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ANTICIPATED SULFUR DIOXIDE EMISSIONS FROM COAL-FIRED POWER PLANTS

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Southeastern Europe (SEE), which includes Serbia, along with Germany and Poland, is one of the largest producers of solid fuels in Europe. Despite growing environmental concerns, coal, especially lignite, persists and remains the dominant fuel for electricity generation in this region. Concurrently, these power plants emerge as the predominant emitters of pollutants in all the observed states. To conduct a comprehensive analysis, data on major emitters within the European Union were gathered, allowing for a detailed comparison with SEE countries. A specific focus was placed on the thermal power plant Kostolac in Serbia, where the calculation of SO_2 *emissions for two thermoblocks was undertaken. Comparisons were drawn with emitters in EU countries, with a particular emphasis on SEE nations. The analysis involved data from wells that have undergone excavation over specific periods, facilitating an exploration of the correlation between calculated values, those from exploited wells, and projections of future* SO_2 *emissions from new wells in areas earmarked for surface mining exploitation.*

Key words*: energy; emissions;* SO_2*; coal; power plants; Serbia*

1. Introduction

Reducing emissions of harmful substances and gases from coal-fired thermal power plants have become an imperative in the wake of growing environmental awareness. In whole Europe, coal production has steadily declined from 835 million metric tons (Mt) in 2010 to 516 Mt in 2021. In EU 27 (without UK) production was 322 and 349 Mt in 2021 and 2022 respectively [1, 2]. Recent events on the political and economic map of Europe are hastening the transition towards completely phasing out coal as a source of electricity [1]. But coal consumption in the European Union (EU 27) increased by 7 % in 2022 as imports from Russia declined during the year and came to an almost complete standstill in October 2022 after the sanctions came into force [2].

As the world is recognizing the dangers of pollutants and the importance of environmental protection, the need for monitoring and controlling of pollutants is becoming the top priority. Emission of SO_2 have always been interesting to monitor in Europe and in other parts of the world. In the work of authors Kato and Akimoto [3] from back in 1992, the anthropogenic emissions of SO_2 and NOx for 25 Asian countries east of Afghanistan and Pakistan (1975, 1980, 1985, 1986 and 1987) were calculated. The paper also presents calculations (provincial and regional) for China and India. All measurements and calculations showed a high increase in emissions. In the research of Chakraborty *et al.* [4], they published the results of on-line SO_2 measurements in some coal-fired TPPs in India over a 2-year period in 2003–2004. The conclusion of these studies is that SO_2 emissions depend on many factors, the most important of which are: the quality of the coal mixture, the quality of oil, the amount of coal and oil per unit of generation, the age of the plant and the quality of maintenance and the amount of air supplied to the furnace [4]. The development and modernization of new technologies and methods contributed to simpler and more accurate measurements and calculations of anthropogenic SO_2 emissions. It is believed that since 1995, satellite observations have been used to monitor anthropogenic SO_2 emissions [5]. In their work, authors Fioletov *et al.* [6] presented a new method applied to measurements with the Ozone Monitoring Instrument (OMI) and a new principal component analysis (PCA) algorithm. About 100 potential sources of SO_2 in America have been tested and it has been concluded that about half of the sources can be considered as point sources [6]. Kourtidis *et al.* [7] presented a new method for creating an inventory of spatial emissions - the Enhancement Ratio Method (ERM), which was applied to measure SO_2 over China from 2007-2011.

Based on the "Developing Pollutant Map of Iran's thermal power plant" project, 50 TPPs in Iran were investigated in 2007-2008. The results of the research are presented in the work of the author Nazari *et al.* [8]. SO_2 emissions from industrial boilers in the Beijing-Tianjin-Hebei region are the focus of research by authors Wang and Chen [9] using the GAINS model. The research is based on allocation methods in chemical species and space, and the obtained results show that the most frequent SO_2 emission is in boilers of the plastic production sector – 51.22%), the cement industry sector – 32.33%, while the paper production sectors and the chemical sector 16.45% of the total emission [9]. Research of Sun *et al.* [10] analysed 66-year emission trends in China indicate that the main emitter of SO_2 is the burning of fossil fuels, and the reduction of SO_2 emissions in the period from 2005-2010 year is the result of the desulfurization of gases produced by the burning of fossil fuels. In addition to monitoring and creating scenarios of future SO_2 emissions, with the methodologies, the authors Ru *et al.* [11] also dealt with the calculation and predictions of SO_2 emissions depending on income per capita, integrated assessment models (IAMs). The model that takes this relationship into account - the Environmental Kuznets curve (EKC) - has been modified and supplemented with knowledge about pollutant pairing. This modified model was applied to research SO_2 emissions in the energy sector, the industrial sector, the residential sector, and the transport sector [11]. The Environmental Kuznets Curve (EKC) represents a hypothetical relationship between different indicators of environmental degradation and per capita income. During the initial stages of economic growth, pollution emissions tend to increase while environmental quality deteriorates. However, beyond a certain threshold of per capita income (which may vary depending on the specific indicators), this trend reverses [12]. At higher income levels, economic growth becomes associated with improvements in environmental conditions. This suggests that environmental impacts or emissions per capita follow an inverted U-shaped function in relation to per capita income. The EKC is named after Simon Kuznets, who proposed that income inequality initially rises and then declines as economic development progresses [13]. Emissions of various pollutants, such as carbon dioxide (CO_2), sulfur (SO_2), and nitrogen oxides (NOx), are closely linked to energy usage. Consequently, the EKC serves as a model illustrating the relationship among energy consumption, economic growth, and environmental considerations [14].

The reduction of SO_2 emissions from coal burning in TPPs in China and the creation of scenarios for SO_2 emissions for the period up to 2050 are presented in the research of Qian *et al.* [15].

In their research, they show the reduction of SO_2 emissions in the period from 2000-2016. in the 30 Chinese provinces covered by the research. Also, by creating a scenario of SO_2 emissions until 2050 based on energy production and coal consumption for energy production, they predict that SO_2 emissions in the period until 2050 will be significantly reduced by using better quality coal, increasing the energy efficiency of TPPs and desulfurization in the production process, and that at the end of this period, total SO_2 emissions will decrease to 3.9 – 4.1 Mt (depending on the scenario) compared to 2016, when the measured SO_2 emissions amounted to 11.0 Mt [15]. In a significant milestone, wind energy and solar energy collectively surpassed gas and coal individually in electricity production for the first-time last year. This marks a crucial shift in the European energy landscape, signalling a move towards cleaner and more sustainable energy sources. The future trajectory for Europe increasingly points towards prioritizing clean energy solutions over traditional coal-based power generation.

In this paper, an analysis, comparison, and future projection of SO_2 emissions from coal-fired power plants in the Republic of Serbia have been conducted, with a specific focus on reviewing current emissions in the Southeast Europe region (SEE) and, to some extent, within the EU territory. For the analysis of the projection of SO_2 emissions in coal power plants in Serbia, SEE and the EU27, data were gathered on the largest emitters within the European Union countries, and a comparative assessment with SEE countries was conducted. The calculation of SO_2 emissions for two thermoblocks at the TPP Kostolac in Serbia was executed. Extensive comparisons were drawn with emitters in EU countries, with particular attention to SEE countries. The analysis was conducted utilizing data from previously excavated wells spanning specific years of operation. This formed the basis for exploring the interdependence between calculated values, those derived from exploited wells, and projections of future SO_2 emissions from new wells in designated areas of surface mining earmarked for exploitation.

