



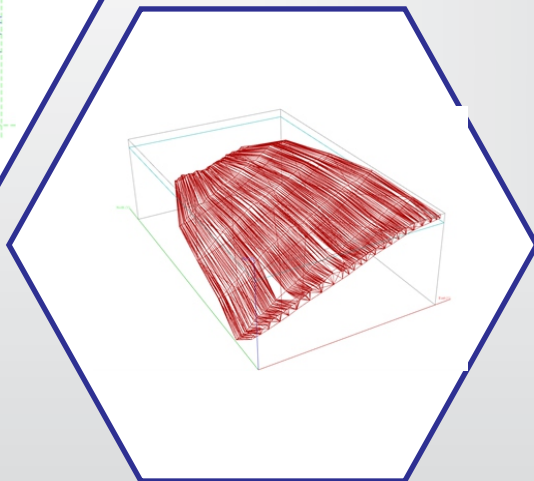
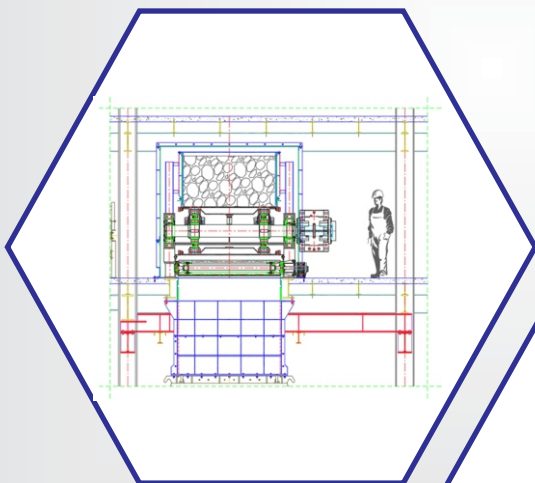
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GEOLOGICAL CHARACTERISTICS OF THE “STRMOSTEN” COAL DEPOSIT IN THE REMBAS-RESAVICA SUB-BITUMINOUS COAL MINE**

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Abstract

The Strmosten brown coal deposit, situated in the northern part of the Senje-Resavica Basin, has been the focus of long-term exploration to determine its reserves, quality, and geological framework. Investigations comprised field geological observations, drilling campaigns, underground workings, and laboratory analyses of collected samples. It was determined that the deposit includes multiple brown coal layers of variable quality developed within the Paleogene succession. Petrographic studies and huminite reflectance analysis reveal the presence of dull to semi-bright brown coals with an average huminite reflectance of 0.45%. The tectonic setting is complex, with pronounced fault structures affecting deposit continuity. Based on the processed data, assessments of on-balance and off-balance reserves, as well as potential mining conditions in the Rembas-Resavica Brown Coal Mine, were performed. The results provide a basis for further planning and economic evaluation of exploitation in the brown coal mine.

Keywords: „Strmosten“ deposit, brown coal, geological exploration

1 INTRODUCTION

The intermontane Senje-Resavica brown coal basin (also known as Resavica – Morava basin) is located 160 km south-east of Belgrade near the Resavica town (21.35-21.75° E, 44.15-43.95° N; Figure 1). It is a north-south elongated tectonic depression with a total length of 45 km, width of about 7 km, and cover area over 200 km². The basin is filled up by Lower Miocene fresh water bright brown coal-bearing sediments

[1], with very complex geological setting. Permian sandstone and Mesozoic rocks overthrusting Miocene sediments [2]. Coal exploration and underground exploitation in the Senj-Resavica basin have been ongoing for over 160 years, and today are carried out within the Rembas-Resavica coal mine company. Within the basin, several deposits (exploitation fields) were separated from north to south [2]: Strmosten, Jelovac,

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Leskovica, Đulska sinklinala, Ravna Reka, Pasuljanske livade and Mine Senje. Strmosten, Jelovac, Ravna Reka-IV blok and Mine Senje are currently being exploited.

The Strmosten and Jelovac deposits (mines) are located in the northern part of the basin, while Ravna Reka – Block IV situated in central part Mine Senje covers the southern part of the basin. All four mines are interconnected by underground headings (Strmosten, Jelovac, Bučar, Northern and Southern headings) which link them to the coal preparation (separation) plant located in Resavica. The Resava-Morava coal basin and surrounding areas have been studied over the past two centuries by both domestic and foreign researchers. The basin is a covered type with rare outcrops, so 19th–20th century studies were mainly mining-oriented, while late 20th and early 21st century research used drilling. Coal exploitation began in 1853 at the Senjski Mine. One of the first researchers was Hofman (1875), who produced the first geological map linking coal to Permian sandstones. Later, Žujović (1888) assigned productive series to the Tertiary, while Cvijić (1893) distinguished the “Ravanička” limestones as a separate unit. Other notable contributions came from Šulc (1896), Antula (1900), Ilić (1905), Radovanović (1907), Jakšić (1930, 1935), and Petković (1937), improving knowledge of the basin’s geology [3].

Studies of tectonic structures were significant, particularly Petković (1935) who described two main thrust phases of Permian sandstones over coal-bearing sediments, and Luković (1937), who added a third thrust. Pantić (1953, 1956) identified Miocene freshwater deposits under Tortonian marine formations. Maksimović (1956) conducted extensive field research and created a detailed geological map of the basin, forming a basis for later studies.

Further important contributions came from Andrejić (1988a, b), Aksentijević

(1988a, b), Grubić and Đoković (1982–1987), Grubić et al. (1989, 1992), and Đinović (1991). Montan-geological studies were performed from 1987 to 1992 (Cvetičanin et al.) and in 2002 (Blečić, 2002) to define geological conditions and reserves. Systematic exploration has been ongoing since 1947 (Andrejić 1988–1998; Aksentijević 1988; Glišić 2006).

Petrographic studies of Senjski Mine coal were conducted by Podgajni (1957), Ercegovac and Podgajni (1961), and Ercegovac (1998). Sedimentological research was carried out by Grubin (1996), with Obradović and Vasić (2007) providing a synthesized overview of previous investigations [3].

The Strmosten deposit situated in the northern part of the Senje–Resava Basin has a polygonal shape, with 2.25 km in length (NW–SE direction) and 0.65 km in width (NE–SW direction), and cover an area of 0.44 km² [2].

The Strmosten deposit represents a significant part of the Senje–Resava basin in terms of balance reserves of coal. This deposit encompasses an area characterized by complex lithological and tectonic settings. Detailed geological investigations—conducted through drilling, underground workings, and laboratory analyses—have enabled precise delineation of deposit boundaries, its stratigraphic position, structural framework, and coal quality [2].

The objective of this study is to present the results of the conducted geological exploration of the Strmosten deposit, with a special focus on its geological framework, lithological characteristics, tectonics, and the distribution of the coal deposits. Understanding the internal structure and genesis of the deposit is crucial for planning and executing efficient and safe exploitation, as well as for evaluating the scope of further exploration and mining activities [2].

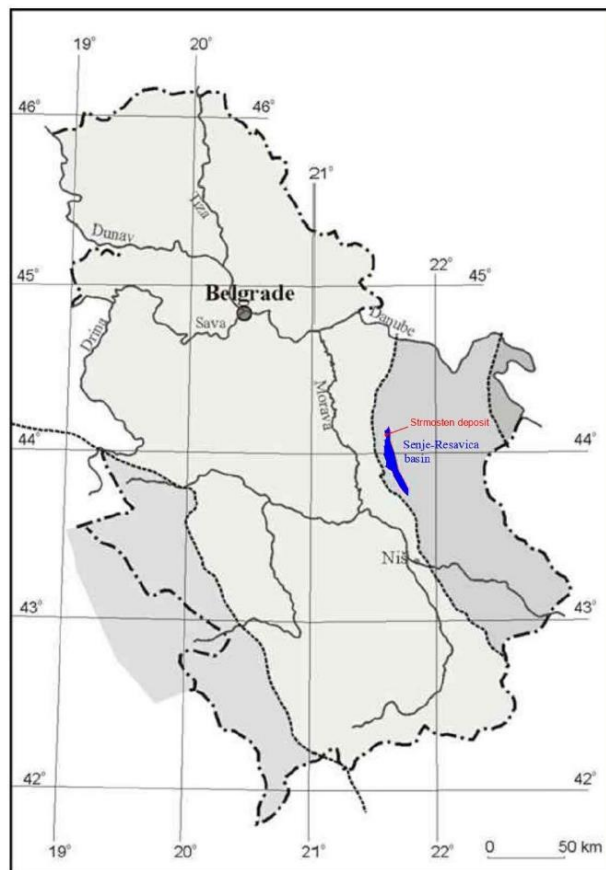


Figure 1 Geographical map showing the location of the Strmosten deposit ([4] modified 2026)

2. GEOLOGICAL SETTING

2.1 Lithological setting of the Senje-Resavica basin

The Senje-Resavica basin consist of Paleozoic schist, Permian sandstone, Mesozoic carbonate sediments, Cenozoic dacite-andesite, coal-bearing sediments and sediments ([2,5], Figure 2 and 3).

The Paleozoic period includes rocks such as Ordovician, Silurian, and Devonian phyllites, shales, sericite schist, chlorite schist, and sandstones. Additionally, Permian red sandstone overlays the coal-bearing layers found within the basin and its under

lying floor. Mesozoic sedimentary rocks include dolomitic limestone, Triassic variegated sandstone, and Jurassic to Cretaceous limestones that range from stratified to massive. Urgonian Cretaceous limestone lies beneath the Miocene series. The Paleogene unit consists of igneous rocks known as banatite. These are andesite and dacite associated with the Ridanj-Krepoljin-Senje fault zone. Tertiary rocks include conglomerates, sandstones, gravels, sands, breccias, coal,

coaly shale, shale, and marl of Lower Miocene age, corresponding to the Aquitanian-Burdigalian stages in the International Stratigraphic Classification. Additionally, Pliocene (Pl) sediments are present, comprising weakly cemented conglomerates, sandstones, sands, sandy limestone, freshwater limestone, coal, and tufa. The complex coal seam in the Senje-Resavica basin has three layers in the northeast, and two layers in the central, eastern, and western areas of the Strmosten deposit as well as in the Jelovac and Senje deposits. The Quaternary is represented by terrace sediments, debris, dilu-

vium, proluvium, alluvium. Most widespread are alluvial deposits, followed by terrace and proluvial sediments in the Resavica and Resava valleys [5].

2.2 Lithological setting of the Strmosten deposit

The paleorelief of the Strmosten deposit consist of Cretaceous limestones and dacite-andesite and andesite, while Permian red sandstone overtrasting early Miocene coal-bearing sediments. Pliocene and Quaternary sediments transgressively laying over the Permian sandstone [5].

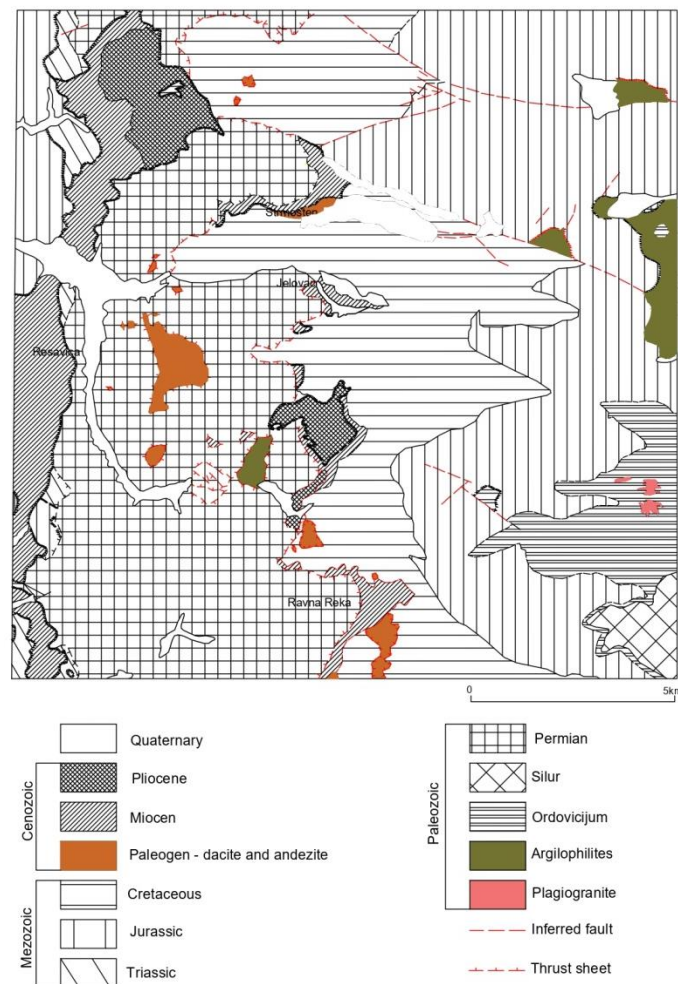


Figure 2 Overview geological map of the Resavica area, scale 1:100,000. ([6] digitized 2026)

Erathem	System	Series	Lithology	Thickness (m)	Description
CENOZOIC	Quaternary		all		Alluvium
	Neogene	Pliocene	PI	250	Conglomerate, sand, carbonate tuffa
		Miocen	M _{1,2}		Clay, sandstone, coal, rarely marlstone, conglomerate and breccia
	Paleogene	Apt	K ₁ ⁴	500	Sandstone and claystone
		Barremian	K ₂ ^{3,4}		Massive limestone of Urgonian facies
		Alb	K ₁ ¹⁻²		Bedded and laminate limestone
	Cretaceous	Tithonian	J ₃ ³	400	Tick-bedded and massive limestone, occasionally reefal with corals, Nerinea and sferactinia
		Oxfordian-Kimmeridgian	J ₃ ¹⁻²	300	Bedded limestone with lenses of jasper nodules
		Middle	J ₂	50	Dolomite
					Limestone, conlomerat and dolomite
MEZOZOIC	Permian		P	80	Red sandstone
	Devonian		D	150	Sandstone and claystones
	Silurian		S	400	Argillites and rare sandstone
					Sandstone and lithic rocks
	Ordovician		γδ	700	Argillophilites and sandstone
			v		Sandstone, quartzites and argillophilites
			O		
PALEOZOIC					

Figure 3 General stratigraphic column of the Senje-Resavica Basin ([6] digitized 2026)

Based on geological exploration, the Strmosten deposit comprises the following lithological units ([3,5]; Figure 4):

- Cretaceous limestones with Paleogene andesite intrusions (paleorelief)
- Basal series (Lower Miocene),
- Underlying series (Lower Miocene),
- Coal seam (Lower Miocene),
- Overlying series (Lower Miocene),
- Permian red sandstone formation and
- Pliocene and Quaternary sediments.

