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Scenarios for transitioning the electricity sector of the Republic of Serbia to sustainable climate neutrality by 2050

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ABSTRACT

By ratifying the Paris Agreement, the Republic of Serbia has committed to reduce greenhouse gas emissions by 13.2% by 2030 compared to the 2010 levels. About 70% of electricity is generated in thermal power plants that use low-quality domestic lignite as fuel. Greenhouse gas emissions from electricity generation amounted to 51.5 Mt CO_2eq in 2014. The Republic of Serbia has a significant renewable energy source (RES) potential for electricity generation. This research aims to define sustainable scenarios for the years 2030 and 2050 in the transition process of the electricity generation sector in the Republic of Serbia. These scenarios provide an opportunity to gradually reduce CO_2 emissions by 2050, with the goal of zero-emission electricity generation in 2050. The scenarios were created using the hourly electricity balance of the Serbian power system in the EnergyPLAN software, with 2010 as the base year for the calculations. The proposed scenarios promote the sustainable use of RES for electricity generation in the Republic of Serbia. The results show a reduction in CO_2 emissions of 35% and 59% in 2030 for the scenarios and 66% and 100% in 2050 compared to the reference year 2010.

1. Introduction

All EU Member States have set some of the most ambitious climate and energy targets for 2050, and the EU is the first region in the world to adopt binding legislation to achieve them. The main EU targets for 2030 are to reduce greenhouse gas emissions by at least 40% compared to 1990, to meet at least 27% of total energy consumption from renewable sources, and to increase energy efficiency by at least 27% (European Commission, 2011). The EU's long-term goal by 2050 is to reduce greenhouse gas emissions by 80%–95% compared to 1990 (European Commission, 2021a,b). The EU is working to achieve the climate targets through a combination of financial support and regulations.

Regarding Serbia's ability to meet the obligations of EU membership, the country continued to align with the EU acquis to achieve 2030 targets for renewable energy sources, energy efficiency, and greenhouse gas emissions reductions. The Republic of Serbia (RS) adopted and signed the 2015 Paris Agreement, i.e., the global agreement to combat climate change, committing to contribute to reducing greenhouse gas emissions at the global level in the future (United Nations Framework Convention on Climate Change, 2015). In addition, RS signed the Sofia Declaration on the Green Agenda for the Western Balkans (Guidelines for the Implementation of the Green Agenda for the Western Balkans), in which RS and the countries of the region committed to several concrete measures, including the introduction of CO_2 taxes and market models to promote RES and the phasing out of coal subsidies (European Commission, 2020).

To analyze sustainable energy scenarios until 2050 in the context of the energy transition for decarbonization, research in planning the development of the electricity sector was considered. Electricity generation and consumption for the main regions of Germany, the energy transition to renewable energy through energy scenarios for the year 2030, is presented in the paper (Moeller et al., 2014; Gomes et al., 2020) present several scenarios for the electricity system for the time horizon until 2040. It has been shown that reducing the number of coal-fired thermal power plants, the expansion of renewable energy sources, and the installed capacity of renewable energy power plants can meet the electricity demand in Portugal. The analysis of the energy sector in Macedonia for the reference scenario and the two scenarios that predict

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renewable energy sources are presented in the papers (Dedinec et al., 2022). In order to achieve a 100% renewable energy system in Macedonia, a high share of biomass, wind, and solar energy is required, as well as various storage technologies. The results show that when considering electricity and heat production, using renewable energy and applying efficient technologies and practices can lead to a 35% reduction in the total primary energy demand if the energy system uses 50% renewable energy. In (Lund and Mathiesen, 2009), the methodology of energy system analysis in Denmark with 100% and 50% renewable energy is presented. The system which utilizes 100% renewable energy in 2050 includes energy from biomass and a combination of wind, wave, and solar energy, and the scenario for 2030 with 50% renewable energy includes the results of detailed socio-economic feasibility studies, electricity market calculations, and sensitivity analyses. In order to achieve a fully sustainable energy system for the Åland Islands by 2030, a scenario analysis was performed using the EnergyPLAN tool (Child et al., 2017) based on different combinations of domestic production of wind and photovoltaic electricity, in-country energy storage solutions, and electrified transport. The quality of resources and the temporal pattern of variable renewable generation vary significantly across Europe and increasingly contribute to power system variability (Gils et al., 2017). Research by (Eriksen et al., 2017) shows the spatial distribution of renewable energy sources to reduce total system costs and estimate the required type and capacity of balancing measures.

Rodrigues et al., 2022 examine the future evolution of energy systems in the context of deep decarbonization. The latest energy-environment-economy models were used for the study. The results show that a transition to carbon neutrality by mid-century is possible under very different future energy systems. Oyewo et al., 2019 presented research on an energy system for South Africa that would be fully decarbonized and economically acceptable. Five scenarios were formed for the time horizon up to 2050. The energy policy and future energy strategy are based on photovoltaic and wind energy technologies, which provide about 71% and 28% of the electricity demand, respectively. The results show that in the 2050 scenario, coal energy can be replaced by renewable energy sources. The analysis of different scenarios of electricity generation and consumption in Egypt for the period between 2020 and 2050 is presented in the paper (El-Sayed et al., 2023), where the basic as-usual scenario assumes the same energy consumption in the period between 2009 and 2019. In the other two scenarios, an increase in the share of renewable energy sources to 42% by 2035 and to 70% by 2050 was studied. The results show that the contribution of natural gas will decrease. The renewable energy scenarios also have the lowest long-term production costs compared to the other scenarios. The paper (Dominković et al., 2016) discusses the transition to a carbon-free energy system by 2050 for Southeast Europe (SEE), where fossil fuel consumption dominates.

In contrast to other works, the sustainable use of biomass is assumed in a 100% renewable energy system, as wind and photovoltaic plants are the dominant technologies, with shares in energy production of 29% and 22.5%, respectively. The paper aims (Bjelić and Rajaković, 2015) to show Serbia's economic national energy plan until 2030 with a minimum cost increase and what energy policy measures should be included. In planning a sustainable national energy system, software tools for simulation of the national energy system and optimization methods (EnergyPLAN and GenOpt) were used in the decision-making process.

The integration of wind energy into the existing Serbian energy system and the level of energy imbalance on an annual basis were calculated using the EnergyPLAN simulation tool and presented in (Bjelić et al., 2013). It has been shown that it is possible to integrate more energy from wind turbines. In (Brown et al., 2018), it is concluded that scenarios predicting 100% renewable energy, as proposed in the literature, are feasible and sustainable. They meet the energy needs of all citizens and are competitive with systems that use fossil fuels, even when externalities such as global warming, water consumption, and pollution are taken into account. In (Khanna et al., 2016), the potential to reduce energy and carbon dioxide (CO_2) emissions by 2050 is quantified for China. They concluded that without renewable energy targets or green deployment, coal will likely continue to dominate China's power mix and could delay the peak of power sector CO_2 emissions to the end of 2030. Long-term planning and operation of the electricity system based on expectations of future electricity demand and future transmission/generation capacity are presented in the paper (Lindberg et al., 2019). Achieve net-zero emissions by 2050 for China's Sichuan province (Bamisile et al., 2022) propose three innovative pathways that consider the additional use of biomass, pumped-storage power plants, and importing clean electricity from neighboring provinces. The analysis in this paper shows that no net zero emissions can be achieved by 2050 based on the government's proposed pathway. However, the three optimized strategies/models show a clearer and faster path to decarbonization. This study can also serve as a template for many countries with high carbon emissions and significant potential renewable energy (RE).