2. Current state

Despite this overall trend, some countries continue to be significant contributors to coal production. In 2022, Germany led with 130.8 Mt, followed by Poland with 108.4 Mt, and Serbia with 34.6 Mt. These countries represent the largest coal producers in Europe, excluding Turkey [16]. Europe currently hosts 243 active coal-fired TPPs, comprising 600 blocks, boasting a collective installed capacity of 147477 MW. Although these capacities played a significant role in supplying electricity to Europe, accounting for 17% of the total electricity produced in 2022, there is a growing emphasis on transitioning away from such sources due to environmental concerns [2,17,18]. Table 1 provides an overview of key characteristics related to electricity production in Germany, Poland, and Serbia [17-23]. These characteristics include population size, total installed capacities, installed capacities from coal, gross electricity generation, electricity generation from coal, and electricity generation per capita. This comparative analysis offers insights into the energy profiles of these countries and highlights the challenges and opportunities associated with their respective electricity generation strategies.

Table 1. Basic characteristics of electricity production and consumption [1,18,24]

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Serbia													
Population (Million)	7.29	7.23	7.20	7.16	7.13	7.10	7.06	7.02	6.98	6.95	6.90	6.83	6.82
Gross electricity generation (TWh)	37.42	38.02	36.19	39.23	33.44	37.59	38.61	36.44	36.67	36.86	37.52	37.32	38.20

Electricity generation from coal (%)	66.8	76.3	71.8	73.9	65.8	71.8	69.9	71.4	68.2	70.5	72.0	64.3	62.3
Electricity generation per capita [kWh/pc]	5133	5259	5026	5479	4690	5294	5469	5191	5254	5304	5438	5464	5601
Poland													
Population (Million)	38.04	38.06	38.06	38.04	38.01	37.99	37.97	37.97	37.97	37.97	37.90	37.75	37.72
Gross electricity generation (TWh)	157.6	163.4	162.1	164.5	158.9	164.8	166.6	170.4	169.9	163.7	157.9	179.4	178.16
Electricity generation from coal (%)	86.6	85.5	83.0	83.7	81.5	79.2	78.2	77.0	76.8	72.1	68.0	72.5	70.4
Electricity generation per capita [kWh/pc]	4142	4294	4258	4324	4181	4339	4387	4488	4475	4313	4168	4752	4722
Germany													
Population (Million)	81.78	80.27	80.43	80.65	80.98	81.69	82.35	82.66	82.91	83.09	83.16	83.20	83.23
Gross electricity generation (TWh)	631.1	611.0	626.5	636.9	625.8	646.5	648.6	652.0	638.9	605.4	571.1	491.5	589.46
Electricity generation from coal (%)	41.4	42.7	43.8	45.0	43.6	41.8	40.1	36.8	35.5	28.1	23.2	29.6	32.8
Electricity generation per capita [kWh/pc]	7716	7612	7789	7898	7728	7914	7876	7888	7706	7286	6867	5907	7082

Germany operates 57 active coal-fired power plants, collectively boasting an installed capacity of 39669 MW, distributed across 106 units. Similarly, Poland maintains 42 active coal-fired TPPs, with an installed capacity of 28698 MW and 138 units. These figures underscore the significant role of coal in the energy portfolios of these countries [18]. In SEE, the presence of numerous outdated coal-fired TPPs poses a substantial risk to public health due to extensive air pollution. Within SEE, there are currently 31 active coal-fired TPPs, accounting for 17813 MW of installed power capacity. Notably, these plants have an average age of 44.5 years, highlighting the urgent need for modernization and environmental considerations.

Figure 1 provides a visual representation of the SEE region, showcasing the locations of TPPs in Bosnia and Herzegovina, Romania, Bulgaria, North Macedonia, Greece, and Serbia. The map emphasizes the concentration of coal-fired facilities in the region. Focusing on the Republic of Serbia, there are currently six active coal-fired TPPs, incorporating a total of 17 thermo block units [24]. The average installed power of these units is 733 MW, and all of them rely on lignite as the primary fuel source [24].