Cretaceous limestones with Paleogene andesite intrusions (paleorelief). Paleorelief of the deposit area, as well as of the basin, consist of Lower Cretaceous limestones with andesite intrusions. Cretaceous limestones occur in the northeastern and southern parts of the deposit area, while andesites have been identified in the southeastern sector. The highest determined thickness is 263.80 m, although it is assumed to be around 1,500 m.

Basal series. The oldest unit of the Miocene succession consists of coarse-clastic sediments (breccias and conglomerates). In terms of composition, these are heterolithic conglomerates composed of clasts of limestone, dacite, and red sandstones. Their thickness decreases from east to west where they pinch out, so in some locations the coal seam lies directly on the limestones.

Underlying series. The series consist of gray-green clayey sandstones with minor interbeds of re-deposited red sandstones in deeper parts, clayey sandstones, mudstones, conglomerates, and more rarely lapilli tuffs. Sediments of Underlying series lie above the basal series with a gradual transition with the maximum thickness of 204.7 m.

Coal seam. The Strmosten deposit hosts a one coal seam with several layers. In the northeastern part of the deposit, it is subdivided into three layers, while in the central, eastern, and western parts it typically splits into two layers. The investigations have established a gradual shift of footwall sand

stone into a coal seam with coal inclusions in the upper parts of floor sandstone [6].

The total thickness of the coal seam in the Strmosten deposit, ranges from 0.05 m to 25.30 m the average of 7.33 m. Coal thickness is approximately 5.87 m [7]. Interburden sediments in the layer are built of marl and coal clay, marl, clayey sandstone and sandstone. Throughout the deposit, the two parts are generally separated by gray clayey sandstones and clays, whose thickness varies from approximately 1 m in the east to about 7 m toward the west. In certain parts of the deposit, in addition to the typical development of the coal seam with marl in the roof, the occurrence of coal above the marl has also been recorded. Above the strongly tectonized marls, there is an intercalated coal seam up to 1.5 m thick, located between the red sandstone and the marl. Based on the distribution and relationships between the lithological units, it is concluded that this coal has a local extent and is probably of allochthonous origin, associated with overthrusting together with the red sandstones.

The coal-bearing series extends in a southeast–northwest direction with a dip to the southwest at an angle of 10° to 20°, while in the eastern parts of the deposit it shifts to a northeast–southwest orientation, dipping toward the northwest.

Overlying series. Overlying series consist of whitish-gray clayey tuffs, clays, and clayey gray-green sandstones. These sediments are partially or completely eroded. A primary characteristic of the remnants of these sediments is their limited thickness and pronounced fissility—resulting from tectonic movements—especially evident in the tuffs. The maximum thickness of the overlying sediments reaches 25.1 m [5].

Permian red sandstone formation. The Permian formation consists of fine- to coarse-grained quartz sandstones ranging in color from red to reddish. The cement matrix is carbonate to siliceous in composition and locally clayey. The thickness of this formation

varies from 176.9 m in the southern part of the to 523.2 m in the western part [5].

Pliocene and quaternary sediments. Pliocene sediments have been identified in the northeastern part of the Strmosten deposit and transgressively lie over the Permian red sandstones. Investigations have revealed the

presence of freshwater limestones, sandy limestones, weakly consolidated sandstones, clays, conglomerates, and coal. Quaternary deposits are represented by alluvial and colluvial formations. The thickness of the Pliocene and Quaternary sediments varies from 0.8 m to 143.0 m [5].

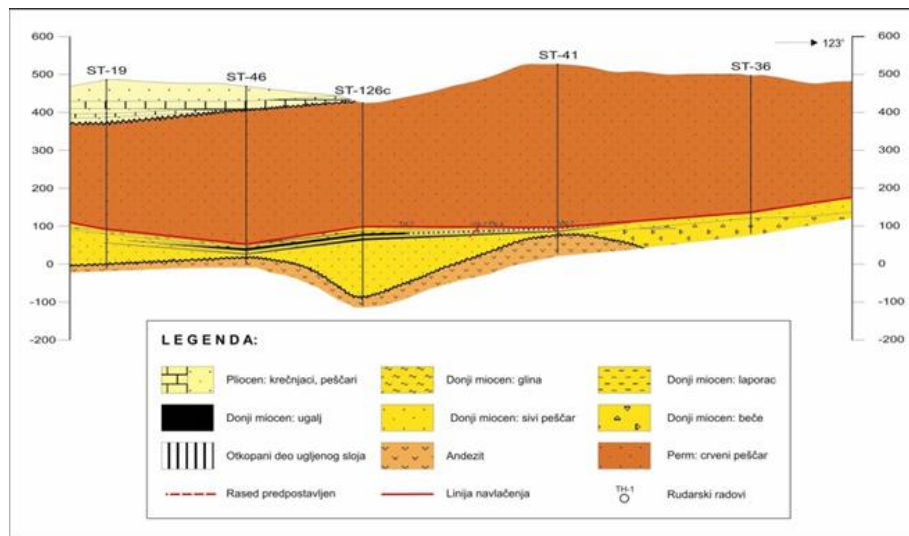


Figure 4 Geological crosssection of the Strmosten deposit ([7] modified 2006)

2.3 Tectonic setting of the Senje-Resavica basin

Tectonically, the Senja-Resavica basin is characterized by a very complex structure with a large number of small-throw faults alongside regional nappes, thrust sheets, and klippes (Figure 5).

The Senje-Resavica basin is a complex tectonic structure that occupies northern part of the western Rtanj and Kučaj nappe. Two large tectonic units are identified in the basin, viz.: (1) Kučaj-Beljanica anticline (autochthon) and (2) nappe of red sandstone and Mesozoic limestone (Ravanica mono

cline, allochthon). The autochthonous tectonic unit Kučaj-Beljanica includes all deposits of the Senje-Resavica coal basin. The allochthon consists of red Permian sandstone and Ravanica limestone thrust over Mesozoic limestones of Rtanj and Kučaj mountains and over Tertiary volcanic rocks along the Ridanj-Krepoljin fracture. It was due to the intricate tectonic pattern of the Senje-Resavica basin with decametric blocks that coal measures deformed and render difficult explorations and coal mining [5].

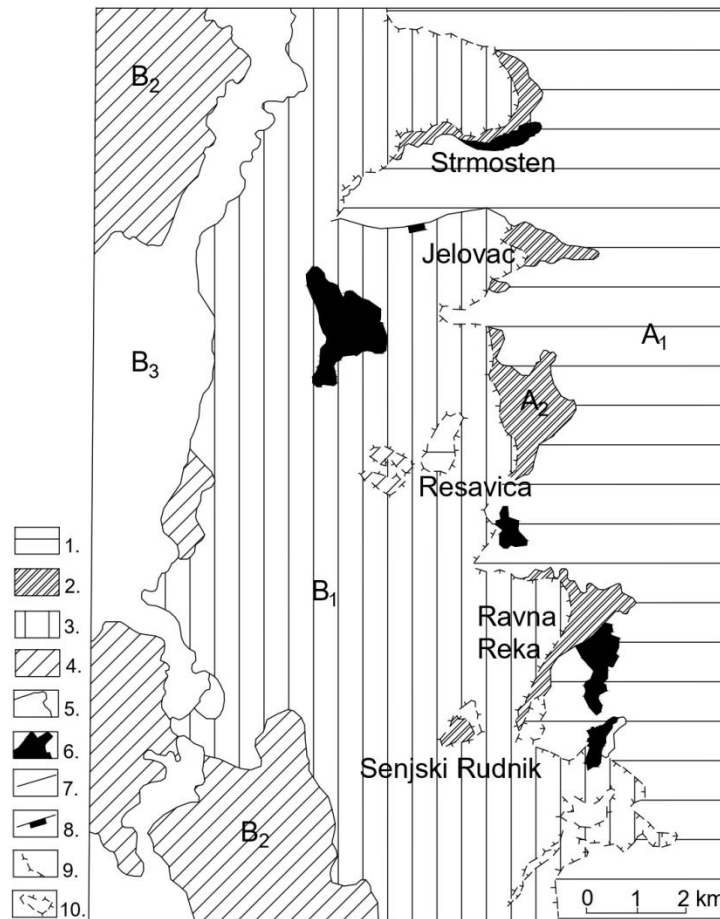


Figure 5 General tectonic map of the Senje-Resava Basin ([4], modified 2026)

1. A1 - First structural level of the autochthon; 2. A2 - Second structural level of the autochthon;
 3. B1 - First structural level of the allochthon; 4. B2 - Second structural level of the allochthon;
 5. B3 - Third structural level of the allochthon; 6. Dacite-andesites; 7. Geological boundary;
 8. Relatively downthrown block; 9. Thrust front; 10. Tectonic window.

2.4 Tectonic setting of the Strmosten deposit

The Strmosten deposit lies in the northern area of the western part of the Rtanj and Kučaj nappe. For the development of the tectonic structure of the Strmosten deposit, the “second klippe” may have been significant, when tectonic movements, reactivating faults (such as the Resava fault) in the al

ready mobile Ridanj-Krepoljin-Senje zone, led to relative subsidence of the autochthonous terrain, over which a red sandstone allochthon was thrust. the Strmosten deposit is located in the southwestern block of the relatively downthrown side of the Resava fault, where four structural levels can be distinguished [5]:

The first structural level comprises Cretaceous limestones and dacites, which form the paleorelief for the productive Miocene coal-bearing series. Photogeological analysis has determined that the limestones in the southern part of the deposit trend east–west or southeast–northwest with a dip toward the north or northeast [5].

The second structural level comprises the rocks of the lower Miocene coal-bearing series. This series lies erosively and discordantly over the first structural level. The coal seam within the Miocene succession trends southeast–northwest with a dip toward the southwest of 10° – 30° , while above elevation 290.0 m in the eastern part of the deposit it shifts to a northeast–southwest trend with a dip toward the northwest. This configuration gives the deposit an apparent undulating appearance due to numerous faults. Tectonic movements during thrusting of the red sandstones onto the Miocene coal-bearing series and the coal deposit severely fractured it into small blocks. The resulting gravity-type faults have a major influence on both the spatial extent of the deposit and the variability of coal thickness. Because the thrust surface of the red sandstones lies directly above the coal deposit in most of the area, even faults with small throws reduce deposit thickness in the footwall side of the faults. Movements that caused tearing of the Permian red sandstones (the overlying unit) together with the coal deposit produced faults of various sizes, with throws ranging from tens of meters down to less than one meter. Such faults occur in the southern part of the deposit, with fault surfaces dipping toward the southwest [5].

The third structural level comprises the Permian red sandstones, which have been tectonically thrust over the Miocene coal-bearing series. Several fault systems have been identified, of which the most pronounced have a strike of approximately 55° . During the development of underground mine workings, clear evidence of

movement—slickensides along the contact surface between the red sandstones and Miocene sediments with an approximate east–west orientation—has been observed [5].

The fourth structural level consists of Miocene and Pliocene freshwater sediments that lie erosively and tectonically discordant over the Permian red sandstones. These sediments are gently inclined toward the west [5].

3 EXPLORATION AND DELINEATION OF THE DEPOSIT

Numerous exploration activities have been carried out within the area of the Strmosten brown coal deposit, largely based on exploratory drilling, mining operations, and laboratory tests of coal quality. These works aimed to characterize the deposit conditions, determine the shape and structure of the deposit, establish the spatial position of coal layers along with their qualitative and technological characteristics, and also to ascertain the physical–mechanical properties of the rocks within the deposit, to a degree sufficient for successful exploitation. To achieve understanding of these characteristics in the Strmosten deposit area, several investigation methods were employed: geological investigation methods, surveying works, hydrogeological studies, geophysical surveys, and laboratory analyses [5].

In the exploration methodology for the Strmosten deposit, exploratory drilling plays a dominant role: boreholes were drilled from the surface, and with the initiation of underground mining works, underground exploration boreholes were also drilled [5].

Delineation of the deposit was performed based on the results of exploration activities—exploratory drilling and mining works. The deposit boundary (the zero contour) was drawn halfway between locations with positive exploration results (i.e., confirmed coal intersections) and those with

negative results (no coal). The primary criterion for delineating the coal layer, i.e., for defining the working contour in the Strmosten deposit, is a minimum recoverable deposit thickness of 1.0 m. The maximum permissible thickness of barren, clayey interlayers is up to 0.5 m (any interlayer exceeding 0.5 m is treated as waste and is not included in the coal deposit). Based on these criteria, the delineation of remaining reserves in this deposit was carried out. Consequently, the remaining portion of the Strmosten deposit is bounded partly by the contour of old workings and partly by the contour projected from results obtained through exploration drilling [5].

