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The Impact of Thermal Power Plants on the Sustainability of the Energy System Under Conditions of Large-Scale RES Penetration †

Dimitrina Koeva * and Dimitar Slavov

Department of Electric Power Distribution and Electrical Equipment, Center of Competence "Smart Mechatronic, Eco- and Energy-Saving Systems and Technologies", Technical University of Gabrovo, 5300 Gabrovo, Bulgaria; d.slavov@tugab.bg

* Correspondence: dkoeva@tugab.bg

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Abstract

It is crucial to understand the market structure and the formation of the electricity mix in the context of the increasingly widespread and global introduction of renewable energy sources as primary energy sources. Due to the cyclical nature of energy production from RES, a long-term plan for seasonal storage is mandatory for smooth and effective energy transition. The stability of the energy system remains a key requirement, especially due to the dynamic changes in the generation, consumption, and pricing of energy resources. This article aims to present the concept that, in the absence of a properly structured and balanced market, thermal power plants prove to be flexible and reliable power sources that can be quickly integrated into the energy system at critical moments when maintaining the grid balance is difficult (such as during peak hours of solar generation).

Keywords: thermal power plant; sustainability; energy system

1. Introduction

We are witnessing a constant and forced restructuring of electricity markets, mainly driven by growth in the use of renewable energy, instability in energy source prices, and varying economies and geopolitical interests. Having the right energy mix during a period of energy transformation is the best strategy for achieving a sustainable energy system and reducing carbon emissions. The use of renewable energy sources (RESs) and smart energy consumption are crucial for the sustainable development of any economy. They contribute to achieving energy security objectives, reducing dependence on price fluctuations in the oil market and trade imbalances, and creating new job opportunities. RESs play a pivotal role in the ongoing transition to green energy. They also help countries reduce their dependence on energy imports and market shocks that cause price increases. On the other hand, decarbonizing the economy requires a complete reform of the national energy sector, as well as a significant investment. To ensure the long-term sustainability of the energy transition alongside low electricity prices, adequate technical means of energy storage, in terms of capacity, location, and coordination, are needed. Over the past 3–4 years in Bulgaria, rapid and exponential penetration of solar energy without adequate preliminary analysis of capacity and connection locations has been very common. There is no clear parallel strategy for the development and expansion of energy storage infrastructure. This

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causes chaos in the energy market, surplus and zero prices for energy that comes from renewable sources, and the creation of an incorrect energy mix. Consequently, energy prices become difficult to predict, which create a huge risk for the economy as a whole.

2. Conceptualization and Approach to Analysis

A technical report by Ember "New Generation": European Clean Power Pathways Explorer, presents the cheapest and most strategic paths for the development of Bulgaria's energy sector [1]. The following indicators were monitored: generating capacity, TWh; distribution of CO_2 eq emissions according to generating capacity, Mt/CO_2 eq; growth in installed capacities, GW; emission intensity trend, gCO_2 eq/kWh; and electricity consumption, TWh. Thermal power plants still play a role in secure and regulated energy generation, and this trend is steady. (Figure 1) [1]. The load profiles used for the analysis are based on available data from the ENTSO-E website [2]. The period from 2020 to 2024 was selected, as this is the period when there are significant investments in photovoltaic installations. The installed capacity of photovoltaic power and thermal-gas power plants increased by four times in 2024 compared to 2020, according to data from ESO EAD (Figure 2) [3].

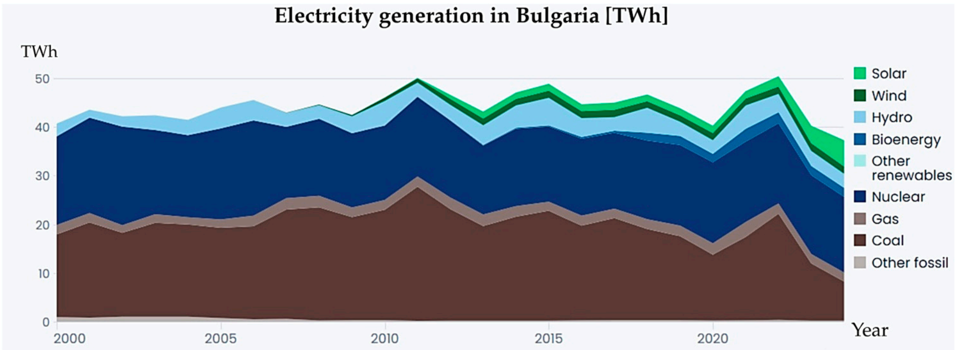

Figure 1. Bulgaria's electricity generation by source, TWh.