This paper presents the methodology and results to build and analyze sustainable energy scenarios through 2050 in the context of the energy transition required to decarbonize the electricity sector of the RS. The methodology includes hourly electricity generation and consumption simulations using a computer model for energy planning with the energy system analysis tool EnergyPLAN. The results are detailed energy system designs and balances for two scenarios. The energy scenarios consider ways CO_2 emissions can be reduced by 2030 and 2050. The Republic of Serbia, in the accession negotiations with the European Union and in the relevant documents resulting from the Paris Agreement, has committed to reducing greenhouse gas emissions compared to 2010.

For this reason, 2010 was chosen as the base year. For 2030 and 2050, a '*with measures*' energy scenario and a '*with additional measures*' scenario have been formed, taking into account increasing energy efficiency, the need to meet emission reduction commitments, achieve carbon neutrality, and maintain electricity supply security to ensure that Serbia has sufficient energy, which implies a gradual reduction of electricity production from fossil fuels and investments in the construction of new energy capacities and job creation. The new energy capacities include new hydropower plants, gas-fired power plants, solar power plants, wind power plants, and a nuclear power plant. The required energy system inputs for each scenario used in the EnergyPLAN model are planned energy consumption in the power sector, renewable energy sources, power plant capacities, and efficiency, planned electricity imports and exports, and available energy resources.

Papers in the reference list dealing with the energy sector of the RS refer to the period before the adoption of the following documents: the recent energy development strategies of the RS, new laws and regulations in the energy sector of the RS, adopted commitments from the accession negotiations with the EU, and the Paris Agreement on climate change. In this paper, the energy scenarios were prepared according to the last redefined RS energy strategy until 2030, focusing on the decarbonization of the electricity generation sector and the increased use of renewable energy sources.

2. Methodology

This paper applies the methodology for predicting the future sustainable electricity sector in Serbia, which is an integral part of the country's economic system. Based on the available database (statistical and qualitative data on the energy sector), energy scenarios until 2050 were defined, and the electricity grid was simulated using an EnergyPLAN computer model for energy planning. In addition to the baseline scenario, sustainable scenarios for 2030 and 2050 are shown, '*with measures*' and '*with additional measures*,' which envisage total electricity consumption and zero CO_2 emissions in 2050.

The energy policy concept underlying the scenario is to increase energy efficiency and energy savings, build new capacity on renewable energy sources (RES) and nuclear power plants, and choose the optimal structure to meet energy consumption and, security and stability of supply for consumers. Long-term power-system planning and operation build on expectations concerning future electricity demand and future transmission/generation capacities.

Considering the significant build-up of new capacities based on using RES to balance power in the system and maintain the required level of system stability, the 2030 and 2050 scenarios include the construction of new pumped-storage hydropower plants (PSH). The total amount of electricity produced from hydropower plants (HPP) is projected to be 9680 GWh in 2021, including the PSH plant. The '*with measures*' and '*with additional measures*' scenarios in 2030 envision 3672 MW of HPP, including 980 MW of PSH plants. The BAU scenario for 2050 envisions a total of 3852 MW of HPP, of which 980 MW is at the PSH plants, while the '*with measures*' and '*with additional measures*' scenarios envision 4831 MW, of which 1580 MW belongs to the PSH plant.

Nuclear power plants as a stable and reliable source of electricity, a source of clean electricity with an electricity price comparable to the price of coal-fired electricity and higher than the price of RES, are a long-term solution for electricity supply (Dimnik et al., 2022) The public's negative attitude toward nuclear power plants today is focused on radioactive waste management and the issue of safety. In the long term, as a transitional solution to achieve the goals of the Green Agenda, the electricity demand in Serbia would be met by constructing a nuclear power plant with a capacity of 1000 MW. The social, economic, and environmental acceptability and competitiveness of small and medium nuclear reactors are predicted in the '*with measures*' and '*with additional measures*' scenarios for 2050.

Various modeling tools are used in energy planning, which allows the analysis of an entire national energy system and the interaction between consumption sectors, the analysis of new technologies for production and consumption, and the calculation of greenhouse gas emissions (Chang et al., 2021; Luo et al., 2021). In the paper (Østergaard, 2015), the simulation tool EnergyPLAN, generally used to evaluate energy systems with high shares of RES, was used to model future energy consumption implemented through scenarios.

2.1. The primary purpose and characteristics of EnergyPLAN

EnergyPLAN is a deterministic model (Official site of EnergyPLAN, EnergyPLAN-Documentation-V11-2013, 2013) that optimizes the operation of a given energy system based on user-defined inputs and outputs and is used in the design of future sustainable energy options with a particular focus on energy systems with high shares of renewable energy sources. The primary purpose of the EnergyPLAN model is to design and analyze the energy, environmental, and economic impacts of various national energy planning strategies to calculate energy balances, gas emissions, and costs annually. The energy balances include electricity production and consumption in the electricity, heat, and transport sectors (Yuan et al., 2021).

In this paper, EnergyPLAN was used as a simulation tool to model the reference scenario and the scenario for 2030 and 2050 and the option of energy systems for comparison. In this case, we used EnergyPLAN for detailed modeling of future technologies, such as solar energy, wind energy, biomass, and synthetic fuels, but also relatively aggregated modeling of present technologies, such as thermal power plants (Lund et al., 2017, 2021). The principle of the energy system model in EnergyPLAN is shown in Fig. 1.

EnergyPLAN is a deterministic model instead of a stochastic one or models using Monte Carlo methods. The model can perform a calculation based on RES data of a stochastic and intermittent nature and still provide system results that are valid for future RES data inputs (Lund, 2013). Consequently, the model can analyze the influence of fluctuating RES on the system.

EnergyPLAN is designed as an input/output model. The required input quantities used in the model include planned energy consumption in the power sector, renewable energy sources, power plant capacities, and their efficiency, planned electricity import and export, and types of available energy sources. Output data are annual production and annual