4 HYDROGEOLOGICAL CHARACTERISTICS OF THE DEPOSIT

Based on geological studies of the Strmosten deposit and its surroundings, according to the relative abundance of rock types (from most to least widespread) participating in the deposit's framework, three rock groups can be distinguished [5]:

- Permian sandstones,
- Paleorelief rocks (limestones and dacites),
- Miocene coal-bearing series.

These sediments, on the basis of their structural-textural characteristics, porosity, and hydrogeological properties, can be classified into two groups: rocks in which aquifers may develop, and conditionally non-water-bearing rocks.

4.1 Types of aquifers

According to porosity in the lithological members of the Strmosten deposit, three aquifer types may develop: fractured-type aquifers, karstic aquifers, and fissure aquifers [5].

- **Karstic aquifer potential in Cretaceous limestones.** Lower Cretaceous limestones that form the paleorelief

(and its margins to the northeast, southeast, and south—e.g., Veliki kamen, Belo Brdo) show karst features (dolines and other karst landforms) at surface, enabling full infiltration of precipitation. Deeper zones of these limestones contain abundant fractures and caverns filled with younger sediments (sands and sandy clays). Given this infill, observed water inflow does not typically exceed about 2.5 L/s (based on measurements from 1974 to 1991), although greater inflow is possible if fractures and caverns become flushed or newly connected.

- **Fractured aquifer potential in Permian red sandstones.** Although Permian red sandstones are generally hydrogeological isolators due to their primary lithology, their tectonic deformation (thrusting over the Miocene coal-bearing series) creates fracture systems enabling fissure-type aquifers. Moreover, the cement in these sandstones includes siliceous-iron and carbonate-iron matrices (in addition to less favorable clay-iron cement), which are relatively more favorable for fissure permeability. At surface, in the zone of weathering, these red sandstones exhibit intergranular porosity, allowing formation of small, compact aquifers that discharge as springs or seeps. In the red sandstones and at their contacts with Miocene sediments, water inflow into mine workings generally does not exceed about 0.5 L/s.
- **Fractured/low-permeability behavior in dacite-andesites and andesites.** Dacite-andesites and andesites crop out in the southeastern part of the deposit and, together with limestones, form the paleorelief above the Miocene coal-bearing series. These rocks are generally of low permeability, but due to the

presence of fracture networks they may develop fractured-type aquifers of limited yield.

4.2 Conditionally non–water-bearing rocks

This group includes all Miocene rocks, i.e., the entire coal-bearing series (sandstones, coal, clayey sandstones, clays, carbonaceous clays, mudstones, and tuffs). These rocks outcrop in the eastern and southeastern parts of the Strmosten deposit and occur in underground workings. Within the Miocene sediments, seepage and wetting from the coal deposit and tuffs may occur, mainly near contacts with red sandstones or along fault zones. Mining works in the productive series have confirmed localized wetting and minor inflows—i.e., low-yield aquifers within these rocks.

Hydrogeological investigations and existing mining operations have identified occurrences of water in parts of the deposit underlain or overlain by permeable rocks. Water may also accumulate in higher-level old workings, with possible inflow from those accumulations into active mine workings if connectivity exists.

These classifications and observations are essential for drainage planning, water-management design in underground workings, and risk assessment of inflows during exploration and exploitation of the Strmosten deposit [5].

5 GEOTECHNICAL CHARACTERISTICS OF THE DEPOSIT

Based on long time of investigation data at the Strmosten deposit, four engineering–

geological environments can be distinguished [5]:

- the Permian red sandstone complex,
- the Coal seam with preserved overburden sediments,
- the Underlying sandstone complex,
- the paleorelief.

The Permian red sandstone complex is composed of compact fine- to coarse-grained quartz sandstones, thrust over the productive Miocene succession and its substratum. According to the compressive strength classification [5], with values ranging from 15.80 to 78.68 MPa, these rocks fall into the category from very weak to strong. Lower compressive strength is observed only in tectonically damaged zones where rock mass disintegration has occurred.

The coal deposit with preserved overburden sediments beneath the red sandstone cover exhibits compressive strength between 24.55 and 38.24 MPa; accordingly, this environment belongs to the group of soft to moderately strong rocks.

The floor sandstones have compressive strength values from 9.70 to 72.65 MPa, placing them, per [5], in the range from very weak to moderately strong rocks.

The paleorelief of the basin consists of Lower Cretaceous limestones and andesite intrusions. Based on compressive strength, this environment belongs to the group of hard, well-cemented rocks. Investigations of the physical and mechanical properties of coal and the accompanying rocks of the “Strmosten” deposit were carried out on several occasions, with the aim of defining their basic geomechanical characteristics. The obtained results are presented in the table 1.

Table 1 Average values of physical–mechanical characteristics of coal and associated rocks of the Strmosten deposit [3,5]

Rock type	Unit weight (γ) [t/m ³]	Compressive strength (σ_c) [Mpa]	Tensile strength (σ_t) [Mpa]	Cohe- sion (c) [MPa]	Internal friction angle (φ) [°]
Coal	1,33	24,533	3,146	11,150	38°
Red sandstone	2,57	65,20	5,123	12,270	56°47'
Floor sandstone	2,31	13,420	1,50	2,880	50°36'
Clayey sandstone	2,42	9,70	1,150	2,880	50°
Carbonaceous clay	2,21	4,778	-	-	52°

6 COAL QUALITY

Petrographic investigations have shown that the coal of the Senje–Resava Basin belongs to the group of bright brown coals. According to data obtained by petrographic and organic-geochemical analysis [7], mean huminite reflectance values in the Strmosten deposit range from 0.43% to 0.46%, while the average value for the entire basin is $0.45 \pm 0.04\%$. These higher values may be attributed to greater depth, more pronounced tectonic disturbance, and proximity to the thrust-sheet root. The Lower Miocene, hard brown coals of the studied basins are typical humic coals with huminite concentrations between 37.9 and 85.5 vol.%, liptinite less

than 17 vol.% and inertinite less than 14 vol.%. Ulminite is the most abundant maceral with variable amounts of gelinite and densinite. Suberinite, sporinite and liptodetrinite are the most common macerals of the liptinite group, while inertodetrinite and funginite are the most abundant macerals of the inertinite group [8,9].

Statistical processing of data obtained from technical analyses determined the arithmetic mean values of quality parameters for the remaining coal reserves in the Strmosten deposit. The results are presented in Table 2, separately for the main and floor parts of the deposit [4,9].

Table 2 Arithmetic mean values of quality parameters for the remaining coal reserves of the Strmosten deposit

	W ^{ar} [%]	A [%]	St [%]	Sa [%]	So [%]	VM [%]	CM [%]	Coke yield [%]	C _{fix} [%]	GCV [kJ/kg]	NCV [kJ/kg]
Main part of the seam	16,96	14,89	1,21	0,62	0,62	36,04	68,15	47,00	32,11	19.092	18.039
Floor part of the seam	14,52	30,65	1,73	0,51	0,99	31,52	54,83	53,96	23,31	15.524	14.793

Legend: W^{ar} – Total moisture content, as received basis; A – Ash; St – Total sulfur; Sa – Sulfur in Ash; So – Combustible sulfur; VM – Volatile Matter; CM – Combustible Matter; C_{fix} – Fixed Carbon; GCV – Gross Calorific Value; NCV – Net Calorific Value.

In the coals of the Senje–Resava Basin, geochemical analyses were conducted on the contents of twelve potentially toxic trace elements (PTTEs): As, Be, Cd, Co, Cr, Cu,

Hg, Mn, Ni, Pb, Sb, and Se. The arsenic content (11.00–160.00 mg/kg, average 45.38 mg/kg; Table 3) is six times higher compared to the Clarke value for lignites

(7.4 ± 1.4 ppm) and slightly higher than the world average value for lignites. Compared to the geometric mean values for world lignites, the coal from the Senje–Resava Basin shows higher contents of cobalt, chromium,

mercury, manganese, nickel, lead, and antimony. A high manganese content was recorded in the Strmosten deposit. Beryllium, cadmium, copper, and selenium exhibit low concentrations [6,10].

Table 3 Contents of potentially toxic and radioactive trace elements (mg/kg) in brown coals Senje-Resava basin

Element	As	Be	Cd	Co	Cr	Cu	Hg	Mn	Ni	Pb	Sb	Se	U	Th
Min	11,00	0,11	0,02	0,82	2,54	2,27	0,16	20,90	2,74	0,85	0,13	0,20	0,19	0,29
Max	160,00	1,46	0,45	49,90	39,60	23,10	1,16	212,00	41,10	12,20	1,54	1,80	4,14	3,56
AMV	45,38	0,57	0,10	10,88	13,42	7,97	0,38	69,62	15,13	5,23	0,54	0,89	1,71	1,22
GMV	31,46	0,40	0,06	5,86	10,00	6,27	0,30	54,39	10,14	3,68	0,44	0,75	1,08	0,97

Legend: min –minimum value in coal; max-maximum value in coal; AMV- arithmetic mean value in coal
GMV- geometric mean value in coal

7. RESERVES OF COAL

The coal reserves of the Strmosten deposit have been determined based on existing geological investigations and processed in accordance with applicable

classifications and criteria for balance and nonbalance reserves. The total geological reserves and their distribution by classes are shown in Table 4 [3,5].

Table 4 Coal reserves of the Strmosten deposit according to the reserve book

	RESERVE*			RESOURCES*		
Class	balance			nonbalance		
Category	A	B	C ₁	A	B	C ₁
Main + floor deposit	327.480	928.970	1.690.930	113.110		
Total by classes	2.947.380			113.110		
Geological reserves	3.060.490					

Legend: * in accordance with the JORC Code

8. CONCLUSIONS

Based on the conducted geological, tectonic, hydrogeological, geotechnical, and coal quality investigations, it can be concluded that the Strmosten deposit represents a significant and complex part of the Senje–Resavica brown coal basin. The deposit is characterized by highly heterogeneous lithological composition and a very complex tectonic structure, which has a strong influence on both the geometry of coal seams and the conditions of exploitation.

The coal-bearing series of Lower Miocene age shows variable thickness and internal structure, with the coal seam divided into two or three layers depending on the location within the deposit. The presence of numerous faults and overthrust structures, especially the influence of Permian red sandstones, has led to fragmentation of the coal deposit into smaller blocks, which complicates exploration and mining activities.

Hydrogeological conditions indicate generally low water inflow, although local occurrences of aquifers within fractured limestones and sandstones may present challenges during mining operations. Geotechnical characteristics of the rocks range from very weak to strong, depending on lithology and tectonic disturbance, requiring careful planning and support design in underground workings.

Coal quality analysis shows that the Strmosten coal belongs to the group of bright brown coals with satisfactory calorific values, making it suitable for energy production. However, variations in ash content and other quality parameters between different parts of the seam must be taken into account in exploitation planning.

The total geological reserves confirm that the Strmosten deposit has significant economic potential. Nevertheless, due to complex geological conditions, further detailed exploration and modern mining approaches are necessary to ensure safe, efficient, and economically viable exploitation.

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EVOLUTION AND COMPARATIVE ANALYSIS OF ASTM AND EN ISO STANDARDS FOR TRIAXIAL SOIL TESTING**

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Abstract

This paper presents the historical development of triaxial soil testing standardization and conducts a detailed comparative analysis between European/international norms (SRPS EN ISO 17892-8 and 9) and American standards (ASTM D2850 and ASTM D4767). Through a chronological review, the paper traces the evolution of this geotechnical test, from the establishment of the theoretical foundations of effective stresses to the modern digitization of instrumentation and global harmonization of laboratory protocols.

Within the comparative analysis, the key stages of conducting the triaxial test are evaluated in detail, including the control of the shearing rate, the sample saturation phase using Skempton's B-parameter, the correction for membrane elastic resistance, and the methodology for defining the point of failure. Although both groups of standards strive for the same ultimate goal, namely the reliable construction of the Mohr-Coulomb failure envelope and the determination of soil strength parameters, significant methodological differences are observed regarding sample geometry, flexibility during saturation, and the rigidity of the procedures themselves.

It is concluded that the ISO methodology, due to the application of analytical mathematical formulas and clearly defined constants, proves to be significantly more practical for the development of algorithms and software for the automatic processing of raw laboratory data. This ensures the efficient generation of complete stress-strain curves, which are essential as reliable input parameters for advanced constitutive models in modern numerical modeling software packages, such as the Slide, Phase2, and Plaxis tools.

Keywords: triaxial soil testing, SRPS EN ISO 17892, ASTM standards, shear strength, pore pressure, numerical modeling

1 INTRODUCTION

The development of standards for triaxial soil testing represents the evolution of the test, from simple strength determination to complex modeling of the interaction between solid particles, water, and air in the

pores. Today, these standards are not merely working instructions, but scientific protocols ensuring that data obtained in a laboratory in Bor or any geotechnical laboratory in Serbia are comparable to those from any part of the world.

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2 KEY PHASES AND ASPECTS OF THE DEVELOPMENT OF TRIAXIAL SOIL TESTING STANDARDS

2.1 Early Period and scientific foundations (1930s – 1950s)

Before the emergence of formal standards, development was tied to the pioneers of soil mechanics. Karl Terzaghi and Arthur Casagrande [1, 2] established the theoretical foundations of effective stresses, which was a prerequisite for the triaxial test.