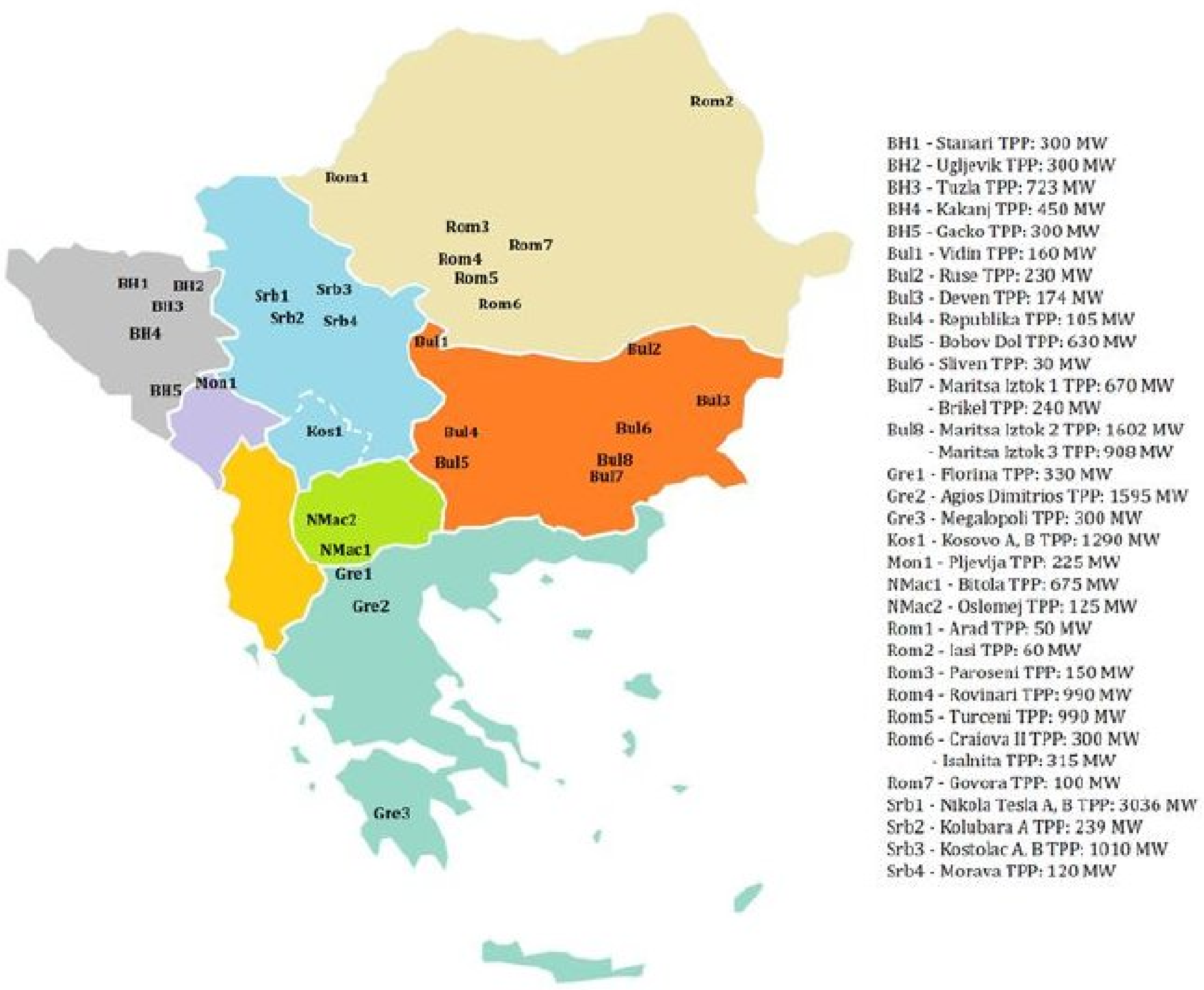

Figure 1. Region SEE with TPP locations

Based on laboratory experimental research by Zivotic *et al.*[25], ultimate and proximate coal analysis for Kolubara lignite and lignite from open pit mine Drmno-Kostolac are summarized in Tab. 2.

Table 2. Ultimate and proximate coal analysis for Kolubara and Kostolac lignite of differing granulations

Coal	Kostolac				Kolubara			
Granulation [mm]	X<0.1	0.1<X<0.25	0.25<X<0.5	0.5<X<1.0	X<0.1	0.1<X<0.25	0.25<X<0.5	0.5<X<1.0
M [%]	7.63	8.32	8.07	7.69	7.06	7.19	7.72	7.43
A [%]	35.57	33.59	30.81	31.12	27.48	28.73	23.79	28.38
VM [%]	63.03	59.55	60.95	61.42	61.76	62.33	61.50	64.95
C	61.81	67.69	67.67	67.11	63.44	67.18	65.13	60.55
H [%]	5.70	6.05	6.34	6.10	6.08	6.29	6.13	6.07
O* [%]	27.24	21.99	22.11	23.24	28.19	24.51	26.48	30.85
N [%]	1.11	1.14	1.06	1.15	0.82	0.88	0.85	0.95
S [%]	4.15	3.13	2.81	2.39	1.46	1.13	1.40	1.59

*Calculated as the difference from 100 %.

In Tab. 2, M represent moisture content, A is ash content, VM is volatile matter, C, H, O, N and S are carbon, hydrogen, oxygen, nitrogen, and sulfur content, respectively.

According to Stefanovic *et al.* [26], Repic *et al.* [27], and Stefanovic *et al.* [28] in raw coal samples from the Kolubara basin, the results of proximate analysis indicate a wide range of water content (W=36-42%), ash content (A=16.68-48.2%), fixed carbon content (Cfix = 5.8-20.4%), volatile matter content (VM=14.6-24.5%), combustible matter (CM=20.9-42.6%), gross calorific value (Qg=3813-11594 kJ/kg), and net calorific value (Qn=2847-9939 kJ/kg). Elemental analysis revealed a wide range of carbon content (C=10.28-28.57%), hydrogen content (H=1.23-2.52%), and combustible sulfur content (Sc=0.06-1.04%). According to Zivkovic *et al.* [29] the result of experimental testing of raw lignite samples from Kostolac open-pit mine from 2022 indicate a wide range of water content (W = 31-52%), ash content (A=16.9-25%), fixed carbon content (Cfix=14.3-17%), and net calorific value (Qn=8031-9455 kJ/kg). Ultimate analysis revealed a wide range of carbon content (C=23.83-27.36%), hydrogen content (H = 2.15-2.40%), and combustible sulfur content (Sc= 0.33-0.56%).

This specific energy profile indicates the prevailing dependence on coal in the Serbian energy sector. As the SEE region grapples with the challenges posed by aging coal-fired power plants, there is an increasing awareness of the need for transitioning towards cleaner and more sustainable energy sources. Addressing air pollution concerns and modernizing the energy infrastructure are critical steps in ensuring a healthier and more environmentally responsible future for the region. SEE which includes Serbia along with Germany and Poland, stands as one of the largest producers of solid fuels in Europe. Despite growing concerns about environmental impact, coal remains the predominant fuel for electricity production in this region. Recognizing the inherent inertia in the mining and energy sectors, coupled with the extended time frames characteristic of development ventures, it is inevitable that it anticipates a gradual decline in the share of solid fuels for electricity generation. Given these circumstances, the coal-fired TPPs in the SEE region emerge as major contributors to environmental pollution. This is particularly noteworthy when considering the broader European context, positioning the SEE region as a significant source of pollutants. Excluding Turkey and Ukraine, the coal-fired facilities in SEE collectively represent the most substantial source of pollution in Europe. This underscores the pressing need for sustainable and environmentally friendly alternatives to address the challenges posed by traditional coal-based power generation. In essence, while SEE countries play a pivotal role in European solid fuel production, there is an urgent call for strategic shifts in energy production methods. As the region grapples with its position as a major polluter, efforts towards cleaner and more sustainable energy sources become imperative for the well-being of both local populations and the broader European environment.

3. Pollutant's emissions in Europe and Serbia

In the Republic of Serbia, there is a Regulation on limit values for emissions of pollutants into the air from combustion plants, which stipulates limit values for emissions of pollutants into the air from combustion plants, methods, and deadlines for submitting data, and procedure for determining the total annual emissions from combustion plants. The provisions of this regulation apply to combustion plants, which can be large combustion plants, medium combustion plants, and small combustion plants [30]. Emissions of pollutants into the air from combustion plants are determined by measurement and/or calculation of emission parameters based on measurement results. Measurement of emissions of pollutants is performed by measuring devices, at measuring points, using prescribed measurement methods in accordance with the provisions regulating the measurement of emissions of pollutants into the air from stationary sources of pollution. The limit values for emissions for large combustion plants define various elements related to [31]: Limit values for emissions of SO_2, NOx, particulate matter, and carbon monoxide (CO) for existing large combustion plants; Limit values for emissions of SO_2, NOx, particulate matter, and CO for existing large combustion plants; Limit values for emissions of SO_2, NOx, particulate matter, and CO for new large combustion plants, and The minimum desulfurisation degree for different plants. Tables 3-6 present data on the TPPs in Europe with the highest emissions of CO_2, SO_2, NOx, and PM10.

The tables provide a comprehensive overview of these significant pollutants, highlighting both the power plants and their corresponding emissions of SO_2 and NOx [32-34]. Table 3 displays TPPs in Europe identified as the largest CO_2 emitters. Consequently, the coal-fired TPPs in the SEE region emerge as the significant contributors to pollution in Europe, excluding Turkey and Ukraine [32,34].