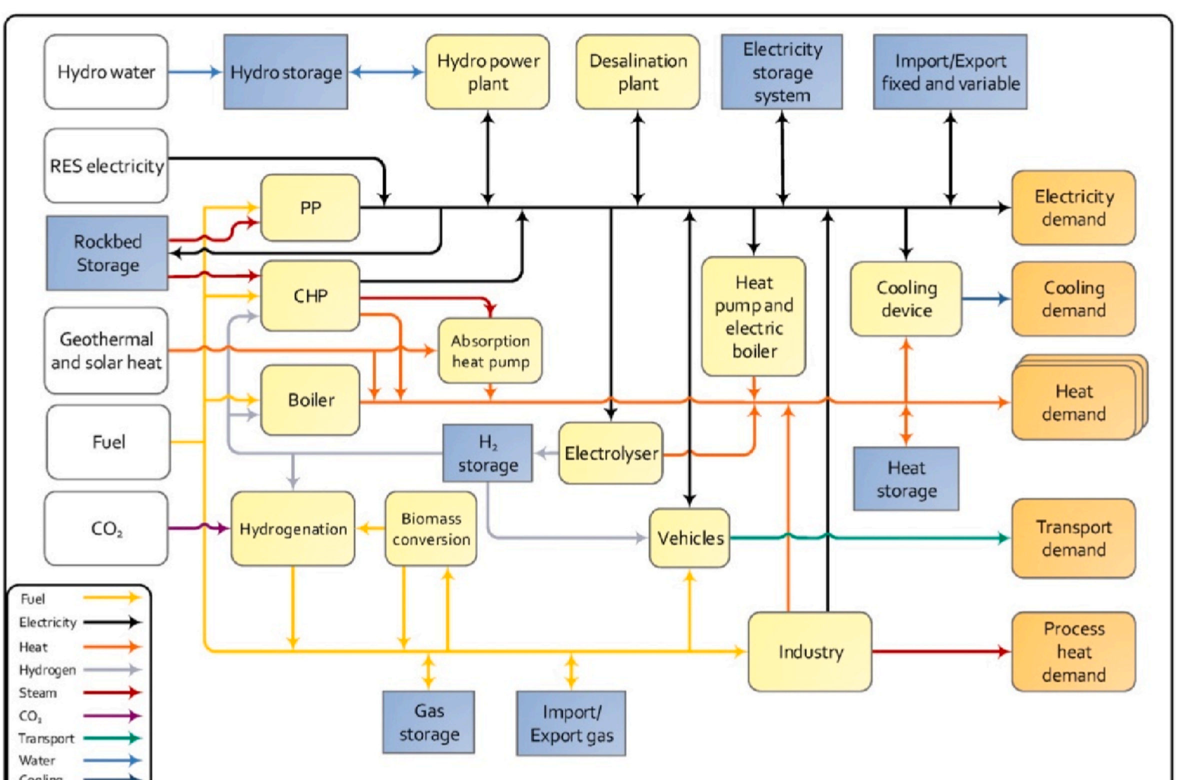

Fig. 1. The flow model of the energy sector in the energy system analysis tool EnergyPLAN.

energy balance, fuel consumption, import and export, electricity, and CO_2 emissions. The EnergyPLAN simulations are presented in annual values, which come from performing calculations at an hourly level. The software does not require hourly-level input data, except for the input data needed for hourly load data for the Serbian power sector and weather files.

2.2. The structure of the electricity sector in RS

The current state of the electricity sector in RS is characterized by an increase in net electricity imports, the age and inefficiency of existing generation capacity, the dominant share of coal in electricity production, the market liberalization process with a substantial 'social' component, and a low, indeed insufficient electricity price.

Coal-fired electricity generation is still the dominant option in the energy strategy of RS. About 70% of the total electricity consumption in Serbia comes from thermal power plants burning lignite (the highest quality lignite with a heat value of about 7500 kJ/kg, ash 15.9%, and moisture 52%). RS has coal reserves for about 45 years of electricity production needs at current exploitation levels. The Kolubara and Kostolac mining basins produce the lignite used in thermal power plants: TPP Kolubara, TPP Nikola Tesla, TPP Kostolac, and TPP Morava. As a result of burning poor quality lignite, domestic thermal power plants emitted over 27.3 million tons of CO_2 in 2019, of which only TPP Nikola Tesla in Obrenovac emitted over 20.3 million tons, 361.000 tons of SO_2, and significant amounts of ash and suspended PM10 particles (TPP Kolubara A 3255 t; TPP Nikola Tesla A 2860 t; Kostolac B 2340 t; Kostolac A 1030 t), which severely affect the health of the local and national population (ECO System,2020).

The installed capacities for electricity production in 2020 are shown in Table 1. The structure of generation capacities (excluding the Autonomous Province of Kosovo and Metohija - APKM) is shown in Fig. 2.

The share of thermal power plants (TPP) and thermal heating plants (THP) is 57.4%, the share of hydropower plants (HPP) is 35.5%, the share of wind power plants (WPP) is 4.5%, and 2.6% of the installed capacities are small power plants (SPS).

In 2020, 35.54 TWh of electricity was produced in Serbia, and gross electricity consumption was 33.85 TWh. Consumption by end users was 29 TWh, and the rest was spent on the operation of power plants, pumping needs in pumped-storage HPP, and as compensation for electricity losses in the networks for transmission and distribution of electricity. In 2020, 4.4 TWh was imported, which was at the same level as in 2019, and 4.7 TWh was exported, 0.75 TWh more than in 2019. The highest daily gross consumption in Serbia (excluding APKM) of 121,114 MWh was reached on January 17th, 2020 (Energy Agency of the Republic of Serbia, 2021).

2.3. CO_2 reduction policy and legislation in RS

The EU Emissions Trading Scheme (EU-ETS) created the largest carbon market in the world. Greenhouse gas emissions trading has successfully focused company attention on the effects of climate change by setting a price on CO_2 emissions. The upper limit on total allowable emissions from the operation of thermal power plants is gradually being reduced. In 2020, emissions were 21% lower than in 2005, and a 43% reduction is proposed by 2030.

Table 1
Capacities for electricity production in 2020.

Technology	Number of power plants	Installed power (MW)
Hydropower plants	12	2941
- river	5	1980
- hydro dam	6	347
- pumped-storage	1	614
Thermal power plants	7	4429
Thermal heating plants	2	330
Wind farms	4	373
Small hydropower plants	18	41
Small power plants-independent producers	310	171

The integration of the provisions of the EU Regulations and the adoption of commitments similar to those undertaken by the EU and its member states under the Paris Agreement arise from the process of accession of the Republic of Serbia to the EU but also from the need to implement the Sofia Declaration (Green Agenda for the Western Balkans) and the accompanying documents. By signing the Sofia Declaration, Serbia committed to comply with the European climate legislation and achieve climate neutrality by 2050, followed by setting targets for 2030, further compliance with EU ETS, i.e., introducing carbon taxes, and developing adaptation strategies and decarbonization.

In 2021, the Parliament of the Republic of Serbia adopted the Law on Climate Change (Official Gazette of RS, 2021), which regulates the system for limiting greenhouse gas emissions and adapting to changing climate conditions and introduces a system for monitoring and reporting, i.e., issuing permits for industrial and energy facilities. With the adoption of this law, the legislation of RS was harmonized with the following legal acts of the EU: Directive 2003/87 EU (European Parliament and Council, 2003); Commission Regulation (EU) No. 600/2012 and Commission Regulation (EU) No. 601/2012 (European Commission, 2012). At the end of 2019, the European Commission adopted the EU Communication on the European Green Deal, which provides for a Carbon Border Adjustment Mechanism (CBAM), based on which a national climate and energy strategy must be established and a clear path to full decarbonization in 2050 must be defined (European Commission, 2021a,b). The CBAM transition period is scheduled to begin on October 1, 2023. CBAM is equivalent to the EU ETS system and aims to "charge" the carbon content of certain products when imported from non-EU countries.

Concrete changes and full implementation of the law can be expected by adopting the Strategy, Action plan, and Program for Adaptation to Changed Climate Conditions, confirming the commitment to transition to a green and circular economy. In this process, green energy will play a central role in the fight against climate change.