- The first apparatuses were developed to overcome the limitations of direct shear (where the failure plane is predefined).
- The focus and goal were to understand the change in soil volume during shearing and the role of pore pressure, which later became the foundation of standards for CU (consolidated-undrained) tests.

2.2 Standardization through national institutes (1960s – 1980s)

During this period, the "bureaucratization" of science occurred to ensure the safety of major infrastructure projects (e.g., dams, mines, high-rise buildings).

- The American Society for Testing and Materials (ASTM) defined the D series of standards early on. The focus was on the practicality and robustness of tests for the needs of the US military and the Army Corps of Engineers [3, 4, 5].

- The British, through BS 1377, developed extremely detailed procedures that were the "gold standard" in Europe and the former Yugoslavia for decades [6].
- Our region followed the development through JUS standards (e.g., the U.B1 series), which heavily relied on European and Russian research of that time [7, 8].

2.3 Global harmonization and the ISO revolution (1990s to present)

With the globalization of the construction market, the need arose to bridge the differences between national standards.

- The ISO 17892 series (whose parts 8 and 9 we use) was created with the aim of replacing a multitude of different European national standards (DIN, BS, AFNOR) [9, 10].
- Modern standards, unlike older ones, take into account advanced instrumentation (Figure 1) - electronic pressure transducers, LVDT sensors for displacements, and automated systems for pressure control.

The development of standards introduced strict requirements for sample saturation, establishing Skempton's B-parameter as a mandatory verification criterion before the initiation of shearing.

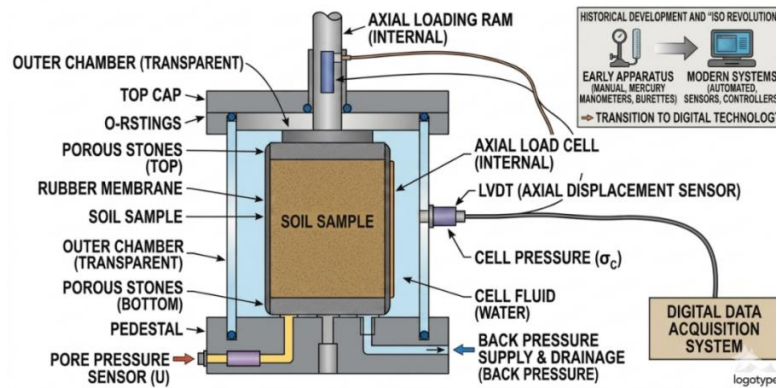


Figure 1 Schematic of a modern triaxial cell with a digital measuring system

2.4 The latest revision (ISO 17892:2018)

The SRPS EN ISO 17892 standard, parts 8 and 9 from 2018, brought several important changes compared to earlier versions:

- More strictly defined strain rates to ensure that pore pressure is evenly distributed (especially important for fine-grained materials from tailings ponds).
- Modern standards provide more detailed mathematical models for membrane resistance, as it has been shown

that in soft soils, rubber elasticity can significantly affect apparent strength.

- The new standards are written in a way that makes them easier to implement in data acquisition and processing software, reducing the room for human error during readings.

The presentation of the origin and evolution of the SRPS EN ISO 17892 standard parts 8 and 9 is shown in the following figure.

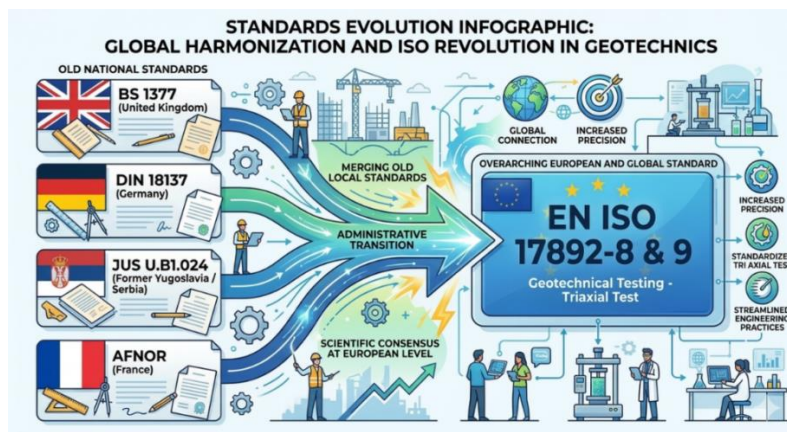


Figure 2 Infographic of the origin and global harmonization of the EN ISO 17892-8 and 9 standards

3 BASIC STRUCTURAL DIFFERENCE OF THE STANDARDS

Precise definition of geomechanical parameters is crucial for stability analysis and the development of advanced stress-strain state indicators. The choice between European (ISO) and American (ASTM) standards for triaxial testing directly dictates the reliability of input parameters for numerical models in software such as Slide, Phase2 [11], or Plaxis, which is especially important when modeling the specific beha-

vior of materials beneath planned infrastructure facilities.

Although both sets of standards strive for the same goal—reliably establishing the Mohr-Coulomb failure envelope ($c' \text{ i } \phi'$) and undrained strength parameters (c_u), there are subtle differences in methodology, scope, and result acceptance criteria. ISO standards pragmatically group the tests, whereas ASTM separates them into completely independent methods.

Table 1 Basic differences between ISO and ASTM standards

Characteristic	SRPS EN ISO 17892	ASTM Standards
Document scope	Consolidates all consolidated tests (CIU, CAU, CID, CAD) into a single document (Part 9). The unconsolidated undrained (UU) test is independent (Part 8).	Separates each type of test: D2850 for UU, D4767 for CU, and D7181 for CD tests.
Sample dimensions	Requires a diameter $\varnothing \geq 34$ mm and a height-to-diameter ratio (H/D) between 1.8 and 2.5.	Requires a diameter $\varnothing \geq 33$ mm (most commonly 38 mm or more is used), with a narrower H/D ratio that is strictly from 2.0 to 2.5.

4 COMPARATIVE ANALYSIS BY TEST PHASES

4.1 Shearing rate

Strain rate control is crucial to avoid generating false pore pressures that can artificially raise or lower the calculated slope stability.

UU tests: SRPS EN ISO 17892-8 prescribes an axial strain rate between 0.3% and 2% of the sample height per minute. For brittle materials, a lower value is explicitly advised. ASTM D2850 is more rigid: it prescribes a fixed 1%/min for plastic materials, while requiring a rate of 0.3%/min for brittle materials.

CU tests: ISO 17892-9 uses formulas to define the maximum rate based on the

consolidation time (t_{50} or t_{100}) applying empirical factors (F) from a table depending on drainage conditions. ASTM D4767 predominantly relies on the t_{50} time to calculate the time to failure, with the specific goal of ensuring pore pressure equalization of at least 95% within the sample at failure.

4.2 Saturation and Skempton's B-value

Both norms require high saturation prior to shearing so that the test faithfully simulates material behavior below the ground-water table. [12]

ISO 17892-9: Strictly defines that the saturation phase is considered complete only when the B-value reaches a minimum of 0.95. If this is not achieved, additional steps of increasing cell and back pressure are required.

ASTM D4767: Also requires $B \geq 0.95$, but is more flexible with overconsolidated or very stiff cohesive materials (where the volumetric compressibility of the skeleton is small), allowing saturation with B-values ≥ 0.90 .

4.3 Correction for membrane elasticity

Corrections are necessary because the rubber membrane provides a fictitious resistance that artificially increases stresses.

ISO Standards: Offer a fast and standardized mathematical approximation. The formula for deviator stress correction relies on an assumed or measured membrane modulus of elasticity (E_m). If a standard latex membrane is used, ISO allows adopting a constant of 1400 kPa.

ASTM Standards: Use a slightly different correction approach, which often relies on empirical curves developed earlier in practice, accounting for membrane extension in a more subtle manner, which complicates rapid automated processing without calibration tables.

4.4 Failure criteria

The interpretation of the point of failure changes the input data for stability index indicators.

ISO approach: Defines failure as the peak deviator stress, peak effective stress ratio, or a specific deformation criterion, such as 10% or 15% vertical strain, leaving room for engineer judgment.

ASTM approach: Most commonly sets an absolute limit for vertical strain at 15%

as the point of failure, unless the material exhibits a distinct peak in deviator stress or principal stress ratio prior to that limit.

5 CONCLUSION

The development of standards directly follows the development of numerical modeling. While early standards served merely to provide a "number" for c and ϕ , modern ISO standards enable the acquisition of complete stress-strain curves. This is crucial for advanced constitutive models during modeling, which are essential for simulating the complex behavior of soil, where static and dynamic stability depend on stress history and the degree of consolidation.

When developing an algorithm for the automatic processing of "raw" laboratory data, the ISO methodology often proves more practical due to clear formulas with defined constants, which significantly facilitates data normalization and the iterative formation of Mohr-Coulomb circles.

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ENHANCING THE TRIBOLOGICAL PROPERTIES AND EXTENDING THE SERVICE LIFE OF CUTTING TOOLS AND INDUSTRIAL COMPONENTS USING HYBRID PVD AND PACVD (DLC) PROTECTIVE COATINGS^{***}

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Abstract

Hybrid physical vapor deposition (PVD) and plasma-assisted chemical vapor deposition (PACVD) technologies for depositing diamond-like carbon (DLC) coatings represent a modern, environmentally friendly and engineering-based approach to the surface protection of cutting tools and tribologically loaded industrial components. Unlike conventional thermal CVD processes, which require high temperatures (800–1000°C) and cause structural changes as well as tempering of previously hardened tool steels, hybrid PVD+PACVD systems operate in a low-temperature range (180–550°C; DLC deposition at ≤250–350°C). This regime fully preserves the microstructure, hardness and dimensional stability of the substrate.

This paper analyses eight different types of coatings (TiN, AlTiN, CrN, TiCN, CrAlSiN, DLC, Al-TiN+DLC and CrN+DLC) using TOPSIS multi-criteria analysis with five key engineering criteria: hardness, thermal stability, corrosion resistance, friction coefficient and substrate compatibility. The results show that hybrid multilayer architectures AlTiN+DLC and CrN+DLC achieve the highest closeness coefficients (0.91 and 0.88, respectively), indicating a pronounced non-linear synergistic effect that cannot be achieved by applying individual layers.

The paper defines a compatibility matrix, a decision tree and an algorithm for selecting the optimal coating architecture based on the dominant wear mechanisms in service. An analysis of contemporary industrial and literature data confirms that the application of hybrid PVD/PACVD systems enables a significant extension of the service life of cutting tools, sliding elements and machine components, while reducing friction, wear and energy losses. The technology is positioned within the concept of green tribology due to the complete absence of wastewater and harmful chemical effluents.

Keywords: PVD coatings, DLC, PACVD, hybrid coatings, TOPSIS, tribology, wear, green tribology

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1 INTRODUCTION

1.1 Research Significance

Wear of cutting tools and industrial components represents one of the key causes of reduced productivity, increased maintenance costs and energy losses in modern industry. Conventional materials, despite their high mechanical properties, are exposed to abrasive, adhesive, oxidative and fatigue wear during service. Therefore, increasing attention is being paid to surface engineering and the application of protective coatings, which enable a simultaneous increase in wear resistance, friction reduction and preservation of the fundamental properties of the substrate.

The aim of this paper is to evaluate the tribological and service characteristics of PVD, PACVD (DLC) and hybrid PVD/DLC coatings using TOPSIS multi-criteria analysis, with the goal of defining

optimal coating architectures for different industrial operating conditions. The scientific contribution of this paper lies in the quantitative ranking of the analysed systems, the identification of the synergistic effect of hybrid coatings and the consideration of their importance within the framework of green tribology and sustainable surface engineering.

2 MATERIALS AND METHODS

2.1 Analysed Types of Coatings

The study analysed eight types of protective layers. The input data and physico-mechanical characteristics were taken from the technical documentation of equipment manufacturers and relevant contemporary literature [1,2,3,4,5,6,15].

Table 1 Comparative specifications of the analysed PVD, PACVD (DLC) and hybrid coatings [1–7]

Coating type	Technology	Thickness (μm)	Hardness (GPa)	Friction coefficient (μ)	Max. working temperature (°C)	Oxidation resistance
TiN	PVD	2–5	20–25	0.45–0.60	500–600	Good
AlTiN	PVD	2–5	25–32	0.30–0.45	800–900	Very good
CrN	PVD	2–6	15–20	0.40–0.55	600–700	Very good (corrosion)
TiCN	PVD	2–4	28–35	0.30–0.45	400–500	Moderate
CrAlSiN	PVD	2–5	28–35	0.25–0.40	900–1000	Outstanding
DLC (a-C:H)	PACVD	1–3	15–40	0.05–0.15	250–350	Low to moderate
AlTiN+DLC	PVD+PACVD	3–6	System-dependent	0.05–0.15	up to approx. 800	Outstanding
CrN+DLC	PVD+PACVD	3–6	System-dependent	0.05–0.15	up to approx. 700	Excellent (corrosion)

2.2 Analysed Substrates and Industrial Applications

To ensure maximum adhesion, mechanical stability and coating functionality, four key groups of substrate materials were identified.

Table 2 Overview of substrates, temperature limitations and recommended coatings [3,4]

Substrate	Typical components	Max. deposition temperature	Recommended coatings
Tool steels (HSS)	Drills, milling cutters, knives and machining tools	Approx. 550°C	TiN, AlTiN, CrN, DLC
Cemented carbides (WC-Co)	Indexable inserts and tribologically loaded components	Above 800°C	AlTiN, TiCN, DLC, AlTiN+DLC
Alloyed structural steels	Gears, shafts, valves and sliding elements	Approx. 550°C	CrN, DLC, CrN+DLC
Hot-work tool steels	Moulds and tools for hot forming	Approx. 600°C	CrN, CrAlSiN, CrN+DLC

2.3 TOPSIS Multi-Criteria Analysis

For ranking the analysed coatings, the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) was applied, one of the most frequently used multi-criteria decision-making methods. The method is based on the assumption that the optimal alternative has the smallest distance from the ideal solution and the largest distance from the anti-ideal solution [8].