Table 3. Top 5 emitters CO_2 by Europe in 2021 [32-34]

	Power plant	Country	CO_2 emissions [Mt]	Coal	Installed power [MW]	Generation [TWh]	Relation [MtCO2/TWh]
1.	Belchatow	Poland	33.2	Lignite	5097	27.4	1.21
2.	Neurath	Germany	22.1	Lignite	3622	25.2	0.88
3.	Nikola Tesla	Serbia	17.5	Lignite	3036	14.32	1.22
4.	Niederaussem	Germany	16.1	Lignite	3021	24.5	0.66
5.	Kozienice	Poland	15.9	Hard coal	3994	11.0	1.45

Emissions of various pollutants in Serbian power plants align with levels observed across European facilities, with SO_2 exhibiting the most pronounced emissivity compared to other pollutants. This phenomenon is a consequence of the historical absence of desulfurization procedures. However, there has been a partial shift in the last two years with the operation of the desulfurization system in TPP Kostolac, marking a crucial development. As of now, the TPP Kostolac B (blocks B1 and B2) houses the sole desulfurization plant in Serbia [24]. The initiation of the desulfurization plant at TPP Kostolac B in 2020, albeit in a trial mode, resulted in a reduction in exceeding the maximum values for SO_2 emissions [24]. However, emissions from coal-fired TPPs in Serbia still surpass the permitted maximum values, as outlined in the "Strategic Impact Assessment for the National Emission Reduction Plan", called NERP [35]. The emissions of pollutants from other TPPs in Serbia exhibit a considerably higher excess of allowed emissions, amounting to 54575t SO_2 according to NERP. A notable reduction in emitted substances, particularly SO_2, was observed in 2021. This significant decrease, amounting to 140%, was achieved through the active desulfurization system, resulting in a decrease of 75900 tons of SO_2 compared to the previous year [24,32,35]. Despite this improvement, coal-fired TPPs in Serbia still significantly surpass the permitted values. The lowest emission value recorded in 2021 is five times higher than the stipulated limit (Fig. 2) [33,35]. This highlights the ongoing challenges in complying with emission reduction targets.

Despite a decline in SO_2 emissions to their lowest levels since 2010 during 2021, coal-fired TPPs in Serbia persistently surpass the approved emission thresholds. Even with this reduction, the lowest emission value recorded in 2021 is still five times higher than the permitted limit (Fig. 2). This emphasizes the urgent need for stringent measures and comprehensive strategies to bring emissions within the defined limits, ensuring a more sustainable and environmentally responsible energy sector in Serbia.

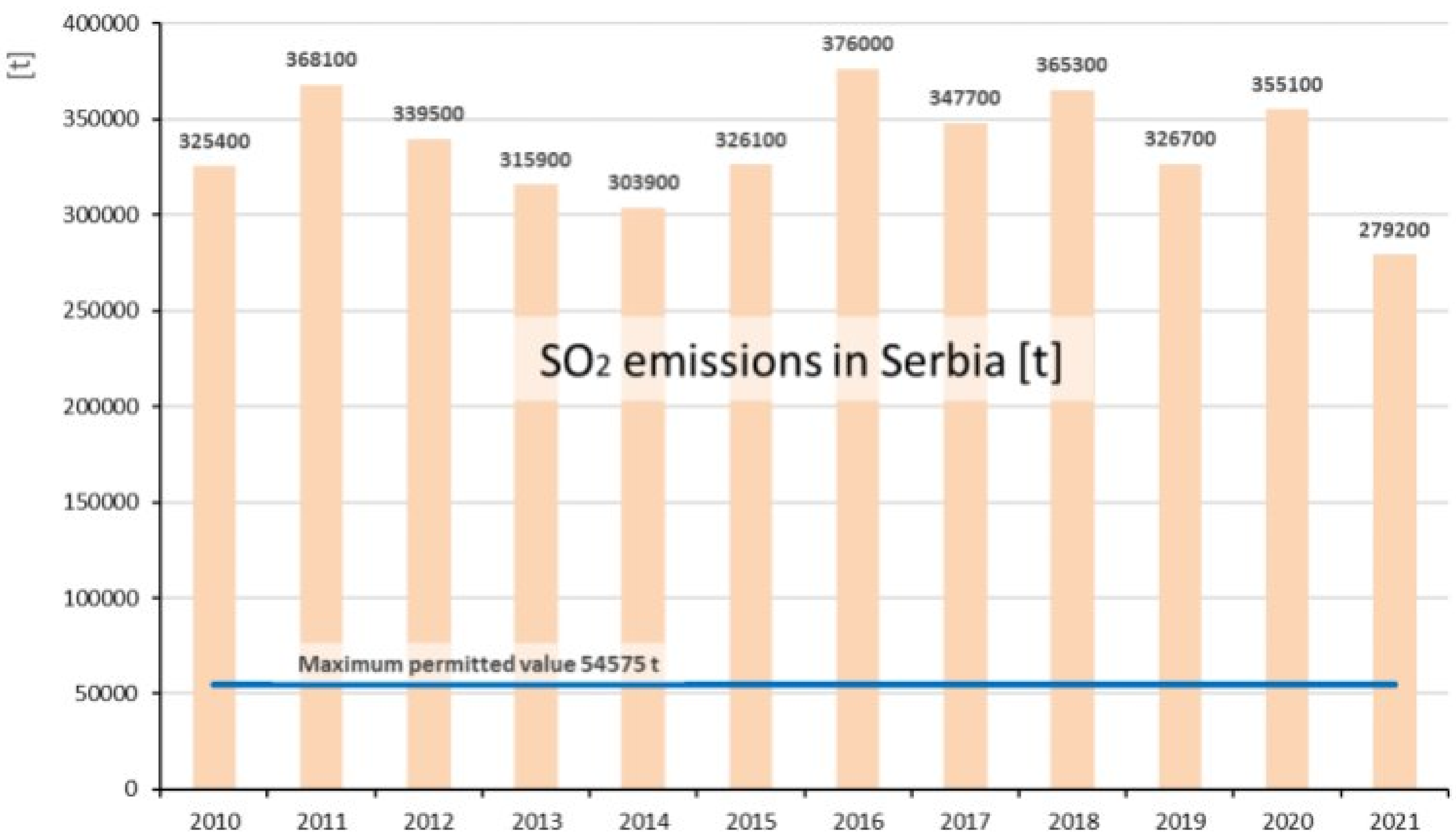

Figure 2. SO_2 emissions from coal-fired power plants in Serbia (not including Kosovo)

Table 4, 5, and 6 provide a comprehensive overview of SO_2, NOx, and PM10 emissions in Germany, Poland, and the SEE region, which stands out as one of the most intensive emitters in EU.