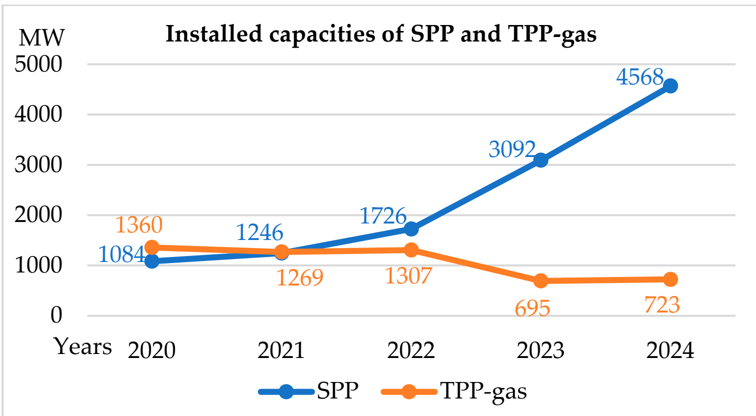

Figure 2. Installed solar and thermal gas power plant capacity from 2020 to 2024.

For all other energy sources during the same period, the installed capacity has changed only slightly. Gas-fired thermal power plants have registered a decline of about 40% in installed capacities due to rising gas prices (Figure 2) [3]. To prove the main concept of this article, we examine the dynamics of the CO_2 market, which is directly related to the restrictions imposed on thermal power plants. During the period in question, the CO_2 market developed quite dynamically, with prices constantly rising. Since November 2021, the price has remained around EUR 60/t, whereas in December 2021 it has increased to around EUR 90/t. This represents a 30% increase over one month. In February 2022, the

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price jumped again to reach an average of EUR 97/t and remained around this level for the rest of the year. The absolute peak came on 21 February 2023, when the price exceeded EUR 100/t, Figure 3, [4].

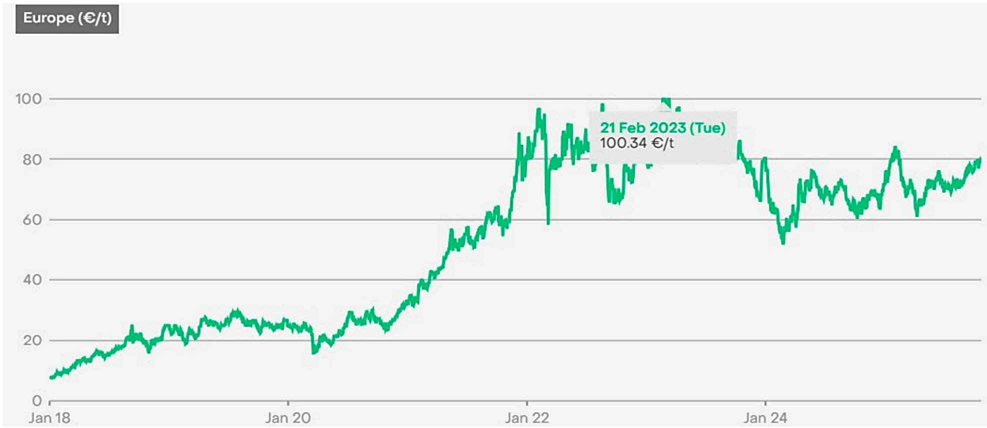


Figure 3. Price trend of carbon emissions for European countries in the period 2018–2024 (EUR/t CO_2).

3. Results and Discussion

Emission intensity (*EI*) is used to calculate the precise quantity of CO_2 emitted when a given type of thermal power plant (condensing, heating, or industrial) produced 1 MWh (1).

$$EI = \frac{\text{Total emissions } (\text{t } CO_2)}{\text{The amount of energy produced } (\text{MWh})} \quad (1)$$

Below is an example that uses data from the annual reports of the largest thermal power plant in Bulgaria, Maritsa East 2. The information was published on the Bulgarian Energy Holding BEH EAD website (Table 1) [5].

$$EI_{2022} = \frac{10926444}{9665636} = 1.13 \text{ tCO}_2/\text{MWh} \quad (2)$$

$$EI_{2023} = \frac{4293437}{3894419} = 1.10 \text{ tCO}_2/\text{MWh} \quad (3)$$

$$EI_{2024} = \frac{5091214}{4486222} = 1.13 \text{ tCO}_2/\text{MWh} \quad (4)$$

Table 1. The carbon emissions emitted during the production of electricity from a thermal power plant.

