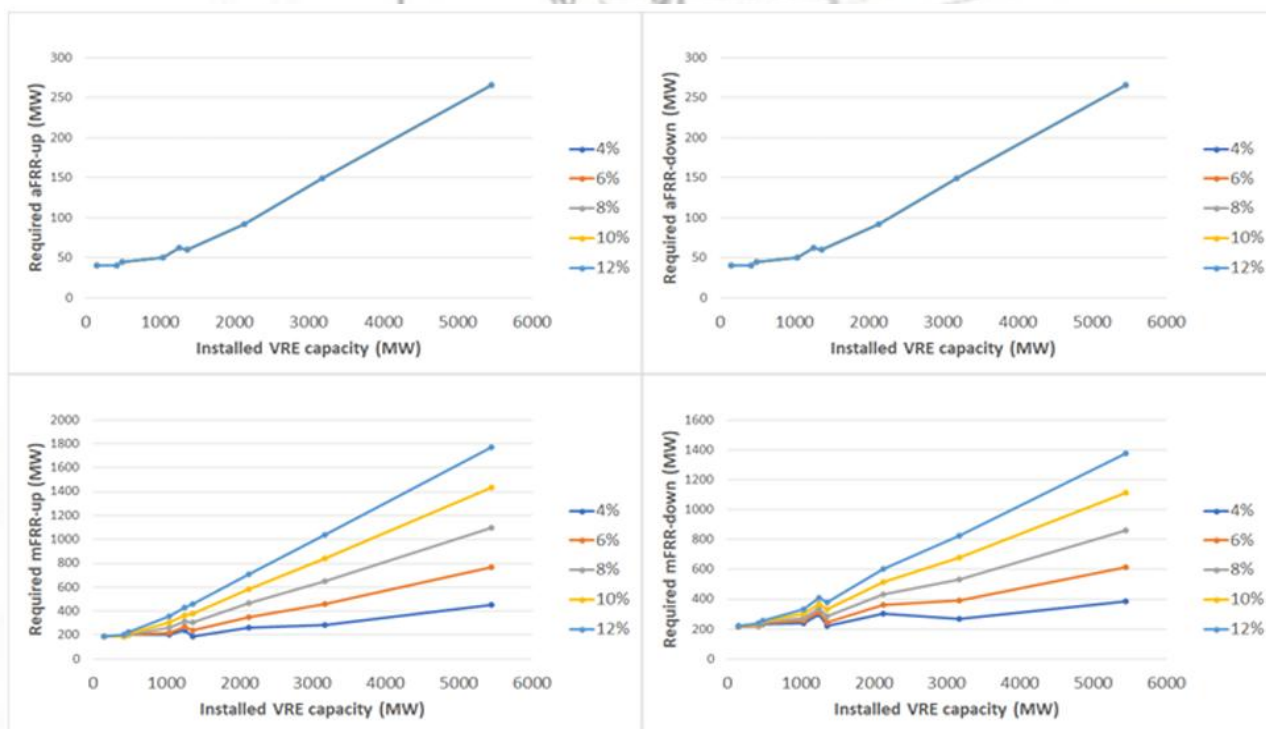


Figure 34. Required Balancing Reserves for Different Levels of RES Integration

The results of the study show that:

- The need for balancing reserves is primarily driven by the variability and forecast errors of RES generation.
- The upward reserve is largely determined by the risk of the largest unit outage and by negative forecast errors in RES generation.
- The downward reserve increases significantly in scenarios with high RES penetration.

To enable the integration of 5,500 MW of RES (solar and wind), according to [7], an increase in balancing reserves is required. The increase in reserves depending on the forecast errors of RES generation is shown in the following table.

Table 9. Required Balancing Reserves for 5500 MW RES

nRMSE	FRR+	FRR-
0%	350	417
4%	719	653
6%	1035	880
8%	1363	1125
10%	1696	1379
12%	2033	1638

Thanks to its diverse generation portfolio, the Macedonian power system has solid preconditions for integrating a significant share of renewable energy sources (RES). However, as the share of variable RES increases, the need for system balancing reserves also rises, due to greater variability and uncertainty in generation.

The analysis of currently available balancing capacities indicates that, technically, the power system has sufficient installed capacity to provide both upward and downward reserves. However, although the physical capacity exists to provide the necessary services, it is not always fully available from an operational or market perspective.

Reserve availability is influenced by multiple factors, such as the current operating regime of generating units, hydrological conditions, minimum technical power limitations, planned outages, unplanned failures, and the level of engagement of generating units in electricity markets. In the case of hydroelectric plants, although they possess high flexibility and fast response, their actual availability to provide reserves can vary depending on reservoir operations and water resource management.

Hence, there is a distinction between the technical potential to provide reserves and the reserves actually available at a given time. This difference is particularly critical under conditions of increased integration of variable RES, where the reliability of availability becomes as important as the installed capacity itself.

Additional reserves required for RES integration can be provided by mobilizing available flexible capacities, including hydroelectric plants, thermal power plants, and battery energy storage systems, with appropriate technical and market activation within the framework of system services and the balancing market.

П 1.4.4. Conclusion on the Risks to the Secure Operation of the Power System and the Need for Implementation of Measures to Provide Balancing Reserves by Producers Using Variable Renewable Energy Sources, in Accordance with the Specific Law

The increased share of producers using variable renewable energy sources (wind and solar) brings significant benefits in terms of decarbonization and reducing dependence on imported fossil fuels, but it also generates additional operational risks for the secure operation of the power system. The primary

source of risk arises from the uncertainty and variability of their generation, which directly leads to increased imbalances, more frequent activation of balancing reserves, and higher system costs.

Historical data show that a significant portion of deviations is associated with insufficient accuracy of short-term forecasts and inadequate discipline in reporting and updating daily schedules. These deviations increase the need to engage secondary and tertiary reserves, place additional operational burden on the transmission system operator – AD MEPSO – and can lead to higher operational risk, especially during hours of high RES generation and low system load.

Therefore, the conclusion is that, in addition to ensuring an adequate level of system reserves at the system level, it is necessary to establish greater market and operational discipline among producers with variable generation. A key measure in this regard is a significant improvement in forecasting methodologies and tools (using advanced meteorological models, shorter update intervals, aggregated forecasting), as well as stricter accountability for deviations through the balancing mechanism.

By reducing imbalances through more accurate forecasts and timely updating of daily schedules, the need for activating balancing reserves will be directly reduced, system costs will be optimized, and the security and stability of the power system will be enhanced. This approach represents a prerequisite for the sustainable integration of new capacities from variable renewable energy sources without compromising the secure operation of the system.