Table 4. Top 5 emitters SO_2 by Europe in 2021 [34]

	Power plant	Country	SO_2 emissions [kt]	Coal	Installed power [MW]	Generation [TWh]	Relation [$ktSO_2$/TWh]
1.	Nikola Tesla	Serbia	167.9	Lignite	3036	14.32	11.72
2.	Bitola	North Macedonia	105.4	Lignite	675	1.86	56.67
3.	Kakanj	Bosnia&Hercegovina	90.2	Lignite	450	1.98	45.56
4.	Ugljevik	Bosnia&Hercegovina	83.3	Lignite	300	1.59	52.39
5.	Kostolac	Serbia	80.7	Lignite	1010	6.23	12.95

Table 5. Top 5 emitters NOx by Europe in 2021 [34]

	Power plant	Country	NOx emissions [kt]	Coal	Installed power [MW]	Generation [TWh]	Relation [ktNOx/TWh]
1.	Belchatow	Poland	25.0	Lignite	5097	27.4	0.91
2.	Nikola Tesla	Serbia	24.5	Lignite	3036	14.32	1.71
3.	Kosovo	Kosovo[1]	19.2	Lignite	1290	5.77	3.33
4.	Neurath	Germany	15.5	Lignite	3622	25.2	0.61
5.	Janschwalde	Germany	14.6	Lignite	3210	12	1.22

[1] This name does not prejudge the status of Kosovo and is in accordance with Resolution 1244 and the decision of the International Court of Justice on Kosovo's declaration of independence.

Table 6. Top 5 emitters PM10 by Europe in 2021 [34]

	Power plant	Country	PM10 [kt]	Coal	Installed power [MW]	Generation [TWh]	Relation [ktPM10/TWh]
1.	Kosovo B	Kosovo[1]	4.6	Lignite	678	3.71	1.24
2.	Bitola	North Macedonia	3.6	Lignite	675	1.86	1.94
3.	Nikola Tesla	Serbia	3.5	Lignite	3036	14.32	0.24
4.	Kolubara A	Serbia	2.6	Lignite	239	0.7	3.71
5.	Gacko	Bosnia&Hercegovina	1.1	Lignite	300	1.52	0.73

[1] This name does not prejudge the status of Kosovo and is in accordance with Resolution 1244 and the decision of the International Court of Justice on Kosovo's declaration of independence.

Emission data for harmful substances in Germany, Poland, and Serbia are presented in Tab. 7 [16]. Notably, the most substantial concern arises from SO_2 and NOx emissions from TPPs in Serbia. These emissions exhibit considerably higher values compared to both Poland and Germany, both in absolute terms and when considering specific values. Additionally, a significant observation is the particulate matter (PM10) emission intensity, which is ten times higher than the average emissions in Poland and Germany, measured per megawatt-hour (MWh) of electricity produced. This underscores a critical environmental challenge in Serbia, highlighting the need for targeted mitigation strategies to address the elevated levels of these pollutants.

Table 7. Pollutant emissions from coal-fired power plants in Serbia (not including Kosovo), Poland, and Germany in 2021 [16]

Emissions	Parameter	Serbia	Poland	Germany
CO_2	Amount of emission [million tons]	28.69	130.20	230.22
	Ratio per unit area of territory [tCO_2/km^2]	324	364	736
	Ratio to the number of inhabitants [tCO_2/h]	4.20	3.45	2.77
	Ratio to electricity production [$kgCO_2/MWh$]	1195	1002	1582
SO_2	Amount of emission [tons]	279200	98800	102470
	Ratio per unit area of territory [tSO_2/km^2]	3.15	0.28	0.33
	Ratio to the number of inhabitants [$kgSO_2/st$]	40.88	2.62	1.23
	Ratio to electricity production [$kgSO_2/MWh$]	11.63	0.76	0.70
NOx	Amount of emission [tons]	36800	92000	114000
	Ratio per unit area of territory [$tNOx/km^2$]	0.42	0.26	0.36
	Ratio to the number of inhabitants [kgNOx/st]	5.39	2.44	1.37
	Ratio to electricity production [kgNOx/MWh]	1.53	0.71	0.78
PM10	Amount of emission [tons]	7400	4372	3660
	Ratio per unit area of territory [$kgPM10/km^2$]	83.62	12.23	11.70
	Ratio to the number of inhabitants [kgPM10/st]	1.08	0.12	0.04
	Ratio to electricity production [kgPM10/MWh]	0.31	0.03	0.03

The energy policies of several European countries remain heavily reliant on fossil fuels, particularly coal. Against this backdrop, the Paris Agreement assumes paramount importance, signalling a pivotal shift in policies aimed at curbing greenhouse gas emissions [21]. Striving for a balance between anthropogenic emissions and the removal of emission sources is a central tenet, aiming for netzero emissions in the latter half of this century. SEE countries, including Serbia, should aspire to attain this ambitious goal by 2050. The generation of electricity, especially from coal, is intricately tied to the climate policies outlined by the European Union (EU) [29]. Each country's adherence to EU guidelines on CO_2, NO_X, SO_2, and coal dust emissions, coupled with electricity demand influenced by varying levels of development, significantly shapes their energy landscape. Notably, advancements in recent years have witnessed a transition toward cleaner energy production from coal in numerous EU coal-fired power plants, resulting in a notable reduction in emissions of CO_2, NO_X, SO_2, and coal dust [36]. Table 8 provides a detailed breakdown of pollutant emissions from TPPs in Serbia, spanning the end of the first decade, throughout the second decade, and into the early years of the third decade of the 21st century. This data serves as a valuable reference for tracking the progress and impact of emission reduction initiatives in the region over time [16,32,33].

Table 8. Pollutant emission from TPP in Serbia (not including KiM), t [16,32,33]

	Nitrogen oxides (NOx/NO_2)	Sulfur oxides (SOx/SO_2)	Carbon dioxide (CO_2)	Suspended particles (PM10)
2010	43100	325400	30820000	18300
2011	51500	368100	34280000	23200
2012	43700	339500	30110000	22100
2013	48900	315900	31290000	15100
2014	41900	303900	24630000	8500
2015	46100	326100	30570000	11900
2016	41000	376000	31070000	12200
2017	44900	347700	31020000	9400
2018	41400	365300	29610000	10300
2019	35200	326700	29600000	9200
2020	36600	355100	30430000	9500
2021	31700	279200	28690000	7400

While positive strides are being made, the SEE region, including Serbia, is still in the process of global efforts to minimize harmful environmental impacts. Established guidelines and positive experiences from more developed nations offer a roadmap for progress. Special attention is warranted for SO_2 emissions, where power plants in the region are leading contributors. Preserving energy security in electricity supply, coupled with the realistic and achievable replacement of coal-fired TPPs by 2050, is imperative for sustainable development.

4. Projection of SO_2 emissions

Currently, Serbia's only desulfurization plant operates at TPP Kostolac, specifically targeting blocks B1 and B2. Significant progress was observed in 2021, as detailed in Tab. 8, but there's still room for efficiency improvement. Table 9 offers a comprehensive breakdown of pollutant emissions from TPP Kostolac B, shedding light on desulfurization's impact. The power plant has a capacity of 300 MWh, with a single stack reaching 250 meters and using sub-bituminous coal with 22.2 wt.% [37]. According to Kozic *et al.* [38] modern TPP complex systems where various materials' flow affects ventilation efficiency and emissions. Coal usage in industrial processes poses several challenges. Fouling and slagging during combustion reduce heat transfer efficiency, impairing boiler performance. Ash fouling in pipes can cause bursts and blockages, leading to equipment failures. Coal mills, crucial for pulverizing coal, face wear, inefficient operation, and explosion risks from coal dust accumulation. Addressing these challenges requires diligent maintenance, monitoring, and control measures for safe and efficient industrial operation [38].