At the beginning of 2021, a set of energy laws were passed, the most important of which is the Law on the use of RES, which aims to reduce electricity consumption in households and allows citizens to produce and sell green kilowatts (Official Gazette of RS, 2021). The new law introduces auctions for the granting of market premiums instead of the current feed-in tariffs, exposing producers to the influence of the market and competition, which reduces costs for citizens and the economy, and at the same time, assuring investors guaranteed stability and predictability of the legal framework. For the first time, the concept of the buyer-producer (also called prosumers or RES-self consumers) was introduced, representing an electricity buyer who can also produce electricity for their own needs, feed surplus electricity to the grid, and reduce the electricity bill. In this way, the passive customer becomes an active market participant who makes independent decisions based on production, consumption, and stored electricity.

Decarbonization of the energy sector for the period up to 2030, with projections up to 2050, is to be enabled by the Integrated National Energy and Climate Plan (INECP or NECP), which is in the final stages of development (The Ministry of Mining and Energy, 2023). The INECP is one of the most important strategic documents defining the energy transition process and one of the most important practical tools for the country to demonstrate how it will achieve its energy and climate goals. Its adoption and the improvement of legislation in the energy sector are expected by the end of 2023.

The INECP aims to provide an overview of the current situation in the Republic of Serbia and, the main policies and appropriate measures to incorporate the five dimensions of Regulation (EU) 2018/1999:

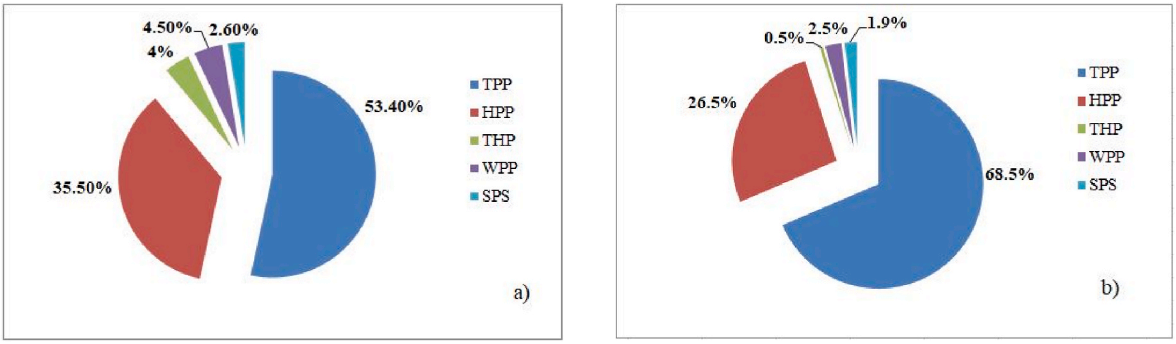

Fig. 2. Structure of production capacities a) and electricity production b) in 2020 (Energy Agency of the Republic of Serbia, 2021).

decarbonization, energy efficiency, energy security, the internal energy market, and research, innovation, and competitiveness. A key task in developing the INECP is to define the scenario that will be used to set new energy efficiency, renewable energy, and greenhouse gas emissions targets. The INECP would contribute to higher economic growth, create new jobs, and achieve a balance between energy sector development and environmental protection, as prescribed by the Green Agenda.

2.4. Assumptions in scenario selection

Table 2 shows the generation, distribution, and final electricity consumption values for the scenarios considered. Based on (Energy Agency of the Republic of Serbia, 2022) for the period from 2010 to 2022, it can be seen that the total losses in the transmission and distribution network are significantly reduced, from 17.5% to 12%. In the transmission and distribution network, the indicators of continuity of electricity supply remained at the five-year average level.

The key assumptions in scenario selection and creation are:

- Ensuring final consumption of electricity (Table 2), based on GDP growth forecast from RS documents (Ministry of Environmental Protection RS, 2017);
- Modernization of the distribution and transmission network to reduce network losses, which are shown in Table 2;

- Fig. 3 shows the projection of the construction of wind turbines and solar energy systems by 2030 and 2050 based on the completed technical documentation and the maximum possible installation capacity from these sources (Jovanović, 2018). At the beginning of 2021, several energy laws were adopted, the most important of which is the law on the use of RES, which aims to reduce household electricity consumption and allows citizens to produce and sell green kilowatts (Official Gazette of RS, 2021). According to this law, households can install a maximum of 10 kW of power. Modernizing the power grid will allow households to increase the installation capacity of solar power systems.
- Gradual shutdown of 10 power plants, burning low-grade lignite, namely TPP Morava, TPP Kolubara, and TPP Kostolac A1 and A2 with a total capacity of 607 MW by 2030, and shutdown of units TENT A1 and A2 with a total capacity of 490 MW by 2050.
- Large thermal power plants with a capacity exceeding 300 MW will be revitalized (TENT units A3-A6, TENT B1–B2, Kostolac B1–B2 with total installed capacity of 3160 MW and an average annual production capacity of 19,000 GWh). Using the best available technologies (BAT) in these thermal power plants could lead to up to 30% energy savings.
- Termination of operation of the old units in Thermal Heating Plant of 536 MW.
- The infrastructure (capacity) of the electricity distribution grid can cover the necessary imports and exports of electricity.

3. Planning of the Serbian electricity sector

In this paper, Business as Usual (BAU) scenarios for 2030 and 2050 were formed in addition to the energy scenario for the reference year 2010. The BAU scenario for 2030 and 2050 assumes that there are no significant changes in electricity production technology. Since the Energy Agency of the Republic of Serbia reports for 2019 and 2020 were available (Energy Agency of the Republic of Serbia, 2020), the BAU scenarios for 2030 and 2050 were also adjusted based on these reports.

In addition to the basic scenarios, the '*with measures*' and '*with additional measures*' scenarios were defined. The '*with measures*' scenario assumes the improvement of the implementation of existing energy policies and measures established by adopting a series of laws in the field of energy and energy efficiency from 2020 so that they are fully consistent with the commitments of the EU accession process. The scenario '*with additional measures*' implies an additional reduction in the final consumption of electricity, i.e., a reduction in electricity production with a gradual tendency to create an electricity system with zero-emissions electricity production based on the use of 100% renewable energy sources.

Table 2
Generation and consumption of electricity for the considered scenarios.

	2010	2030			2050		
		BAU	Scenario '*with measures*'	Scenario '*with additional measures*'	BAU	Scenario '*with measures*'	Scenario '*with additional measures*'
	GWh	GWh	GWh	GWh	GWh	GWh	GWh
Final electricity consumption	28,487	32,894	31,344	28,210	40,885	36,796	32,708
Grid losses	6022	4139	2726	2453	3555	3200	2844
Gross final electricity consumption	34,509	37,033	34,070	30,663	44,440	39,996	35,552
Pump storage (import + export)	600	600	600	600	1100	0	−900
Net electricity production	35,109	37,633	34,670	31,263	45,540	39,996	34,652
Grid losses (%)[a]	17.5	11	8	8	8	8	8

[a] To the final gross consumption.