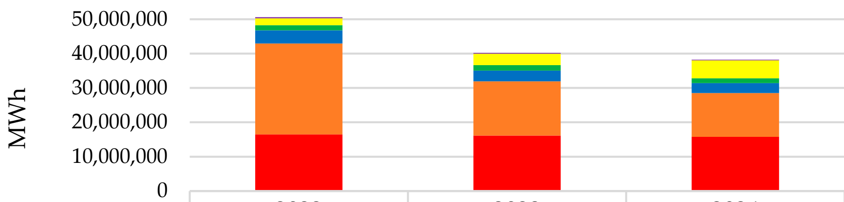
Year	2022	2023	2024
Current data on CO_2 emissions [t/CO_2]	10,926,444	4,293,437	5,091,214
Gross amount of electricity produced [MWh]	9,665,636	3,894,419	4,486,222

Therefore, on 21 February 2023, the carbon emissions price that have been emitted by the power plant when producing 1 MWh were as follows:

$$\text{Price } €/\text{tCO}_2 \times EI_{2023} = 100.34 \times 1.10 = 111.38\ €/\text{MWh} \quad (5)$$

with average daily electricity prices at EUR 149/MWh on the exchange market. In recent years, carbon emissions have become the main factor that has turned thermal power plants into an unprofitable part of the electricity market.

In 2022, Bulgarian's electricity sector went through a dynamic and challenging year, marked by recovery in production, changes in consumption, and record export levels. Gross electricity production in Bulgaria that year was about 50,579 GWh, which represents a 6.5% increase compared to the previous year. The main reason for this growth was production from thermal power plants (especially those using local lignite coal), which reached an undisputed dominant position in the energy mix with a share of 42.8%. During that year, they produced 13 times more electricity than solar power plants (Figure 4). Unlike them, the decline in internal electricity consumption in the country ranged between 1.5% and 1.8%. The combination of increased production and reduced domestic demand led to historically high levels of electricity exports. These exports have grown by over 40%, placing Bulgaria third among the largest exporters in the European Union (Figure 5) [3].



	2022	2023	2024
Biomass	318,391	234,441	214,732
Solar	2,022,607	3,334,895	5,220,293
Wind onshore	1,499,125	1,583,852	1,377,086
Hydro	3,810,674	3,100,152	2,899,470
Fosil	26,463,339	15,757,953	12,735,758
Nuclear	16,464,662	16,166,599	15,780,180

Figure 4. Gross electricity produced for the period 2022–2024.

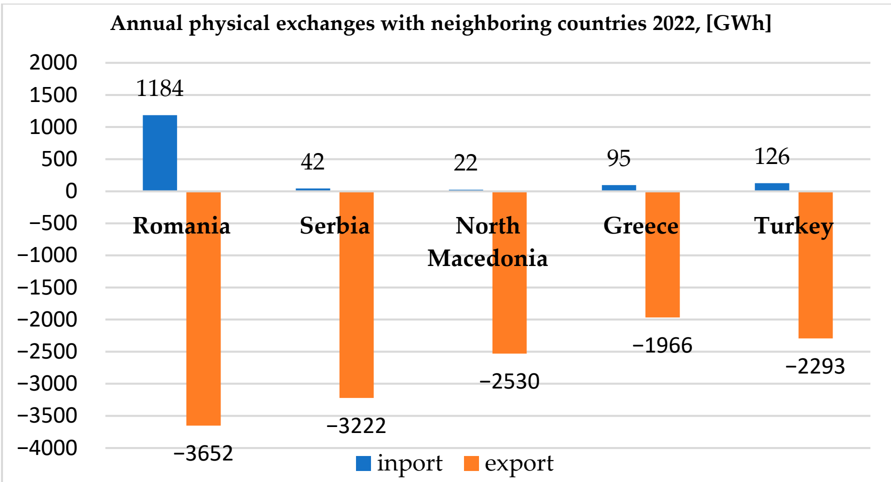


Figure 5. Annual physical exchanges for 2022.