Air pollution from coal-fired TPPs crosses borders, impacting neighboring countries. Serbia's coal-fired thermo-blocks, notably TPP Kostolac B, were significant SO_2 emitters in Europe until 2021. The TPP began reducing SO_2 emissions in 2021 with its desulfurization system, operational since late 2020 after a trial period. This led to a notable decrease in SO_2 emissions. However, optimal levels haven't been reached yet. In 2022, block B1 emitted 184.2 mg/Nm^3 and block B2 emitted 192.3 mg/Nm^3, both below the 200 mg/Nm^3 limit. This data obtained directly from the TPP Kostolac B - Production and Gas Emission Monitoring Department. Block B1 operated for 7726 hours, with the desulfurization system active for 5143 hours [24,32]. Block B2 operated for 7469 hours, with the system active for 4664 hours [24,32]. The desulfurization system must operate 85-90% of the unit's total operation time for optimal TPP function [20], reflecting ongoing efforts to balance efficiency and environmental impact mitigation in the region's coal-fired TPPs.

The anticipated calorific value of coal designated for combustion in the boiler plant of TPP Kostolac B stands at 7327.25 MJ/t. Over the recent years, the actual calorific value of delivered coal has ranged between 8100 and 8800 MJ/t, exerting an impact on the optimal production of electricity. The average coal consumption during the period 2010-2022 hovered around 1.31-1.32 t/MWh, translating to a total calorific value of approximately 24-25 million GJ [20,21]. Figure 3 illustrates the correlation between annual SO_2 emissions, and the total calorific value of coal utilized at the TPP Kostolac B. This data obtained directly from the TPP Kostolac B - Production and Gas Emission Monitoring Department. Up until 2021, corresponding to the commencement of the desulfurization system, a clear interdependence between these two parameters was evident.

Table 9. Pollutant emission from TPP Kostolac B, for the period 2010-2022 [20-22] [t]

	Nitrogen oxides (NOx/NO_2)	Sulfur oxides (SOx/SO_2)	Carbon dioxide (CO_2)	Suspended particles (PM10)
2010	5600	58700	3291049	2700
2011	8675	97802	4960630	6951
2012	2900	43100	3433855	4300
2013	7700	89100	4848705	3700
2014	3400	34500	2481250	300
2015	7832	113462	4739136	1120
2016	8820	127641	5075989	2342
2017	8627	110187	5385400	1253
2018	8077	113913	4870377	1268
2019	5171	79113	3937134	810
2020	5209	95097	4940692	1064
2021	4838	26015	3955429	410
2022	4014	36560	4884123	498

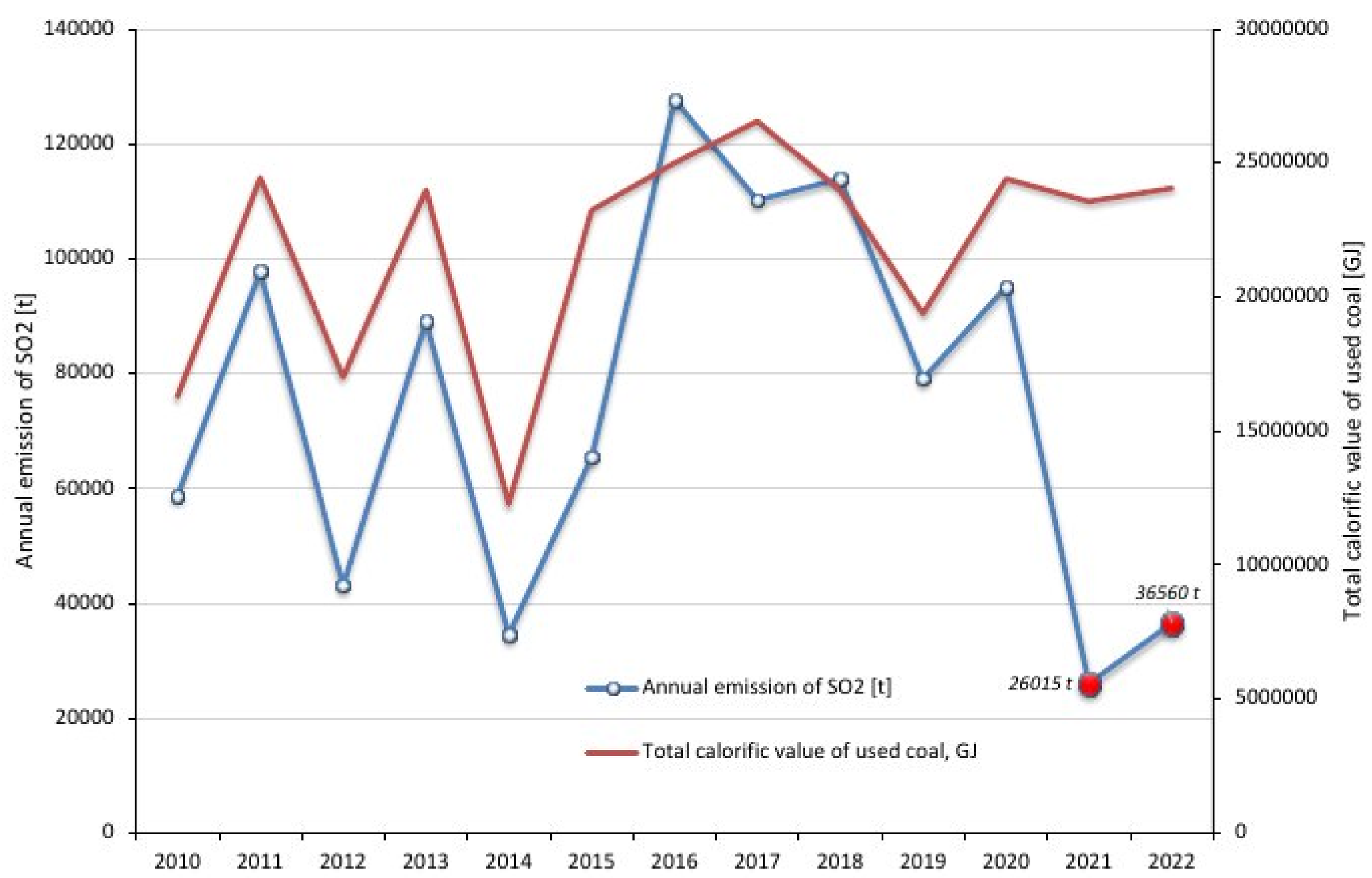

Figure 3. The dependence between the annual SO_2 emissions and the total calorific value of coal consumed in the TPP Kostolac B

Post-2021, there was a notable shift in this relationship, presenting a more environmentally favorable scenario. This shift is underscored by the tangible environmental benefits resulting from the desulfurization system implementation at TPP Kostolac B. From 2010 to 2020, the average ratio of coal's calorific value to total SO_2 emissions was 277 GJ/tSO_2 [24,32,33]. However, during 2021-2022, this ratio increased significantly to 782 GJ/tSO_2, indicating a remarkable 2.82-fold reduction in SO_2 emissions relative to coal burned in blocks B1 and B2 of TPP Kostolac B. This quantifiable improvement highlights the desulfurization system's effectiveness in significantly reducing harmful emissions. To project future SO_2 emissions and plan for coal desulfurization from the Drmno surface mine, data on combustible sulfur percentage in the coal is crucial. This data includes areas where coal has been previously extracted and those designated for future extraction for combustion in TPP Kostolac B until mining operations conclude. This information is derived from the geological model of the surface mine and the annual progress plan for mining activities.