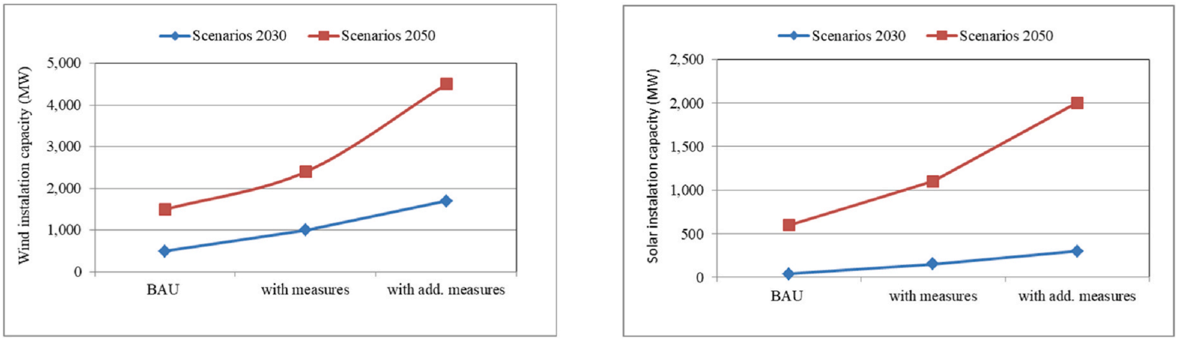

Fig. 3. Wind and solar installation capacity for different scenarios.

3.1. BAU scenario for the reference year 2010

The structure of electricity generation capacities of PE EPS in the year 2010 (Energy Agency of the Republic of Serbia, 2020) is as follows: hydropower plants 2835 MW, thermal power plants 3936 MW, cogeneration power plants 353 MW, and small power plants owned by PE EPS 20 MW. The electricity energy balance of the Republic of Serbia in 2010 is shown in Table 3. The total electricity generation in 2010 amounted to 35,867 GWh. The largest generation was achieved in thermal power plants (64.5%) and hydropower plants (34.6%). Electricity import was 1286 GWh, while electricity export was 2559 GWh, so net export in 2010 was 1273 GWh. Transmission and distribution losses amount to 17.3% of final gross consumption.

3.2. Scenarios for 2030

3.2.1. BAU scenario for 2030

In recent years, RS has invested significant financial resources in the revitalization and modernization of thermal and hydropower plants so that the installed capacity of thermal and hydropower plants in 2019 (PE, 2020) increased by about 5% compared to 2010, with the installed capacity of thermal power plants amounting to 4079 MW and that of hydropower plants amounting to 2992 MW in 2019. Significant electricity losses characterized the transmission and distribution network of the Serbian electricity sector. In parallel with the modernization and revitalization of energy units, the Republic of Serbia has invested significant financial resources in the improvement of the transmission and distribution network, so that the losses, which amounted to 17.3% (5895 GWh) of gross consumption in 2010, were reduced to 12.8% (4333 GWh) of gross consumption in 2019. Electricity generation in 2019 was 34,832 GWh (Energy Agency of the Republic of Serbia, 2020), which was 2.9% lower than the base year 2010.

The RS electricity sector development plans until 2030, according to the 2030 BAU scenario, assume that there will be no significant changes in electricity sector attitudes and priorities, i.e., there will be no significant changes in electricity generation technology, economics, and policies. Based on the plans for the development of the electricity sector until 2030, the construction of the following power plants is planned: Kostolac B3 thermal power plant with a capacity of 350 MW, Pancevo thermal power plant with an installed capacity of 200 MW, construction of wind power plants with a capacity of 500 MW and a biogas power plant with a capacity of 30 MW. The total installed electric power of the power plants for the BAU scenario for 2030 is: Thermal Power Plant 4429 MW, Thermal Heating Plant 536 MW, and hydropower plant 2992 MW.

The increase in final electricity consumption in the BAU scenario for 2030 compared to 2010 is estimated to be 17% based on the adopted official documents RS (Ministry of Environmental Protection, 2017), with most of the final electricity consumption in the industrial sector. During this period, significant attention will be paid to the further reduction of losses in the transmission and distribution network, estimated at 11% of the gross final consumption. Based on the measures adopted according to the BAU scenario for 2030, the total electricity generation in the power plants amounts to 37,633 GWh.

Table 3
Electricity energy balance in 2010.

		GWh
1.	PRODUCTION	35,867
2.	HYDROPOWER PLANTS[a]	12,422
3.	THERMAL POWER PLANTS	23,162
4.	PUBLIC CHP	222
5.	Other	61
6.	Import	1286
7.	Export	2559
8.	Losses	6022

[a] Including pumped-storage HPP Bajina Bašta.

3.2.2. Scenario 'with measures' for 2030

The "*with measures*" scenario for 2030 is characterized by a significant increase in the share of renewable electricity sources and a decrease in the installed capacity of thermal power plants. Based on the RS Electricity Strategy, it is planned to reserve significant capacities of thermal power plants, namely TPP Morava, TPP Kolubara, and TPP Kostolac A1 and A2, with a total capacity of 607 MW, so the total installed capacity of thermal power plants at the threshold is 3822 MW.

According to (the Ministry of Mining and Energy, 2016), RS's total theoretically available hydropower potential is about 25,000 GWh/year. The technically useable potential is about 19,53 GWh/year, of which about 16,31 GWh/year are plants larger than 30 MW, Table 4. The significant hydropower potential in the Republic of Serbia is located in the Drina River basin. The scenario for 2030 envisages the construction of the HPP Bistrica power plant, which consists of four dams of 170 MW each and operates as a PSH plant, so the total installed hydropower capacity according to this scenario will be 3672 MW.

The "*with measures*" scenario envisions the installation of significant energy capacity from renewable energy sources: 1000 MW wind power plants and 150 MW solar power plants, along with 100 MW biogas

Table 4
Hydro potential of Serbia.

Hydropower	Available technical potential utilized (GWh)	Unutilized available technical potential (GWh)	Total available technical potential (GWh)
Total: Hydropower	10,57	8,95	19,53
For capacities up to 10 MW	0,05	1,76	1,80
For capacities of 10–30 MW	0,23	1,19	1,42
For capacities over 30 MW	10,99	6,01	16,31

power plants and 286 MW biomass power plants. The total technically useable potential of wind energy for the entire territory of Serbia at the annual level is 2,47 GWh/year. The average annual wind energy per unit area at a height of 100 m ranges from 900 kWh/m^2 in the southwest and south to more than 2700 kWh/m^2 in the eastern part of Serbia. The maximum technically useable potential of solar radiation energy for electricity production is 540 GWh/year (Ministry of Mining and Energy, 2016; Serbian Chamber of Commerce, 2020).

Furthermore, this scenario envisages introducing and applying various energy efficiency measures, mainly reflected in the further reduction of losses in the transmission and distribution network and the reduction of electricity consumption in households for heating purposes. Total electricity generation in this scenario is 8% lower than in the BAU scenario for 2030, or 34,670 GWh.

3.2.3. Scenario 'with additional measures' for 2030

With the adoption and implementation of a series of laws in the field of energy, mainly laws in the field of energy efficiency, the scenario '*with additional measures*' for 2030 foresees that the total electricity production at the output of the power plants will be 10% lower than the electricity production according to the scenario '*with measures*' for 2030, and will be 31,203 GWh. This scenario provides for the possibility of a larger share of electricity from renewable energy sources compared to the previous scenario, so the installed capacity of renewable sources for this scenario is as follows: 1700 MW wind power, 300 MW solar power, 120 MW biogas power plants, and 350 MW installed capacity from biomass.