The analysis included eight alternatives (A1 to A8), representing different types of PVD, PACVD and hybrid coatings. The evaluation was carried out based on five

criteria of importance for tribological performance and industrial application:

- C1 - Hardness ($w_1 = 0.30$)
- C2 - Thermal stability ($w_2 = 0.25$)
- C3 - Corrosion resistance ($w_3 = 0.15$)
- C4 - Friction coefficient ($w_4 = 0.20$)
- C5 - Substrate compatibility ($w_5 = 0.10$)

The weighting coefficients were determined based on the relative importance of individual properties for the service life and functionality of protective coatings under industrial conditions.

Table 3 Performance matrix for TOPSIS analysis

Coating	C1	C2	C3	C4	C5
TiN	6	5	4	3	8
AlTiN	8	9	6	5	7
CrN	5	6	9	6	8
TiCN	8	6	5	5	7
CrAlSiN	9	9	7	6	6
DLC	6	3	6	9	8
AlTiN+DLC	9	9	7	9	7
CrN+DLC	7	7	9	9	8

The TOPSIS procedure was carried out through five consecutive steps:

1. **Normalisation of the decision matrix** to eliminate the influence of different numerical ranges of criteria, formula (1):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (1)$$

2. **Formation of the weighted normalised matrix** by multiplying the normalised values by the corresponding weighting factors, formula (2):

$$v_{ij} = w_j r_{ij} \quad (2)$$

3. **Determination of the ideal (A+) and anti-ideal (A-) solutions**, where the ideal solution contains the best values of all criteria, and the anti-ideal solution contains the most unfavourable values.

4. **Calculation of the Euclidean distance** of each alternative from the ideal and anti-ideal solutions, formulas (3) and (4):

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (3)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (4)$$

5. **Calculation of the closeness coefficient to the ideal solution**, formula (5):

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (5)$$

The value of the closeness coefficient (C_i) belongs to the interval from 0 to 1. Higher values indicate greater similarity to the ideal solution and, therefore, better overall performance of the analysed coating. Based on the obtained values, a final ranking of all analysed systems was made according to their expected tribological and service efficiency.

3 THEORETICAL FOUNDATIONS – PROTECTION MECHANISMS

3.1 Fundamental Principles of Coating Tribology

According to Holmberg and Matthews [1], the tribological behaviour of hard thin

films is determined by the ratio of hardness to elastic modulus (H/E and H^3/E^2), the critical load in the scratch test (L_c) and the surface topography (pp. 45–52). The H/E parameter defines the resistance of the coating to elastic deformation, while H^3/E^2 represents an indicator of resistance to plastic deformation and the occurrence of cracks.

3.2. Structure and Low-Friction Mechanisms of DLC Coatings

As extensively discussed by Donnet and Erdemir [2], DLC coatings are metastable amorphous carbon materials with a combination of sp^2 and sp^3 hybridised bonds (Chapter 2, pp. 25–40). The proportion of the sp^3 phase directly affects hardness, while the hydrogen content in a-C:H systems controls the friction coefficient [9]. The ultra-low friction coefficient of DLC layers ($\mu = 0.05$ – 0.15) results from:

1. **Tribo-induced graphitisation** – under the action of pressure and shearing in the contact zone, a local phase transformation of the surface layer into an sp^2 graphitic film occurs, which acts as a solid lubricant.
2. **Passivation of dangling bonds** – hydrogen atoms on the surface saturate the remaining free carbon bonds, thereby reducing surface energy and preventing the formation of adhesive bridges.

The thermal stability of monolithic DLC layers is limited to approximately 350°C , which is why DLC is used in modern systems as a final functional layer over thermally stable nitride bases [9,10].

3.3 Evolution of Hybrid PVD/PACVD Systems

According to Vetter [3], modern hybrid reactors integrate cathodic arc evaporation, magnetron sputtering and PACVD processes within a single vacuum cycle (pp. 215–

218). Such systems enable the synthesis of multilayer and gradient nanostructures with superior adhesion, controlled roughness and optimised tribological functionality [11,15].

3.4 Impact on Tool and Component Performance

According to Bobzin and colleagues [4], during high-speed machining of materials, AlTiN coatings extend the service life of tools due to the formation of a protective Al₂O₃ film at high temperatures (pp. 3–5). In contrast, DLC layers show superior performance under conditions of pronounced adhesive wear, particularly when machining aluminium and copper alloys [2,5,13].

4 MATERIAL COMPATIBILITY AND ENVIRONMENTAL ASPECTS OF THE PROCESS

4.1. Environmental Profile of the Technology (Green Tribology Concept)

According to Freschi and colleagues [11] and Ihara and colleagues [12], hybrid vacuum processes represent clean technologies that successfully replace conventional galvanic and high-temperature processes (pp. 3–5 in [11] and pp. 2–4 in [12]).

The environmental advantages include:

- Complete absence of wastewater – the entire material transformation takes place in a dry regime
- Absence of hazardous liquid chemicals – only inert gases (Ar, N₂, CH₄, C₂H₂) are used

- Minimal gas emissions – vacuum systems operate as closed loops
- Low energy consumption compared to high-temperature CVD processes
- Closed vacuum system without the release of harmful effluents

4.2 Preservation of Microstructure and Dimensional Stability of the Substrate

In conventional CVD processes, high temperatures (800–1000°C) cause tempering of the martensitic structure, a dramatic drop in core hardness and deformation of the tool, which often requires subsequent re-hardening.

In contrast, PVD and PACVD systems operate in a low-temperature range [3]:

- PVD nitride layers: 180–550°C
- PACVD (DLC) layers: ≤250–350°C

In this way, the hardness, toughness and dimensional stability of the substrate are fully preserved, with dimensional accuracy within ±0.02 µm [4]. Similar effects on surface stability under thermal loads were identified by Wu and colleagues [14] in ultra-precision diamond machining.

5 RESULTS

5.1 Quantitative Results of TOPSIS Ranking

By applying the mathematical algorithm of the TOPSIS method [8], the closeness coefficients (Ci) relative to the ideal configuration were calculated.

Table 4 Final ranking of coatings according to TOPSIS analysis

Rank	Coating type	Closeness coefficient (Ci)
1	AlTiN + DLC	0.91
2	CrN + DLC	0.88
3	CrAlSiN	0.82
4	AlTiN	0.76
5	TiCN	0.69
6	CrN	0.66
7	DLC	0.62
8	TiN	0.58

5.2 Interpretation of Results and Synergistic Effect

The results show the dominant performance of hybrid multilayer systems AlTiN+DLC and CrN+DLC [4,6,7]. The combination of a hard nitride base and a DLC top layer enables a simultaneous increase in load-bearing capacity, wear resistance and friction reduction.

In the AlTiN+DLC system, the hard nitride sublayer (AlTiN, 25–32 GPa) provides mechanical stability and resistance to plastic deformation, while the DLC top layer ($\mu = 0.05\text{--}0.15$) reduces heat generation and

tangential stresses in the contact zone [2,4]. The closeness coefficient for AlTiN+DLC ($C_i = 0.91$) is significantly higher than the values for the individual layers AlTiN (0.76) and DLC (0.62), which confirms a **nonlinear synergistic effect**.

5.3 Quantitative Effects of Extending Component Service Life

Based on pilot projects and the literature [2,4,5,13]:

Table 5 Typical effects of applying PVD, PACVD and hybrid coatings

Component type	Coating	Service life extension	Mechanism
Cutting tools for steel machining	AlTiN	+50% to +150%	Formation of Al_2O_3 oxide film [4] p. 6
Tools for machining Al alloys	DLC	2 to 4 times	Elimination of adhesive galling [2]
Sliding tribological elements	CrN+DLC	2 to 3 times	Corrosion protection + low friction [6,7]
High-temperature tools	CrAlSiN	+80% to +200%	Oxidation stability up to 1000°C [6]
Mining picks (reconditioning)	AlTiN	+60% to +80%	Combined treatment [5] pp. 87–90

6 DISCUSSION

6.1 Decision Tree for Selecting the Optimal Coating Architecture

Based on the analysis of dominant wear mechanisms, the following engineering decision tree was defined [1–4,6,7]:

Start: Identification of the dominant wear mechanism

1. **High temperatures (above 600°C)**
 - Extreme (above 800°C) → CrAlSiN (or with DLC top layer)
 - Moderate ($600\text{--}800^\circ\text{C}$) → AlTiN
2. **Abrasive wear**
 - High pressure, dry cutting → TiCN or AlTiN
 - Standard conditions → AlTiN

3. Adhesive wear / Built-Up Edge (BUE)

- Aluminium, copper, brass → DLC top layer (mandatory)
- Steel, cast iron → AlTiN + DLC

4. Corrosive environment

- Corrosion + high friction → CrN + DLC
- Pure chemical exposure → CrN

5. Impact and interrupted loading

- Severe impacts → TiCN or TiN
- Moderate impacts + low friction → AlTiN + DLC

The Figure 1 shows a decision tree for selecting a coating depending on wear mechanisms during use.

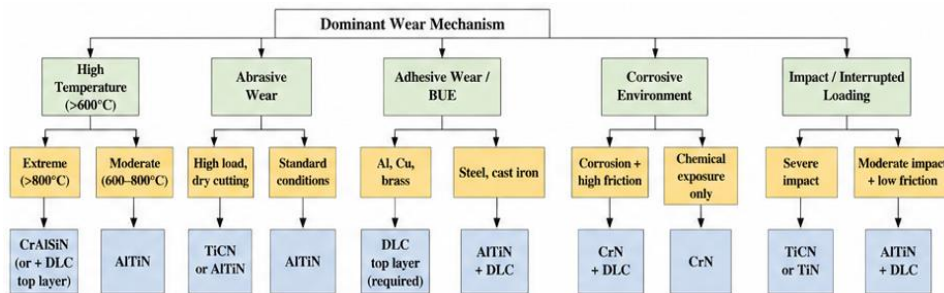


Figure 1 Decision tree for selection the optimal coating architecture

A typical layout of coating layers (AlTiN + DLC) is shown in Figure 2.

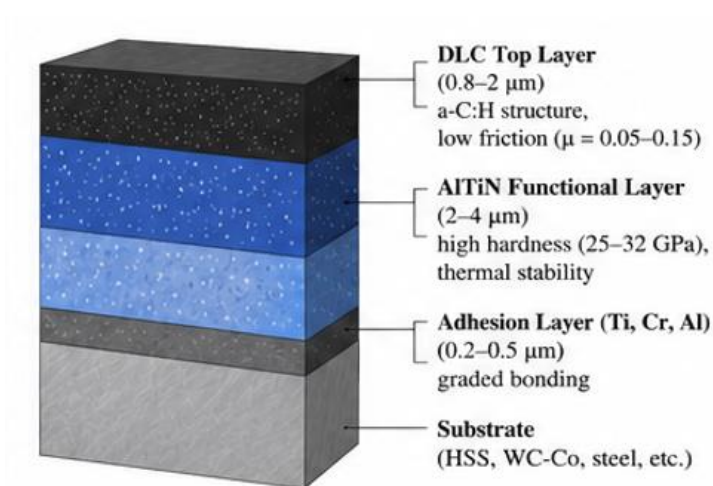


Figure 2 Typical hybrid multilayer architecture (AlTiN + DLC)

6.2 Positioning of Hybrid Coatings in the Tribological Space

Monolithic coatings show superiority along individual performance axes (CrAlSiN – thermal stability up to 1000°C; DLC – friction coefficient 0.05–0.15), while hybrid

systems (AlTiN+DLC and CrN+DLC) integrate high hardness, thermal stability and low friction coefficient, thereby occupying the **Pareto-optimal zone** of the tribological space [7,10].

6.3 Comparative Techno-Ecological Profile of Processes

Table 6 Comparative analysis of PVD, PACVD and CVD processes [3,11,12]

Parameter	PVD	PACVD (DLC)	Conventional CVD
Temperature	180–550°C	≤350°C	800–1000°C
Impact on substrate	Minimal	Minimal	Significant (tempering)
Layer thickness	2–6 μm	0.8–3 μm	5–15 μm
Wastewater	None	None	Present
Emissions	Low	Low	High (toxic precursors)

6.4 Limitations of DLC Coatings

DLC layers show limited thermal stability above 350°C due to graphitisation and relaxation of internal stresses [9]. Therefore, in demanding service conditions (cutting edge temperatures above 400°C), DLC is used exclusively as a top layer over thermally stable nitride bases (AlTiN, CrAlSiN) [10,14,15].

7 CONCLUSION

1. Hybrid PVD and PACVD (DLC) technologies represent a modern, environmentally friendly and technologically superior alternative to conventional surface protection methods. The low-temperature deposition regime (180–550°C for PVD, ≤250–350°C for DLC) enables the preservation of the microstructure and dimensional stability of the substrate, with the complete absence of wastewater and harmful chemical effluents, positioning them within the concept of green tribology [11,12].
2. The TOPSIS multi-criteria analysis showed a clear superiority of hybrid multilayer systems, with AlTiN+DLC achieving the highest closeness coefficient ($C_i = 0.91$) and CrN+DLC taking second place ($C_i = 0.88$).
3. A pronounced nonlinear synergistic effect was identified in combined PVD/PACVD systems, where the hard nitride base (AlTiN, 25–32 GPa) provides load-bearing capacity and resistance to deformation, while the DLC top layer ($\mu = 0.05$ – 0.15) enables an ultra-low friction coefficient and reduction of adhesive wear [2,4].
4. The developed decision tree enables a systematic selection of the optimal coating architecture based on five dominant wear mechanisms: thermal, abrasive, adhesive, corrosive and impact.
5. Contemporary industrial and literature data confirm that the application of advanced PVD, PACVD and hybrid multilayer coatings enables a significant extension of the service life of cutting tools (50–150%), tribological systems (2–4 times) and machine components, with reduction of wear, friction and energy losses [2,4,5,13].