Two essential models were developed to ascertain sulfur content: a digital geological model of the Drmno coal deposit and a detailed mine scheduling model representing the annual progression plan. These models utilized data from 1232 boreholes and considered factors like coal calorific value, sulfur, water content, and ash [40]. The detailed mine plan was based on TPPs' operation and production requirements, with spatial constraints from the mine boundaries [41]. The sulfur content model and the detailed mine plan are visually depicted in Fig. 4, while Tab. 10 provides calculated values of fundamental coal parameters for completed and planned annual coal production from the Drmno surface mine expansion study [41].

Table 10. The share of combustible sulfur in the coal deposit of the Drmno surface mine, period 2010-2040, the quantity of sufur that has been burned and will be burned (projection after 2022)

2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
1.11%	1.12%	1.13%	1.11%	1.15%	1.15%	1.11%	1.10%	1.09%	1.04%
44709 t	67599 t	47560 t	64191 t	33548 t	64021 t	66570 t	68101 t	59840 t	46149 t
2020	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**
1.01%	1.03%	1.07%	1.06%	1.06%	1.07%	1.11%	1.12%	1.13%	1.12%
56088 t	57023 t	62431 t	61480 t	61480 t	62060 t	64380 t	64960 t	65540 t	64960 t
2030	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
1.08%	1.07%	1.06%	1.07%	1.08%	1.10%	1.11%	1.12%	1.13%	1.10%
62640 t	62060 t	61480 t	62060 t	62640 t	63800 t	64380 t	64960 t	65540 t	63800 t

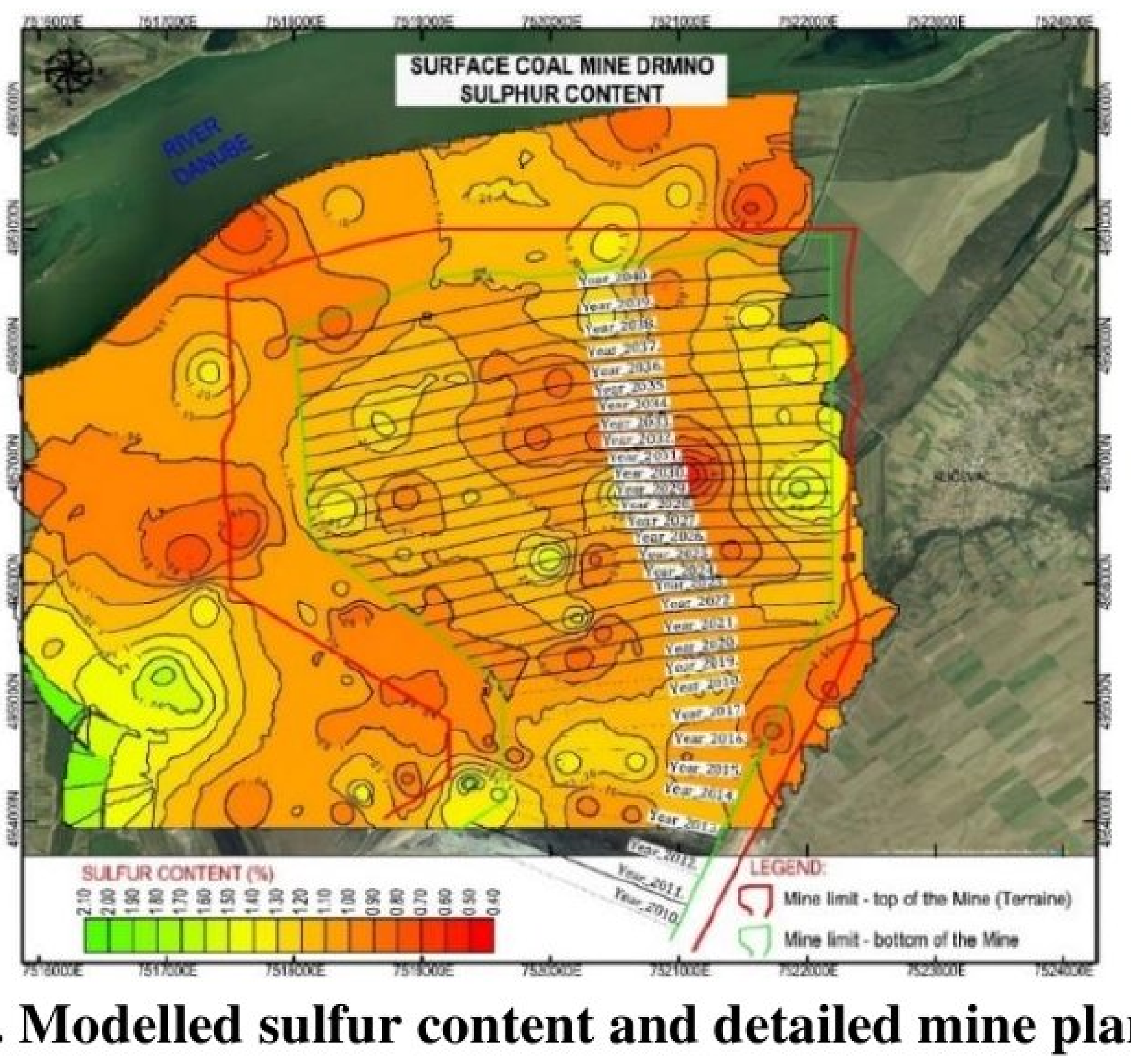

Figure 4. Modelled sulfur content and detailed mine plan

The analysis of the combustible sulfur percentage in the Drmno surface mine coal deposit spans specific timeframes. Historical data from 2010-2022 provides insight into the actual combustible sulfur percentage. Beyond 2022, a projection model anticipates the combustible sulfur percentage, incorporating geological and mining progress data. When examining the sulfur quantity, historical data (2010-2022) outlines the actual amount of sulfur burned during this period. A projection model, accounting for future mining plans and thermal energy production, estimates the sulfur quantity expected to be burned post-2022. Collectively, these parameters offer a comprehensive understanding of sulfur dynamics in the Drmno surface mine coal deposit. This insight is instrumental in effective planning and environmental impact assessment. Based on the sulfur content in the coal layer of the Drmno surface mine and the operation of the desulfurization system at the TPP Kostolac B, a projection of SO_2 emissions can be made for the period up to 2040. TPP Kostolac B is currently the only plant with installed desulfurization systems in Serbia. The desulfurization system is only in the initial stages of its operation, based on the operating parameters of the system. Until 2021, the TPP Kostolac B was one of the biggest SO_2 polluters in Europe. In 2021, the TPP Kostolac B began to reduce SO_2 emissions due to the start of operation of the desulfurization system. Figure 5 illustrates the projected SO_2 emissions at the TPP Kostolac B, assuming optimal utilization of the desulfurization system. This implies that each year, the desulfurization system must remove SO_2 more than 5 times the total input of SO_2. There is a clearly expressed dependence between the amount of SO_2 emitted and the calorific value of the coal used.