3.3. Scenarios for 2050

3.3.1. BAU scenario for 2050

For the 2050 BAU scenario, a 20% increase in final gross electricity consumption was assumed compared to the 2030 BAU scenario, which is consistent with (SEERMAP, 2017). Such forecasts of an increase in final gross electricity consumption result in total electricity production at the power plant output of 45,540 GWh.

In this scenario, the electricity generation capacities in 2050 are characterized by increased capacities of hydropower plants, thermal power plants, wind farms, and solar power plants. The structure of installed capacities of individual electricity sources for this scenario is as follows: Thermal power plants 3852 MW, thermal heating plant 980 MW, hydropower plants 3852 MW, wind power plants 1500 MW, solar power plants 600 MW, biogas power plants 120 MW and biomass power plants 300 MW.

Based on the development strategy for constructing new TPP capacity, PE EPS forecasts that by 2050, the construction of the following coal-fired thermal power plants will be realized: Kolubara B 350 MW and Kostolac B3 350 MW. At the same time, 1097 MW will go into reserve. In Kolubara B units, fluidized bed technology will be used to combustion coal quality out of the contractual range from Kolubara open cast mines. Imports will cover the shortfall in coal quantities for power generation until 2050. Compared with 2010, smaller quantities of coal will be needed because the imported coal will be of better quality, and the energy efficiency of the existing units will be improved.

3.3.2. Scenario 'with measures' for 2050

The scenario '*with measures*' for 2050 envisages a 10% lower gross final electricity consumption than the BAU scenario 2050 (electricity production at the power plant output in this scenario is 40,08 GWh). The scenario is characterized by a significant decrease in electricity production from thermal power plants, thermal heating plants, and a significant increase in installed capacity from renewable energy sources, mainly installed wind and solar power plants, whose capacity is higher compared to the BAU scenario for 2050, as well as the achievement of a maximum installed capacity of hydropower plants. The structure of electricity production capacities in this scenario is as follows: thermal power plants 1570 MW, thermal heating plant 450 MW, hydropower plants 4831 MW, wind power plants 2400 MW, solar power plants 1100 MW, biogas power plants 240 MW, and biomass power plants 400 MW. In this scenario, in addition to power plants based on conventional fossil fuels and RES, a nuclear power plant with a 500 MW capacity is planned. In addition to the nuclear power plant, the stability of the power grid is ensured by constructing a new power plant of 600 MW PSH (Đerdap3).

3.3.3. Scenario 'with additional measures' for 2050

The scenario '*with additional measures*' for 2050 envisions a 20% lower gross final electricity end-use compared to the BAU scenario for 2050. According to this scenario, electricity production at the power plant site is 34,73 GWh. This scenario does not include electricity production from coal-fired thermal power plants and thermal heating plants. The structure of electricity generation capacity in this scenario is hydropower plants 4831 MW, wind power plants 4500 MW, solar power plants 2000 MW, biogas power plants 240 MW, and biomass power plants 400 MW. This scenario envisages an increase in nuclear power plant capacity to 1000 MW to meet the required power consumption due to fossil fuel capacity shutdown and grid stability.

4. Results and discussion

4.1. Reference scenario validation and data source

The data collection and analysis and, the modeling of energy scenarios are based on the various adopted national reports, energy studies, annual reports, and national statistics. Fig. 4 presents hourly load data for the Serbian electricity sector, provided by the Public Enterprise Electric Power Industry of Serbia (PE - EPS) for 2010.

The reference energy model and its validation were performed for 2010, chosen as the base year. The reference data for the base year obtained from (PE, 2010; Energy Agency of the Republic of Serbia, 2018 and the Statistical office of the Republic of Serbia, 2011) and the reference scenario for Serbia in the EnergyPLAN model comply, as seen in Table 5.

Electricity production in the Republic of Serbia is primarily based on the combustion of domestic low-quality lignite in thermal power plants, the dominant fossil fuel in electricity generation, with a share of 98% (Statistical office of RS, 2011) compared to gas and fuel oil. In the EnergyPLAN model, when calculating carbon dioxide emissions for Serbian lignite, the value of the carbon emission coefficient 29.68 tC/TJ (Stefanović et al., 2012) was adopted, i.e., the emission coefficient for carbon dioxide of 109.5 kgCO_2/GJ.

4.2. Share of energy sources in electricity production

Fig. 5 shows the energy balance of the electricity sector of the Republic of Serbia for different scenarios. Of all renewable energy sources, the share of hydropower is the most significant in all scenarios, with a maximum possible production of 16.52 TWh in 2050, which is 47% of total electricity production in a scenario where electricity production has zero greenhouse gas emissions.

From the adopted strategic documents of RS in the energy field and the application of renewable energy sources in the period up to 2050, it was emphasized that great attention would be paid to generation from wind, which is included in the considered energy scenarios.

Generation from wind power in 2030 in the scenario '*with additional measures*' is 3.95 TWh while in 2050 it is 10.46 TWh. In all scenarios '*with measures*' and '*with additional measures*' for 2030 and 2050, the share of fossil fuel power plants decreases compared to the BAU scenarios in 2030 from 26.48 TWh (BAU scenario) to 14.62 TWh ('*with additional measures*' scenario), and from 25.6 TWh (BAU scenario) to 11.07 TWh in the '*with measures*' scenario for 2050.

The reasons for lower electricity consumption in the scenarios '*with measures*' and '*with additional measures*' for 2030 and 2050, compared to

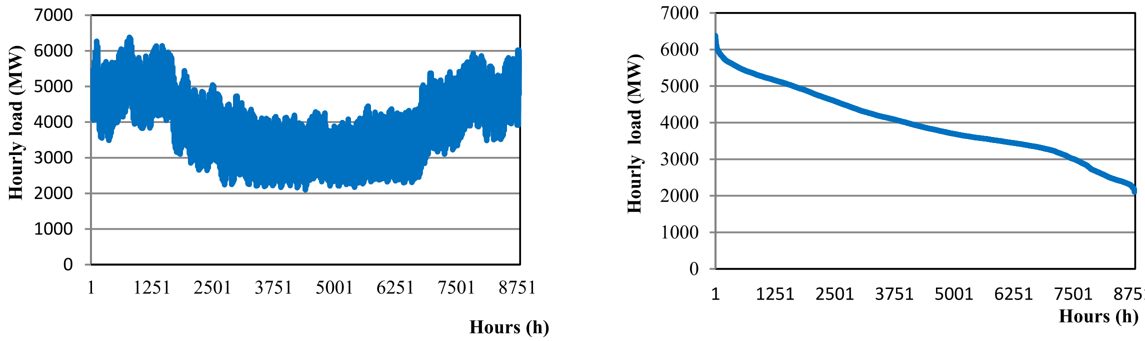

Fig. 4. Hourly load data for the Serbian power sector.

Table 5
Comparison of the reference data and reference scenario for the EnergyPLAN model for 2010.