Over a period of one year (2022–2023), the installed capacity of solar power plants increased by 1.8 times (Figure 2).

Thermal power plants remain the only energy source capable of providing the necessary balance and stability to the electricity system. Currently, there are insufficient battery facilities for storing and exchanging energy flows, and repairs to the Chaira pumped storage plant are ongoing.

TPPs manage to receive and respond to changes in consumption during the energy-intensive first quartile of 2022, Figure 6. They are also the main source of the following:

- primary control reserve—according to Article 97, paragraph 4, item 1 of the Rules for the Management of the Electricity System (RMES) of the Energy and Water Regulatory Commission [6];
- secondary regulation reserve—according to Article 98, paragraph 4 of the RMES;
- quick tertiary reserve—according to Article 106, paragraph 2 of the RMES.

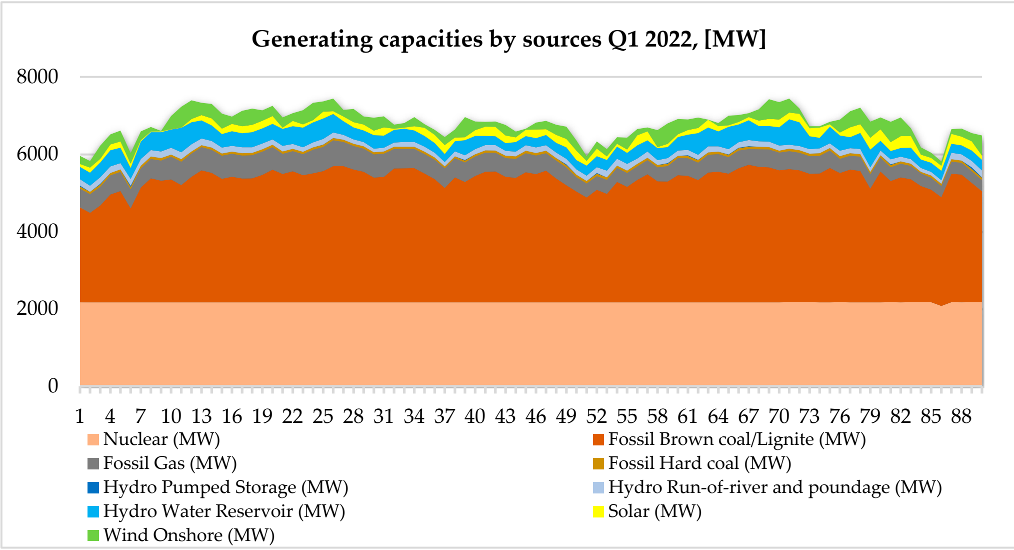


Figure 6. Load profile from January to March, Q1, 2022.

According to data from ESO EAD, the provided system reserve quantities are as follows (Table 2):

Table 2. System reserves provided.

Types of Reserves, MW	2022–2024
Primary regulation	45
Secondary regulation	155
Secondary regulation for balancing RES	100
Quick tertiary reserve	1210
Slow tertiary reserve from producers	500
Slow tertiary reserve from consumers	150
Total system reserve	2160

During the year, the European Union and the US imposed major sanctions against Russia due to the conflict in Ukraine. In response, Russia restricted energy supplies to Europe. As a result, gas and electricity prices reached record levels (Figure 7) [7]. Due to high electricity prices, thermal power plants generated profits from sales despite economic pressure from carbon emission prices and the introduction of the European Green Deal in September 2022. With Regulation (EU) 2022/1854, revenue caps for electricity producers that do not use gas (wind, solar, nuclear, coal, and hydro) were imposed. The upper limit is set at approximately EURO180/MWh [8].