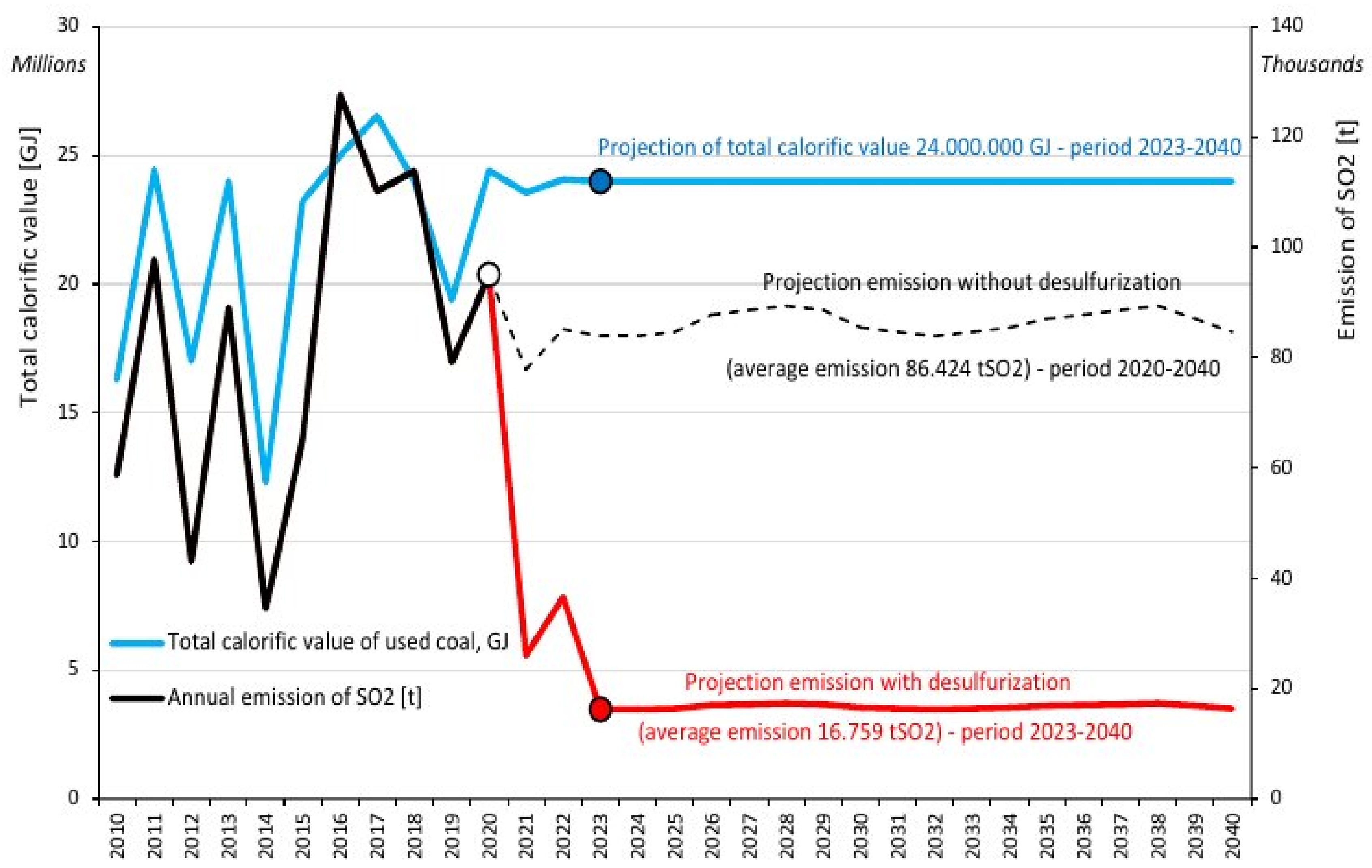

Figure 5. Projection of SO_2 emissions in the TPP Kostolac B

Out of the total average SO_2 production amounting to 86424 tons, an average of 16759 tons of SO_2 should be released into the atmosphere. This value represents the permissible limit. Data indicates that in 2022, TPP Kostolac B, Serbia allocated almost 80000 MWh to the desulfurization process, engaging approximately 16 MW of the installed capacity during system operation. Recognizing the significance of environmental protection, this mode of energy consumption is considered advantageous. The data shown in Fig. 5, representing the projection of SO_2 emissions in the TPP Kostolac B, were obtained through detailed monitoring and analysis of the plant's operations and emissions. It is based on the average coal values for the period 2010-2022, on the average emissions without desulfurization for the period 2010-2021, and emission projection with desulfurization based on EU recommendations. This includes data on fuel usage, combustion processes, desulfurization system efficiency, and other relevant factors affecting SO_2 emissions. Historical emissions data, environmental regulations, coal composition, as well as future operational plans were also considered in generating the projection. Figure 5 represents a model based on these data sources to forecast future SO_2 emissions from the power plant under different scenarios and conditions, alongside accompanying data derived from the geological model of the surface mine and the annual progress plan for mining activities in designated areas of the surface mine [41].

5. Conclusion

The evolving energy landscape in Europe necessitates a shift away from coal towards cleaner alternatives, aligning with global sustainability goals. As Europe navigates this transition, it is essential to consider the economic, social, and environmental implications to ensure a balanced and resilient energy future. While coal remains prominent in Germany, Poland, and SEE, awareness of environmental risks is growing. Strategic planning, investment in cleaner technologies, and international collaboration are crucial for a sustainable energy future. SEE, including Serbia, stands as a major coal pollutant emitter, emphasizing the need for advanced systems in coal plants for pollutant reduction. This paper critically examines the link between electricity generation, particularly coal, and EU climate policies. EU countries, the SEE region, and Serbia play pivotal roles, with detailed analyses of emissions guidelines. Positive trends in EU coal plants reflect successful environmental policies, aligning with global sustainability efforts. However, challenges persist in the SEE region, especially Serbia, in transitioning to cleaner energy. SO_2 emissions, a significant concern, require a realistic replacement of coal plants by 2040 for energy security and sustainable development. The article provides valuable data on pollutant emissions in Serbian TPPs, acting as a reference for tracking progress over time. The reduction in PM10 particle emissions by over 50% highlights the favourability of desulfurization systems. A comprehensive environmental management approach in Serbia involves advanced technologies, stringent regulations, and potential shifts to cleaner energy. International collaboration is key for adopting best practices.

Future research should focus on identifying specific sources and factors contributing to elevated emissions in Serbia, including SO_2, CO_2, NOx, and PM10. Detailed inventories, source studies, and analysis of mitigation measures' efficiency are needed. This may involve detailed emissions inventories, source apportionment studies, and an in-depth analysis of the efficiency of existing mitigation measures. Moreover, exploring the socio-economic implications of these environmental challenges and potential policy interventions could provide valuable insights for a holistic and sustainable approach to environmental management in Serbia's energy sector.

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