	Power Plant (fuels)	Power Plant (production)	Hydropower (production)	CO_2 emission
	[TWh]	[TWh]	[TWh]	[Mt]
Reference data	73.97	23.162	12.42	28.894
EnergyPLAN	71.34	22.620	12.47	27.920

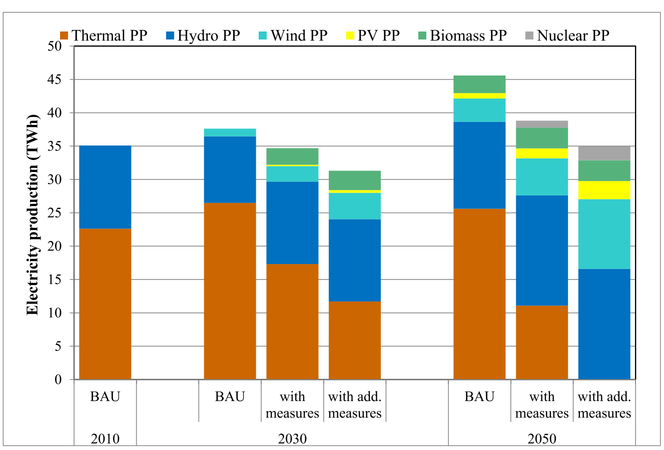

Fig. 5. Electricity production for different scenarios.

the BAU scenarios for the same years, are the modernization of the electricity distribution network, the increase in the energy efficiency of the electricity system or its consumption, the application of more energy-efficient technologies in the industry, the public sector, and households, and the monitoring and control of energy consumption in real-time (smart grids) (Ministry of Environmental Protection, 2017; Ministry of Mining and Energy, 2016). The population forecast RS for the year 2050 shows a decrease of 30% compared to 2010, which is one of the assumptions that should be considered to reduce the total electricity consumption in the considered scenarios (Penev, 2013).

In the reference year 2010, the share of renewable energy sources was 35.53%. This year is characterized by significant electricity production from hydropower plants of 12.47 TWh, the highest electricity production in the last ten years, based on historical data from the Energy Agency of the Republic of Serbia (Energy Agency of the Republic of Serbia, 2021). For this reason, electricity production from hydropower plants for the scenarios in 2030 and 2050 was validated based on data on electricity production from 2019.

The highest electricity production from RES in 2010 is one of the reasons why the share of renewable energy sources in electricity generation for the BAU scenario for 2030 is 5.95% lower than the share of RES in the BAU scenario for 2010. Another reason for the lower share of RES in the BAU scenario for 2030 is the construction and commissioning of the new unit of PP Kostolac B3 with 350 MW, which is expected in late 2023. For the BAU scenario 2050, the share of electricity generation from RES is 44%, which is 8.5% higher than the share of RES for the reference year 2010. The share of energy systems with zero CO_2 emissions for different scenarios is shown in Fig. 6. Electricity generation from energy systems that use renewable energy sources is shown in Fig. 7. It can be seen that electricity generation from hydropower plants dominates compared to the others.

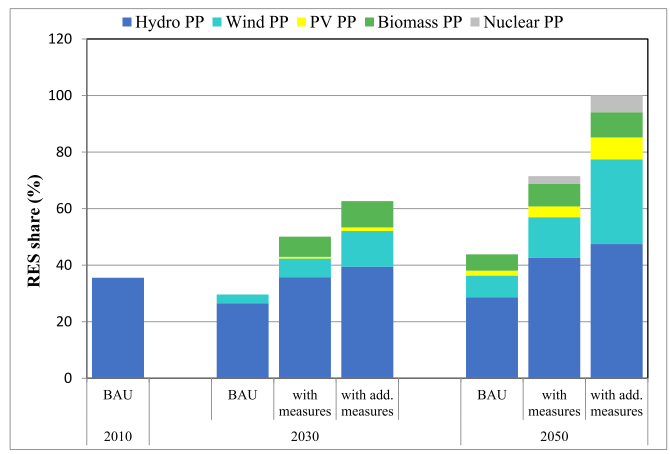

Fig. 6. RES share in the electricity production for different scenarios.

Due to the increased engagement of renewable electricity generation capacity, the share of electricity generation from RES is projected to be 52% and 65% in 2030 and 2050, respectively, in the scenarios '*with measures*' and '*with additional measures*,' while it is 71% in 2050 in the scenario '*with measures.*' In the scenario '*with additional measures*' for 2050, this share is 100%.

The increase in the share of RES in the scenarios '*with measures*' and '*with additional measures*' in 2030 compared to the reference year 2010 is 16.5% and 29.5%, respectively, i.e., 35.5% in the scenario '*with measures*' in 2050.

4.3. CEEP and import/export

Fig. 8 shows the import-export of electricity, while Fig. 9 shows the CEEP (Critical Excess Electricity Production) for the scenarios in 2050 '*with measures*' and '*with additional measures*,' in which the share of renewable energy sources is highest, at 71% and 100%, respectively. One of the key assumptions in analyzing all scenarios in this paper is that the infrastructure (capacity) of the electricity distribution grid can cover

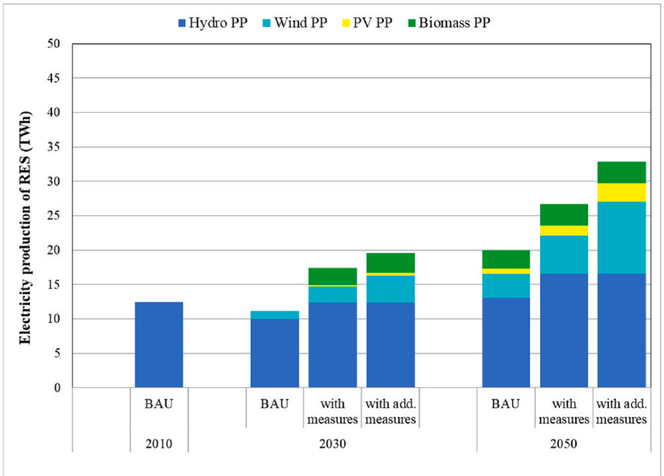

Fig. 7. Electricity production of RES.

the necessary imports and exports of electricity.

The summer months in the Republic of Serbia are characterized by lower wind intensity, which leads to an increase in the import of electricity when the scenarios saw an increase in the share of wind turbine capacity, as seen in Fig. 8(b). The CEEP value for the 2050 scenario '*with additional measures*,' which characterizes the use of the largest share of energy systems based on renewable energy sources, has acceptable values in all months except April, which is also characterized by significant electricity exports. CEEP and the export of electricity in April and November are different from other months because they are months without heating and cooling. This section shows the imports/exports and CEEP for the scenarios with a significant share of RES, while in all other scenarios, the values of these quantities are negligible and close to zero.

4.4. CO_2 emissions

Fig. 10 shows the CO_2 emissions of the Serbian electricity sector for the BAU scenario, in the reference year 2010, for the years 2030 and 2050, and for the different energy scenarios for 2030 and 2050. The CO_2 emissions for the BAU scenario for 2010 are 26.05 Mt, while for the BAU scenario for 2030, this is 10% higher at 28.98 Mt. By applying energy efficiency measures and increasing the use of RES, CO_2 emissions in 2050 for the BAU scenario amount to 23.61 Mt and are 10% lower compared to the BAU scenario for the 2010 reference year. By increasing the use of renewable energy sources and reducing the use of energy systems that use fossil fuels, the level of CO_2 emissions is significantly reduced in the scenarios '*with measures*' and '*with additional measures*' for 2030, to 17.79 Mt and 10.67 Mt respectively, and 9.45 Mt, for 2050 in the scenario '*with measures*.'