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WEAR RESISTANCE OF DIAMOND-COATED WC TOOLS WHEN MACHINING Al-12% Si

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Abstract

The study began with experimentally obtained wear curves for diamond-coated and uncoated tungsten carbide turning inserts after 100 min of continuous machining of Al-12%Si alloy. With the help of a mathematical model, more precisely, numerical interpolation methods, these curves have been "expanded" to quite reliable wear curves up to 1700 min. of continuous cutting and during this time, wear resistance curves were determined as the best parameter for expressing various tribological characteristics, and above all, the durability of tungsten carbide turning inserts with diamond coating during machining of Al-12%Si. Wear resistance also indicates the machinability properties of Al-12%Si. The experiment is only related to recording wear curves; everything else has a theoretical approach.

Keywords: numerical interpolation, wear resistance, theoretical approach

1 INTRODUCTION

All tool materials have the property of resisting wear, i.e. have a certain wear resistance.

By resistance to wear we essentially mean the ratio of the work spent (W_τ) from the frictional force to convert the worn body into wear products, and the mass of the wear products (m_τ),

$$R = \frac{W_\tau}{m_\tau} \quad (1)$$

Wear resistance depends on a number of factors such as: contact kinetics, contact surface, friction coefficient, pressure and temperature on the contact surfaces, etc. The parameters affecting wear resistance may vary during contact depending on the physical and mechanical properties of the contacting bodies. Consequently, wear resistance should be regarded as a variable

property rather than a fixed material characteristic. Therefore, the wear resistance of cutting tools is defined as the quantitatively expressed ability of the material to resist wear under specific cutting conditions. The quantitative assessment of tool wear resistance is expressed by the first derivative of the cutting time function (τ) by the amount of tool wear (h).

$$R = \frac{d\tau}{dh} \quad (2)$$

where R (min/mm).

In this paper, we started from the wear functions obtained experimentally during the machining of Al-12%Si on a lathe after 100 minutes of continuous cutting. These curves were then "expanded" with the help of the Numerical Interpolation Method (which will be presented later in the paper)

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to wear curves after 1800 minutes of continuous cutting, from which the durability of the used diamond-coated tool can be determined with sufficient reliability. Then, the wear resistance was obtained on the basis of the wear curves thus obtained, and from the wear resistance curves the durability of the tool was determined.

It should be noted here that wear resistance is the best parameter for expressing various tribological characteristics, such as tool durability, which will be shown later. Given that wear resistance is a function of tool wear, on the basis of relation (2) in practice, tool durability is often determined using the radioactive method.

2 EXPERIMENTAL CONDITIONS

Diamond-coated tungsten carbide inserts were used in this study. The coatings were obtained by means of two different pre-treatment procedures: (a) oxygen-acetylene flame treatment, dissolution of Co in strong acids (HCl and HNO₃), ultrasonic seeding of the surface with fine diamond powder; (b) processing with Murakami's solution [1,2], passivation of Co using a mixture of

H₂O₂ + H₂SO₄. The following application conditions were used: temperature T=1073 K; time t=20 min; R - ratio of C₂H₂ and O₂ flow rate=1.5

To study the wear behavior, the machining mode was applied [3-5]. Processing of Al-12%Si alloy: cutting speed n=400 revolutions/min, displacement speed s=0.1 mm/revolution; depth of cut d=0.5 mm; sample diameter Ds=75 mm.

An optical microscope was used to determine individual points for the wear curves. After the specified time of machining, the size of the crater on the back surface of the worn turning plate was measured - V (μm). In the following text, the diagrams will show the size V(μm) instead of h.

3 DETERMINATION OF CURVE WEAR OF TOOLS

Based on the experimental results, wear curves were obtained without a diamond coating (Figure 1) and with a diamond coating (Figure 2), as well as with a diamond coating obtained by applying the Murakami solution (Figure 3).

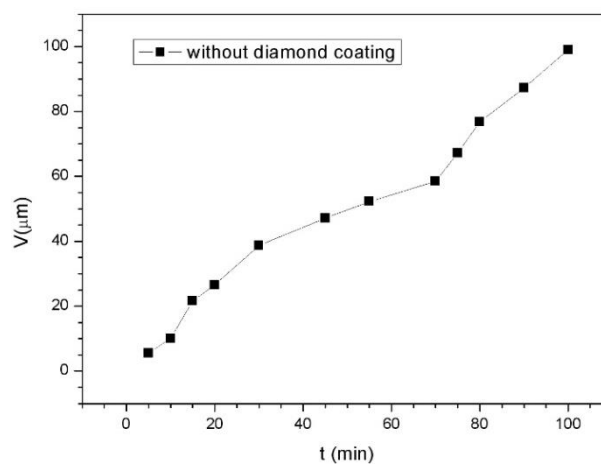


Figure 1 Experimental wear curve of tools without diamond coating

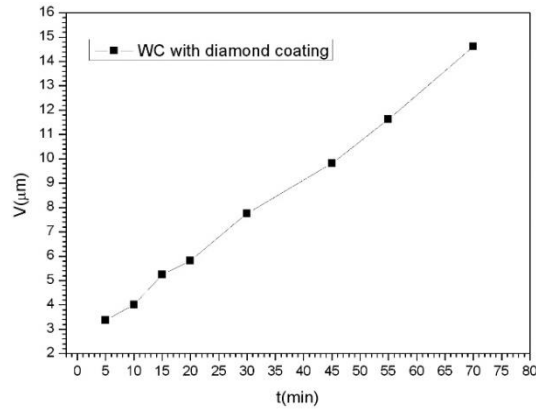


Figure 2 Experimental wear curve of diamond-coated tools

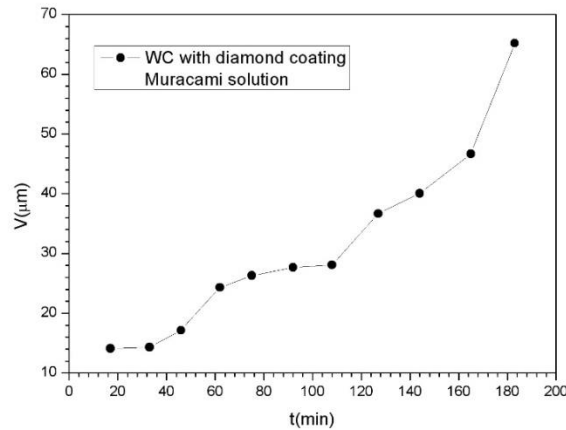


Figure 3 Experimental wear curve of diamond-coated tools obtained using Murakami solution

The tool wear function describes the tribological state and behavior of the machining process. In this case, the wear process on the back surface of the tool is primary, and on the chest surface is secondary. The width of the wear belt on the back surface of the tool, as a linear parameter, in theory and practice in the science of cutting tools, is most often represented by functions of the form:

$$h = B_1 \cdot \tau^{\Psi_1} \quad (3)$$

$$h = h_0 + B \cdot \tau^{\Psi} \quad (4)$$

Based on the experimental curves shown above and the mathematical model, "extended" tool wear curves will be shown, which can be applied in practice with high accuracy.

In order for the regression function of wear (4) to satisfy two arbitrary points 1 and 2 on the curve, in the second stage of wear there will be:

$$h_1 = h_0 + B \cdot \tau_1^{\Psi}, h_2 = h_0 + B \cdot \tau_2^{\Psi}$$

Dividing these equations gives:

$$\frac{h_2 - h_0}{h_1 - h_0} = \left(\frac{\tau_2}{\tau_1} \right)^{\Psi}$$

The exponent in the regression function will be from here:

$$\Psi = \frac{\ln\left(\frac{h_2 - h_0}{h_1 - h_0}\right)}{\ln\left(\frac{\tau_2}{\tau_1}\right)} \quad (5)$$

For a more accurate determination of ψ according to (5), several points on the wear curve obtained experimentally can be taken and the method of mean values can be applied.

If the experimental points are chosen so that they form a geometric progression, solving the problem becomes much easier:

$$\frac{\tau_3}{\tau_1} = \frac{\tau_2}{\tau_3}, \quad \tau_3 = \sqrt{\tau_1 \cdot \tau_2} \quad (6)$$

If the exponent ψ is expressed according to (5), through points 1 and 3, i.e. 2 and 3, it will be:

$$\Psi = \frac{\ln\left(\frac{h_3 - h_0}{h_1 - h_0}\right)}{\ln\left(\frac{\tau_3}{\tau_1}\right)}$$

$$\Psi = \frac{\ln\left(\frac{h_2 - h_0}{h_3 - h_0}\right)}{\ln\left(\frac{\tau_2}{\tau_3}\right)}$$

Hence, given (6), it follows that:

$$\ln\left(\frac{h_3 - h_0}{h_1 - h_0}\right) = \ln\left(\frac{h_2 - h_0}{h_3 - h_0}\right)$$

By solving this equation, the size of the section of the regression function on the ordinate is obtained:

$$h_0 = \frac{h_1 h_2 - h_3^2}{h_1 + h_2 - 2h_3} \quad (7)$$

The accuracy of relation (7) will be higher if the distance between points 1 and 2 is larger, which must be taken into account.

Based on this mathematical model and our experimental results, an "extended" tool wear curve without diamond coating is obtained:

$$h = 23,78 + 0,543645 \cdot \tau^{0,9877} \quad (8)$$

and the "extended" diamond-coated tool wear curve:

$$h = 0,704606 + 0,29124 \cdot \tau^{0,9044} \quad (9)$$

The curves are then shown in Figures 4 and 5.

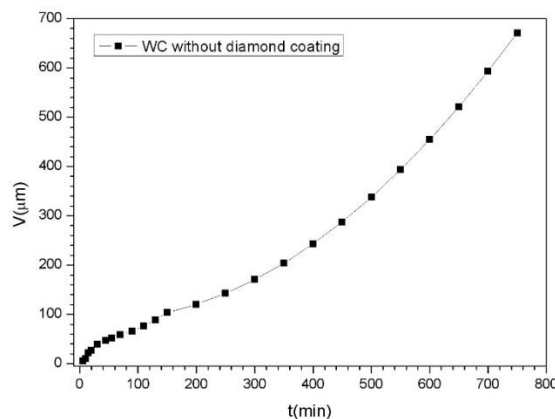


Figure 4 "Extended" tool wear curve without diamond coating

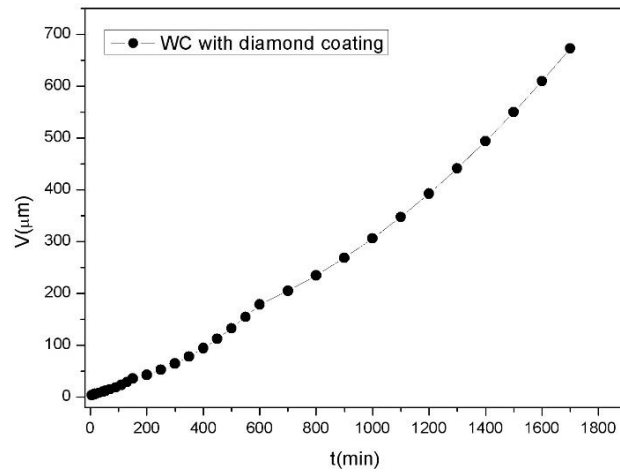


Figure 5 "Extended" wear curve for diamond coated tools

4 DETERMINATION OF WEAR RESISTANCE OF TOOLS

Based on the diagram from Figures 4 which is shown in Figures 6 and 7. and 5, the function $\tau=\tau(h)$ was created,

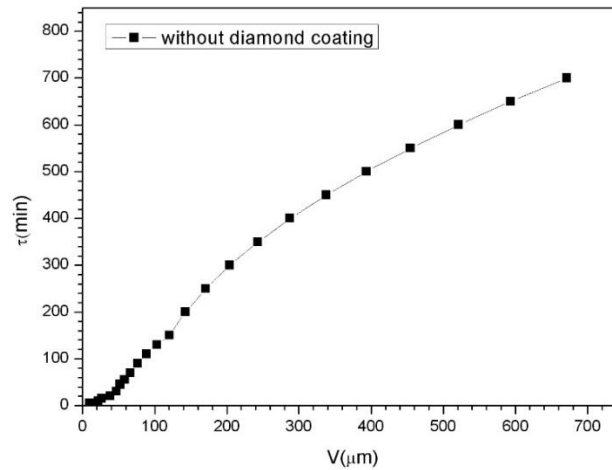


Figure 6 Wear curve in the coordinate system $\tau=\tau(h)$ for the tool without diamond coatings

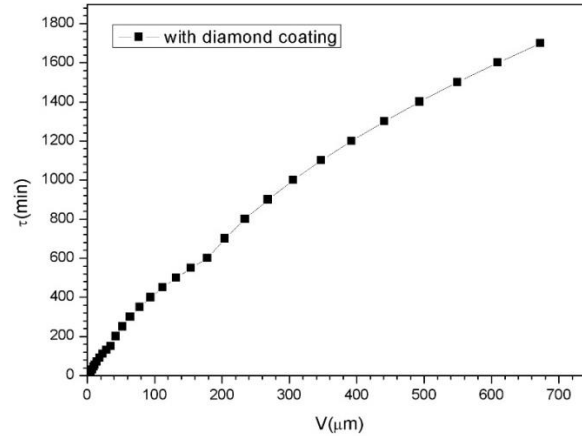


Figure 7 Wear curve in the coordinate system $\tau=\tau(h)$ for the tool with diamond coating

The experimental function $\tau=\tau(h)$, Figures 6 and 7, for area I of intense wear ($h \leq .25$ mm), can be mathematically described with sufficient accuracy by a regression function:

$$\tau = 318,30 \cdot h^{1.4967} \quad (10)$$

In the same way for class II stabilization wear ($0.25 \text{ mm} \leq h \leq 0.7 \text{ mm}$), we get that:

$$\tau = 109.54 \cdot (h - 0.25)^{0.7884} \quad (11)$$

By differentiating expressions (10) and (11), according to definition (2), we obtain

analytical wear resistance functions for areas I and II:

$$R_I = 476,40 \cdot h^{0.4967} \quad (12)$$

$$R_{II} = \frac{86.361}{(h-0.25)^{0.2116}} \quad (13)$$

Figures 8 and 9 show a graphical representation of the obtained functions (12) and (13) for tools without and with diamond coating, where different monotony is observed depending on the wear phase.