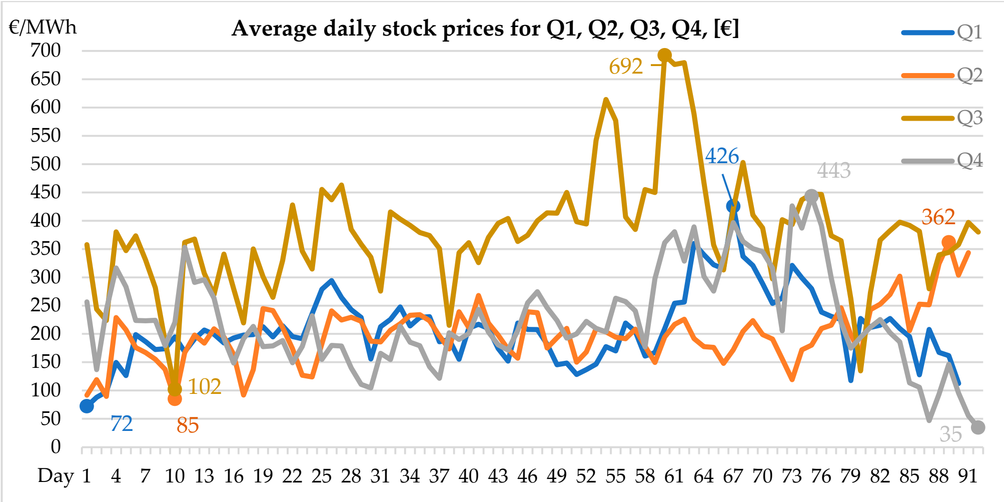


Figure 7. Average daily exchange electricity prices (IBEX) for 2022.

In 2024, the installed capacity of solar power plants is expected to increase by almost 50% compared to 2023 (see Figure 2). The lack of storage systems for surplus electricity and the unavailability of the Chaira pumped-storage plant will once again have a negative impact on the balance of the energy system. Electricity prices on the exchange market have an average annual price of around EUR 100/MWh in 2024, compared to an average annual price of around EUR 255/MWh in 2022 (Figure 8) [7]. From March to October 2024, large amounts of solar power are generated. The price of carbon emissions remains relatively high at EURO 70 per ton of CO_2. Average daily stock prices remain low. These factors force thermal power plants to operate at lower capacity In the second quartile (Q2) of the year (Figure 9), which also includes the day with the lowest load (Figure 10), electricity production from TPPs is the lowest of the whole year.

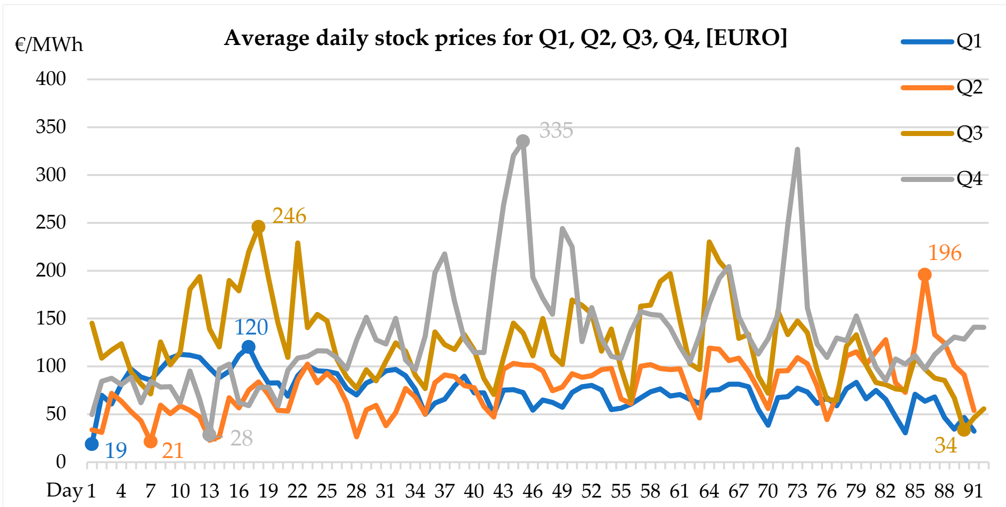


Figure 8. Average daily exchange electricity prices (IBEX) for 2024.