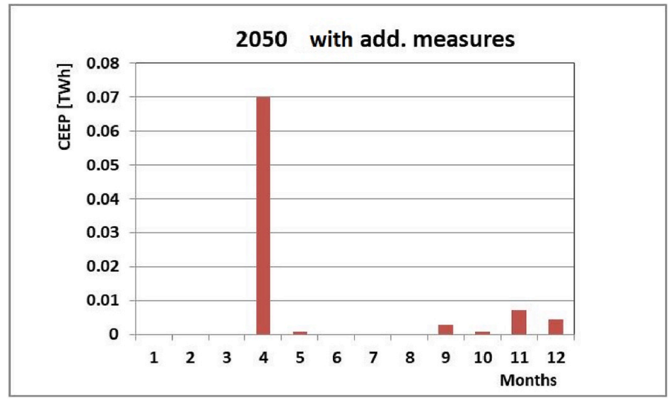

Fig. 9. CEEP for scenarios in 2050 *'with additional measures'*.

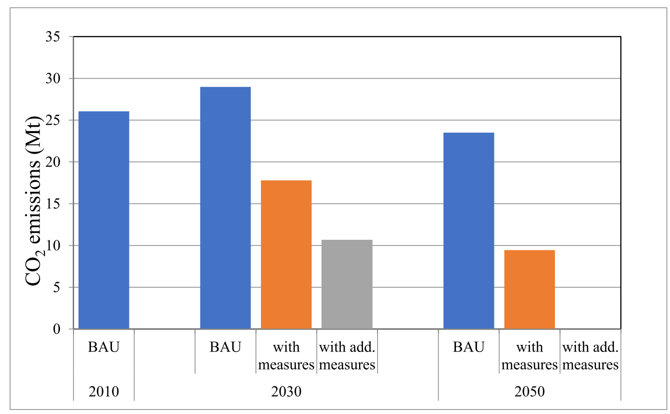

Fig. 10. CO_2 emissions for different scenarios.

In the scenario '*with measures*' for 2030, CO_2 emissions are 32% lower, or 59% lower in the scenario '*with additional measures*,' compared to the reference year 2010. In the scenario '*with measures*' for 2050, CO_2 emissions are 64% lower compared to the reference year 2010.

As described in Section 4.2, a significant reduction in CO_2 emissions was achieved in the scenarios for 2030 and 2050 compared to the reference year 2010 by reducing electricity consumption (with the help of various measures) and increasing the share of renewable energy sources in electricity generation.

5. Conclusions

The electricity sector of RS , which is particularly important for the entire economy and society, is one of the biggest polluters of the environment, as electricity production is mainly based on fossil fuels (mainly

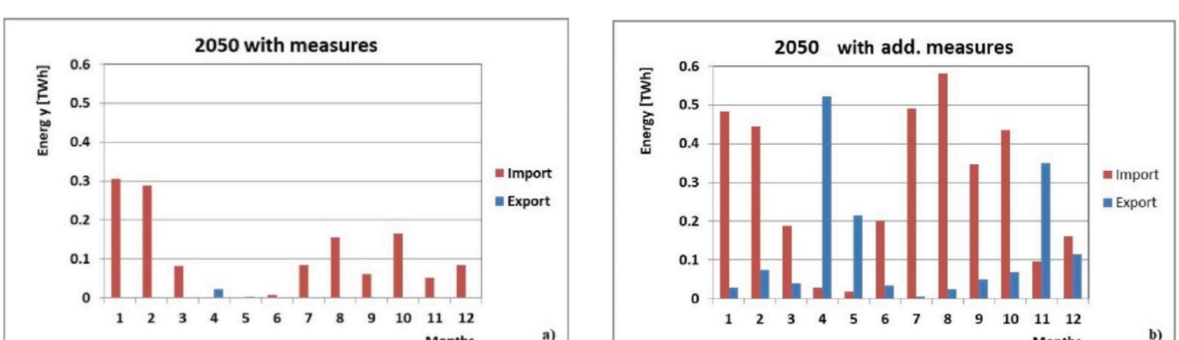

Fig. 8. Electricity imports and exports for the 2050 scenarios *'with measures'* a) and *'with additional measures'* b).

domestic lignite, gas, and oil). In order to assess the long-term reduction of CO_2 emissions in the electricity generation sector in Serbia by 2050, this paper analyzes different energy scenarios. In order to evaluate the extent of decarbonization potential, '*with measures*' and '*with additional measures*' scenarios were adopted. The BAU scenario for 2030 and 2050 assumes no significant changes in electricity generation technology. The data and assumptions used in the EnergyPLAN energy model are based on existing energy policy documents from RS.

Based on this research, the following conclusions can be drawn. First, in the projected energy scenarios through 2050, the share of electricity generation from renewable sources increases. Second, hydropower and wind with shares: '*with measures*' scenario for 2030 of 38% and 7%; '*with additional measures*' scenario for 2030 of 41% and 13%; '*with measures*' scenario for 2050 of 41% and 17%; and a '*with additional measurec*' scenario for 2050 of 45% and 37%. Third, in the '*with additional measures*' scenario, the share of electricity generation from photovoltaics increases from 1.3% in 2030 to 11% in 2050.

In order to achieve the use of 100% renewable energy in the country, the following pumped-storage hydropower plants are planned as energy storage: Bajina Bašta 300 MW, Bistrica 680 MW, and Đerdap 3 of 600 MW. This plan ensures a reliable and stable supply of electricity to the system. When thermal plants are withdrawn from service, the construction of a 1000 MW nuclear power plant is envisaged to support the electricity sector in 2050.

In this paper, the goal of achieving a clean energy transition by 2050 is demonstrated by the proposed scenarios focusing on electricity generation with a gradual reduction in CO_2 emissions with covered electricity consumption, as shown in Table 2. Based on the obtained results using the simulation tool for modeling analyzed energy systems EnergyPLAN, CO_2 emissions are relatively lower:

- by 35% in the scenario 'with measures' and 59% in the scenario 'with additional measures'

  for 2030 (compared to the reference year 2010) and;

- by 66% in the scenario 'with measures' for 2050 (compared to the reference year 2010).

The realization of these scenarios for 2030 and 2050 will largely depend on political decisions, the adoption of accompanying legislation, the application of energy efficiency measures, and various incentive measures for using renewable energy sources. The analysis only considered the electricity sector since the share of CO_2eq emissions from this sector of total GHG emissions in the energy sector at RS was 74% in 2014. Serbia is committed to reducing CO_2 emissions as well as other harmful gases that cause the greenhouse effect, so in the next ten years, ten units of thermal power plants will be shut down. The biggest challenge in the decarbonization strategy RS is expected in the electricity generation sector.

However, the goal achieved in this paper is that the energy policy packages represent a more realistic new decarbonization strategy aiming for net zero by 2050. The projected energy supply and demand trends over the coming decades are closely linked to demographic and economic trends. They are also strongly influenced by government energy and environmental policies. Cost analyses and simulations of electricity and heat consumption in other sectors will be investigated in further work, as well as energy security, which is the basis for promoting renewable energy sources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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