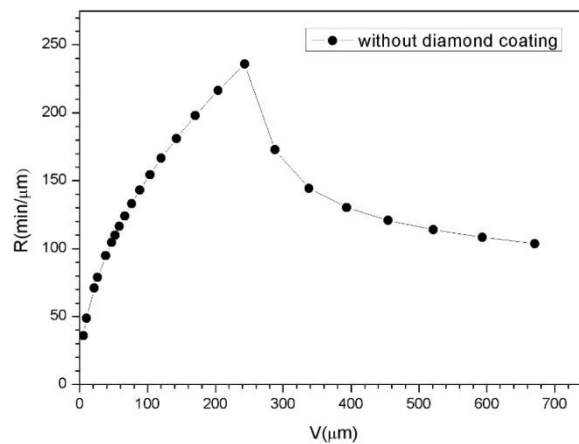


Figure 8 Wear resistance function of tools without diamond coating

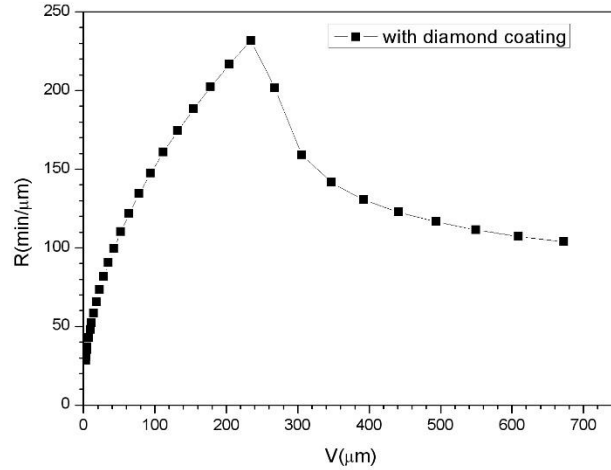


Figure 9 Wear resistance function of diamond coated tools

If we compare the wear resistance functions obtained according to the analytical expressions (12) and (13) with the same functions in Figures 8 and 9 obtained by the graphical method, it is noted that the deviations are relatively not high. It is interesting that according to the diagrams in Figures 8 and 9, the maximum wear resistance value is $R_{\max} = 239$ (min/μm).

Starting from relation (2), the elementary cutting time can be expressed as:

$$\tau = R \cdot dh \quad (14)$$

Integrating this relation within the appropriate limits will yield:

$$\int_{T_0}^T d\tau = \int_{h_0}^{h_k} R dh \quad (15)$$

In relation (15), T and h_k represent durability, i.e. tool wear criterion. By solving the integral (15), we get that the stability of the tool can be expressed in the form:

$$T = \int_0^{h_1} R_I(h) dh + \int_{h_1}^{h_k} R_{II}(h) dh \quad (16)$$

that is,

$$T = \tau_I + \tau_{II} \quad (17)$$

If we replace the sub-integral functions R_I and R_{II} from (12) and (13) in (16), and perform integration, tool stability is obtained as an analytical solution.

In this case, tool durability without diamond coating when machining Al-12%Si is $T_{bp} = 95.349$ min, and tool durability with diamond coating is $T_{sp} = 102.29$ min.

5 CONCLUSIONS

Taking into account the presentation in this paper, the following conclusions can be drawn:

1. Using the experimental results obtained during the machining of Al-12%Si tools without and with diamond coating, it is possible to obtain, with sufficient reliability, an "extended" tool wear curve with all three wear phases.
2. Based on the used mathematical model, the tool wear resistance functions without and with diamond coating are obtained, where the maximum value of the tool wear resistance is $R_{\max} = 239$ (min/μm).

3. Based on the presented mathematical model, as an analytical solution, tool durability without diamond coating is $T_{bp} = 95.349$ min, tool durability with diamond coating is $T_{sp} = 102.29$ min.
4. It is the first time that you can through the wear resistance of tool material by analytical solution using adequate mathematical model find work life of tool with sufficient accuracy.

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REPURPOSING POST-MINING AREAS IN THE ENERGY TRANSITION OF REPUBLIKA SRPSKA: CHALLENGES AND OPPORTUNITIES

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Abstract

The subject of this paper is the energy transition process in Republika Srpska, with a primary focus on the strategic repurposing of post-mining areas into solar power plants. The research examines the transformation of degraded technogenic land into potential energy capacities, contributing to decarbonization and the revaluation of previously degraded areas. The aim of the study is to assess the technical feasibility, environmental justification, and socio-economic implications of installing solar systems on sites where mining activities have ceased. The theoretical framework integrates concepts such as EROEI and green innovation, while a quantification model applied to the Stanari case study illustrates long-term potential. Empirical research conducted on a sample of 180 respondents indicates a high level of social acceptance (83%) for the solarization of open-cast mines. The results suggest that repurposing post-mining land may contribute to mitigating economic stagnation and improving energy security through the modernization of technogenic landscapes.

Keywords: energy transition, solar energy, Republika Srpska, decarbonization, technogenic soil.

1 INTRODUCTION

The global goal of climate neutrality by 2050 requires a gradual transition from fossil fuels to renewable energy systems [1]. In coal-dependent economies such as Republika Srpska (Bosnia and Herzegovina), this process creates significant socio-economic and structural challenges. The regional energy sector relies on thermal power plants (TPPs) in Stanari, Gacko, and Ugljevik, which ensure energy stability but also cause environmental degradation and technogenic soil disturbance [2]. Therefore, the repurposing of post-mining land for utility-

scale solar photovoltaic (PV) systems represents an important pathway for a just energy transition. Land reclamation in mining areas has traditionally focused on agricultural and forestry restoration, often producing low-fertility deposols with limited economic value [3]. Recent energy policies increasingly recognize brownfield mining sites as suitable locations for large-scale solar projects because they use existing grid infrastructure and reduce pressure on undeveloped land [4]. However, the deployment of PV systems on technogenic soil depends on terrain stability,

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2 THERMAL POWER SECTOR IN REPUBLIKA SRPSKA

2.1 Generation Structure and Coal Dependency

soil consolidation, workforce adaptation, and public institutional support [5]. This paper evaluates the technical feasibility, environmental justification, and socio-economic aspects of solar energy development on post-mining land in Republika Srpska, using the Mine-TPP Stanari system as a case study. The research applies the Energy Transition Index (Iet) and empirical survey data from N = 180 respondents to assess public acceptance and generational perspectives regarding the energy transition. The results indicate that combining land reclamation with renewable energy development may support sustainable regional growth and improve the utilization of degraded mining areas.

The electricity sector is an important economic driver in Bosnia and Herzegovina, relying on domestic natural resources to support energy stability and regional electricity exports [1], [2]. In Republika Srpska, electricity generation is predominantly based on lignite and brown coal [3]. Most extracted coal is used in thermal power plants (TPPs), while smaller quantities are supplied to industry and district heating systems. The main production centers are TPP Gacko, TPP Ugljevik, and TPP Stanari, connected to the Gacko, Ugljevik, and Stanari coal basins.

Table 1. Coal Reserves Balance in the Republika Srpska

No.	Mine (type)	Balance reserves (000 t)	Potential reserves (000 t)	Exploitable reserves (000 t)	Hd (GJ/t)	Ash (%)	Sulfur (%)
1	Ugljevik (B)	247,409	114,558	206,507	13.28	19.4	4.59
2	Stanari (L)	82,559	9,596	73,271	9.65	5.74	0.17
3	Gacko (L)	269,958	-	245,662	10.28	15.78	1.48
4	Miljevina (B)	21,200	40,100	19,080	11.7-14.8	24.83	2.2
5	Kotor Varoš(B)	16,410	1,359	-	14.5	26.06	1.4
6	Lješljani (B)	8,843	10,000	-	14.39	28.04	1.53
7	Ramići (L)	37,596	37,596	33,836	9.68	15.82	3.88
Total	-	683,975	175,613	578,356	-	-	-

Source: ERS, Thermo-energetic potential (Accessed: March 2026)

Although significant reserves exist in Kotor Varoš, Ramići, and Lješljani, their exploitation is currently not planned due to

high transport costs and distance from existing processing facilities.



Figure 1 Spatial distribution of coal deposits and thermal power plants in Republika Srpska
Source: Adapted from ERS and Znanje.org.

2.2 Environmental Impact of the Thermal Power Sector

Thermal power plants generate significant environmental impacts through gaseous emissions, particulate matter, and solid waste streams [4]. Due to the dominant use of coal, thermal power generation remains one of the largest sources of sulfur dioxide (SO₂) and carbon dioxide (CO₂) emissions in Bosnia and Herzegovina [5]. In addition to combustion-related pollution, open-cast coal mining causes extensive land degradation. Excavation alters geological structures, haulage activities generate dust and vibrations, while waste rock dumping creates permanent technogenic landforms. Research shows that replacing diesel haulage with conveyor transport systems and relocating crushing facilities closer to mining fronts can improve energy efficiency and reduce dust, noise,

and greenhouse gas emissions [6], [7]. Mining activities and waste disposal sites also reduce the availability of agricultural and forest land [8]. Fly ash, slag, and industrial waste heat additionally contribute to soil and groundwater degradation [9], [10]. To reduce the risk of heavy metal contamination, waste disposal sites must be constructed on stable, low-permeability surfaces with adequate drainage systems [11]. Effective mitigation of these impacts requires continuous institutional supervision and environmental regulation [12]. Environmental performance can be evaluated using the Overall Performance Trend (OPT) index:

$$OPT_t = \frac{1}{n} \sum_{i=1}^n \frac{X_{rnf,i} - X_{t,i}}{X_{rnf,i}}$$

Where OPT_t represents the overall performance trend in year t , $X_{ref,i}$ is the baseline value of indicator i in the reference year, $X_{t,i}$ is the measured value in the observed year, and n denotes the total number of monitored indicators. Positive index outcomes signal progressive environmental restoration, whereas negative trends confirm ecological regression and operational inefficiencies.

3 MANAGEMENT OF POST-MINING AREAS AS AN ECOLOGICAL TRANSITION ELEMENT

3.1 Management Models and Reclamation Concepts in Republika Srpska

Land reclamation is necessary to reduce mining impacts and restore degraded areas to functional use [13]. In Republika Srpska, reclamation activities are primarily defined by legal obligations and mine development plans and may be conducted during or after mining operations [14]. The basic reclamation cost per unit area (Tr) is calculated as [15]:

$$T_r = \frac{C_t + C_b}{S_v}$$

Where C_t and C_b represent technical and biological reclamation costs, while S_v denotes the reclaimed area. More advanced assessments also include geological degradation factors and socio-economic parameters [16], [17]:

$$E_p = A \cdot t_p \cdot T_r$$

Where A is annual production and t_p the duration of land occupation. The overall effect of restoring natural potential is expressed as:

$$E = \sum_{i=1}^n (P_r - P_p) (C_i - C_{vi}) S_{vi} \cdot t_{vi}$$

Where P_r and P_p represent productivity before and after reclamation, C_i and C_{vi} denote unit prices and variable costs, S_{vi} is the

reclaimed surface area, and t_{vi} is the duration of land use. Mechanical stabilization of technogenic soil is a prerequisite for the installation of photovoltaic (PV) systems. Historically, only 15–20% of degraded land in Bosnia and Herzegovina has been reclaimed, while reclamation levels in the Gacko, Ugljevik, and Stanari basins remained around 10% during the 2009–2010 period [15], [18]. Traditional reclamation methods mainly included afforestation and grassland development, whereas recent studies emphasize the potential of technogenic land for bioenergy and solar infrastructure [13], [19]. Projects such as TPP Gacko II include integrated technical and biological reclamation measures [20], although implementation is often limited by financial and technical constraints. At the Ugljevik Istok 1 mine, overburden is deposited in 10 m benches with a planned capacity of 116 million m³ [21]. Long-term slope stability remains essential for the safe installation of PV systems, with recommended gradients generally ranging from 1:4 to 1:2 under controlled conditions [22].