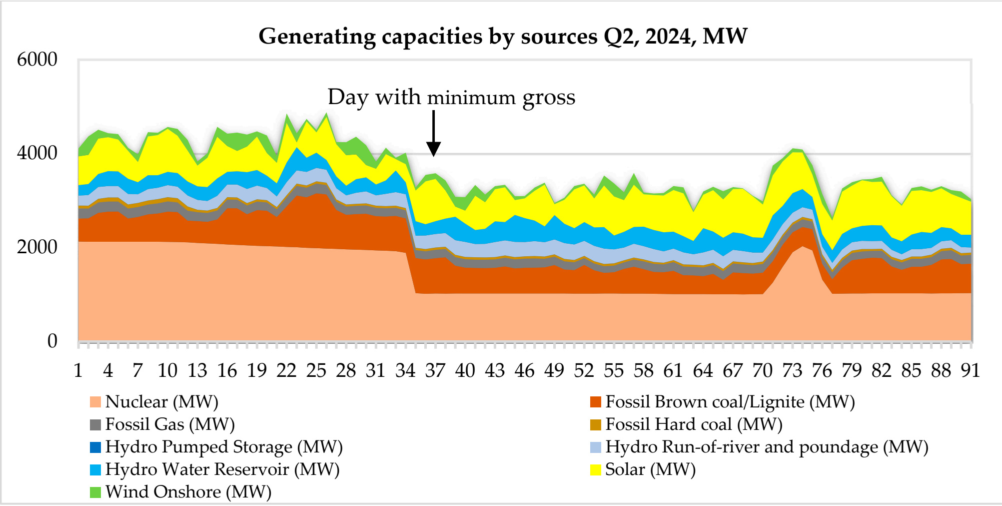


Figure 9. Load profile for the period from April to June, Q2, 2024.

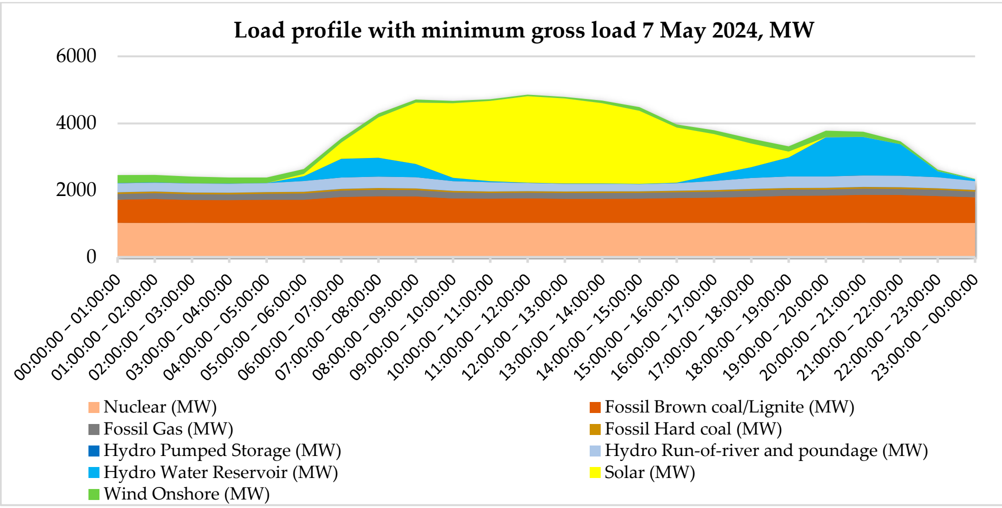


Figure 10. Load profile by sources for 7 May 2024.

The last two years have been marked by a decrease in electricity production from lignite coal and natural gas (Figure 4), and by clear variability and increasing values of solar generation, with permanent peaks in the time range 9:30–15:30. During this period, PVPP production reaches 70% of total capacity (Figure 10). This requires systems for storing "excess" energy to achieve balance; however, such systems are still under development [9,10]. The absence of the Chaira pumped-storage plant, which in pump mode can consume up to 784 MW of surplus electricity from RES, also contributes to the chaotic and poorly managed energy flows.

4. Conclusions

Through these analyses, the authors prove the concept that when serious challenges to the sustainability of the electricity system arise (such as dynamic over-generation from RES and/or failures in base power capacities), thermal power plants remain the only reliable source of adjustable reactive energy. In cases of energy imbalance, the flexibility and reliability of capacities such as TPPs can be quickly integrated into the energy system. They are also critical for maintaining grid balance while ensuring uninterrupted electricity supply.

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Abbreviations

The following abbreviations are used in this manuscript:

RES	Renewable energy sources
ENTSO-E	European Network of Transmission System Operators for Electricity
ESO	Electricity system operator
SPP	Solar power plant
TPP	Thermal power plant
EI	Emission intensity
BEH	Bulgarian Energy Holding
RMES	Rules for the management of the electricity system
NEK	National electricity company

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