3.2 Energy Transition Quantification Model: The Case of TPP Stanari

To operationalize the structural shift from fossil fuels to renewable energy, this study applies the Energy Transition Success Index (I_{et}) to systematically evaluate the macro-potential of the Stanari mining basin [23]:

$$I_{et} = \frac{P_{sol}}{P_{ug} \cdot IQI}$$

Where I_{et} represents the Energy Transition Success Index for a specific Mine-TPP system, P_{sol} is the assumed capacity of solar power plants on reclaimed areas (MW), P_{ug} denotes the existing capacity of the coal-fired thermal power plant (MW), and IQI is the Institutional Quality Index (ranging from 0.1 to 1.0). To prevent an unrealistic inflation of the transition index, uncertainty weighting

was applied to the *IQI* coefficient, assigning lower weights to operational variables that lack comprehensive legal regulation. The EFT Mine and TPP Stanari system serves as a highly representative case study due to its advanced technological efficiency and infrastructural setup. Based on strategic projections, the baseline scenario involves an initial 5 MW solar installation on technogenic land acting as an innovation seed impulse [24], with a strategic scaling target

of 300 MW by 2040. Spatial planning relies on available asset polygons within the Stanari basin: the northern Raškovac open-pit mine encompasses 1,123 ha [25], while the southern Ostružnja open-pit mine covers 893 ha [26], encompassing mining fields, overburden dumps, and utility corridors. The simulation targets a full structural substitution by 2040, where the baseline thermal capacity ($P_{ug} = 300$ MW) is systematically matched by planned solar capacity ($P_{sol} = 300$ MW), as detailed in Table 2.

Table 2 Simulation of the Energy Transition Index (I_{et}) based on the projected scenario

Transition Phase	Solar Capacity (P_{sol})	Coal Capacity (P_{ug})	Assumed <i>IQI</i>	Results (I_{et})
Phase I (2025)	5 MW	300 MW	0.9	0.018
Projected Goal (2040)	300 MW	300 MW	0.9	1.11

The simulation demonstrates that by 2040, the index exceeds unity ($I_{et} > 1$), indicating a successful structural transition [23]. Crucially, this macro-scenario aligns with a high baseline of social readiness and ensures long-term employment stability for up to 1,250 workers. Clarification on Workforce Feasibility: The capacity of 1,250 employees does not represent the direct operational crew required for PV panel maintenance, which is inherently low. Instead, this figure reflects the total workforce retention capability of the integrated Mine-TPP Stanari complex during its phased transition. Maintaining this employment level is technically and economically feasible because the gradual decommissioning of coal generation triggers a labor reallocation toward extensive, long-term post-mining activities. These include complex technical and biological land reclamation, continuous environmental monitoring, mine closure conservation, grid infrastructure modernization, and the management of regional circular economy initiatives. Within the framework of the internal-influence growth pattern [24], this holistic absorption model prevents regional socio-economic stagnation by treating the legacy

workforce as an internal institutional asset. Consequently, instead of relying on external labor markets, the system dynamically reallocates its existing human capital to drive localized ecological and infrastructural value creation throughout the decommissioning lifecycle [24].

3.3 Comparative Analysis of European Practices in Mining Area Repurposing

European examples confirm the feasibility of converting post-mining land into utility-scale solar facilities using existing grid infrastructure. One example is the Klettwitz lignite mine in Germany, which was transformed into a 170 MW photovoltaic plant [27]. Within the framework of the European Green Deal, such projects combine land reclamation with renewable energy development to support climate neutrality goals [28], [29]. Successful transition models generally rely on gradual implementation. In the Horná Nitra region of Slovakia, phased mine closure combined with renewable energy projects contributed to regional economic

stability [30]. In contrast, rapid coal phase-out without compensatory development may lead to demographic and employment decline, as projected in parts of Polish Silesia [31], [32]. For Republika Srpska and the Western Balkans, the Green Agenda for the Western Balkans emphasizes decarbonization, ecological restoration, and a just transition framework [33]. In this context, the repurposing of degraded mining land into solar energy facilities represents a practical approach for supporting both environmental goals and long-term energy security.

4 DEVELOPMENT POTENTIAL OF SOLAR ENERGY ON TECHNOGENIC MINING LAND

4.1. Technical and Environmental Potential

Reclaimed mining land represents a suitable location for utility-scale solar energy development because it combines land restoration with low-emission energy production. Unlike conventional thermal power plants, photovoltaic (PV) systems do not produce carbon dioxide (CO₂) or particulate emissions during operation [34]. Their installation on degraded mining areas enables the use of existing brownfield sites without additional occupation of agricultural or undeveloped land. Solar energy also provides reliable electricity generation, local economic benefits, and increased public environmental awareness [35]. In Republika Srpska, post-mining landscapes therefore represent significant potential for renewable energy deployment. However, successful implementation requires the stabilization of technogenic soils together with ecological restoration through forestry, bioenergy, or controlled agricultural use.

4.2 Socio-economic Aspects and Constraints of the Energy Transition

The energy transition in coal-dependent regions has significant socio-economic implications. Energy costs account for

15–40% of mining operating expenses, making the sector highly sensitive to market changes and energy price fluctuations [36]. Research shows that reducing fossil fuel dependence and increasing renewable energy use may contribute to lower carbon emissions and improved long-term economic stability [37]. One of the key indicators used to evaluate alternative energy systems is the Energy Return on Energy Invested (EROEI) [38]:

$$EROEI = \frac{E_{output}}{E_{input}}$$

Where E_{output} represents the total energy produced, while E_{input} denotes the energy required for construction and maintenance. Fossil fuels traditionally achieved high EROEI values, while early photovoltaic systems showed lower efficiency ratios. To accelerate the energy transition, financial support for research, development, and grid modernization remains necessary [39]. The economic competitiveness of renewable energy systems is additionally defined by the backstop technology condition [40]:

$$p_t \leq R$$

Where p_t represents the unit price of renewable energy and R denotes the operational cost threshold of conventional technologies. As the costs of photovoltaic systems and energy storage continue to decline, solar energy is becoming increasingly competitive in Republika Srpska. Combined with strong public support (83%), this indicates that the repurposing of degraded mining land into solar energy facilities may support employment preservation and long-term energy security.

5 ANALYSIS OF EMPIRICAL RESULTS

5.1 Materials and Methods

An empirical survey was conducted between February and March 2026 to examine public perceptions regarding the conversion of post-mining land into solar energy facilities.

ties in Republika Srpska. Data were collected through a structured questionnaire distributed in digital and printed form across mining-dependent municipalities. The survey ensured respondent anonymity and confidentiality. Of 183 contacted individuals, 180 completed the questionnaire, resulting in a final sample of $N = 180$ and a response rate of 98.3%.

5.2 Socio-demographic and Geographical Profile of the Sample

The sample consisted of 63.0% male and 37.0% female respondents. The largest age groups were 26–35 years (25.0%) and 36–45 years (24.0%), followed by respondents aged 46–55 years (20.0%). These groups

represent the core working population directly connected to the mining and thermal power sector. Respondents originated primarily from energy- and mining-dependent municipalities. The largest shares came from Dobož (27.8%) and Stanari (15.0%), while Gacko, Ugljevik, and Bijeljina each accounted for 8.3% of the sample.

5.3 Public Perception of Technological, Economic, and Environmental Drivers

Respondent attitudes were analyzed through three focused operational indicators: support for solar installations on post-mining land (P1), regional employment expectations (P2), and environmental concerns related to biodiversity protection (P3) [41].

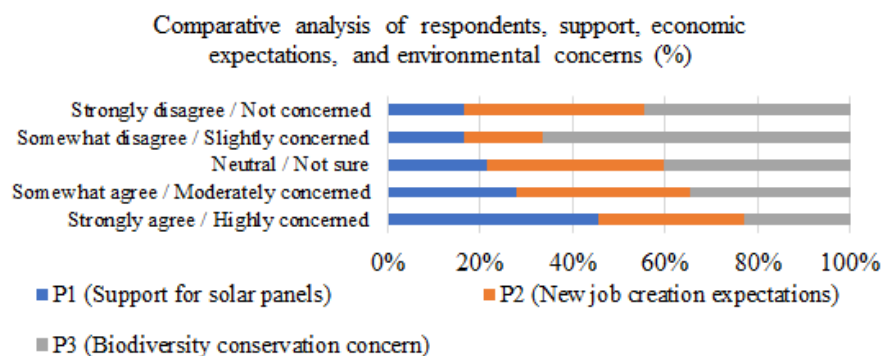


Figure 2 Comparative analysis of respondents' attitudes toward solar park installation (%)

Source: Author's own research (2026).

The empirical results presented in Figure 2 indicate the following key findings:

- P1 (Support for installation): A cumulative 62.0% of respondents express explicit support for the construction of solar parks on post-mining land, combining those who strongly agree at 46.0% and somewhat agree at 16.0%. This strong consensus indicates a highly positive public attitude toward brownfield renewable energy development.
- P2 (Employment expectations): Socio-economic expectations remain more moderate, with 54.0% of respondents believing that solar projects will contribute to regional employment (comprising 31.0% who strongly agree and 23.0% who somewhat agree). This points to a measured, cautious stance when comparing renewable integration with traditional, highly stable mining employment.

- P3 (Environmental concern): Local ecosystem integrity remains an active public focus, with 23.0% of respondents expressing high levels of apprehension regarding potential biodiversity loss and the reduction of active green areas, emphasizing the necessity of embedding strict ecological mitigation measures into early project planning.

5.4 Cross-Sectional Generational Analysis (Age Groups 26–35 and 36–45)

A separate analysis was conducted for the two dominant workforce groups: respondents aged 26–35 years (n = 45) and 36–45 years (n = 43).

- P1 (Support for installation): Support for solar projects was higher among respondents aged 26–35 years (71.1%) compared to the 36–45 group (58.1%).

- P2 (Employment expectations): The 36–45 cohort expressed lower confidence regarding employment opportunities from solar projects (41.9%) compared to respondents aged 26–35 years (60.0%).
- P3 (Environmental concern): Environmental concerns were more pronounced among younger respondents aged 26–35 years (28.9%) than in the 36–45 group (18.6%).

The results indicate that younger respondents show stronger support for renewable energy projects, while middle-career workers express greater concern regarding long-term employment stability.

5.5 Social Responsibility and Generational Consensus

Additional indicators evaluated perceptions of community support, industrial infrastructure utilization, and public well-being (Figure 3).

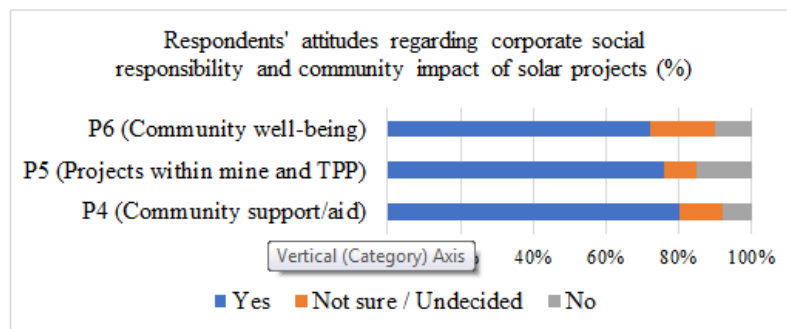


Figure 3 Respondents' perception of community support and social benefits (%)

Source: Author's own research (2026).

The results show:

- P4 (Community support): 80.0% of respondents support structured assistance programs for mining-dependent communities during the energy transition process.
- P5 (Projects within mining and TPP systems): 76.0% support implementing solar projects within existing mining and thermal power infrastructure systems.
- P6 (Community well-being): 72.0% consider solar energy projects

beneficial for long-term community development and environmental improvement.

Overall, the empirical findings indicate broad public support for renewable energy development on post-mining land in Republika Srpska. However, respondents also emphasize the importance of employment protection, environmental reclamation, and institutional support measures during the transition process.

6 CONCLUSION

This research confirms that the energy transition in Republika Srpska can be progressively achieved through the phased technical reclamation of post-mining landscapes and their functional conversion into utility-scale solar clusters. The quantification model applied to the Mine-TPP Stanari complex demonstrates that scaling solar capacity to 300 MW by 2040 drives the Energy Transition Index above unity ($I_{et} > 1$). This macro-level trajectory enables a non-disruptive phase-out of legacy coal generation while systematically safeguarding regional grid and energy stability. These structural projections are firmly validated by the cross-sectional empirical findings, which document a high baseline of social readiness and institutional trust regarding brownfield infrastructure substitution. The empirical insights reveal that successful deployment cannot rely solely on technical installation; rather, it demands a hybrid planning model that seamlessly binds technological substitution with intensive post-mining biological reclamation and socio-economic workforce reallocation frameworks. This approach bridges the structural perception gap between localized employment security expectations (P2) and underlying anxieties regarding ecosystem integrity (P3), a dynamic most pronounced within the critical 26–35 and 36–45 workforce cohorts. Furthermore, strategic social safe

guarding represents a fundamental condition for long-term project viability, as evidenced by the overwhelming public mandate for binding institutional and financial assistance for affected communities (P4). This requirement directly aligns with the foundational pillars of the Green Agenda for the Western Balkans, illustrating that regional decarbonization must secure alternative livelihood mechanisms to prevent structural stagnation.

Future research should focus on further differentiating empirical responses between active mining jurisdictions and non-extractive municipalities to eliminate aggregation bias and strengthen the spatial robustness of socio-economic impact assessments. In conclusion, integrating advanced technogenic land reclamation with brownfield renewable energy development represents a highly efficient model for transforming disrupted industrial basins into active drivers of sustainable regional growth. This integrated approach serves as a vital strategic pathway for strengthening long-term energy security, technological modernization, and economic resilience in Republika Srpska.

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