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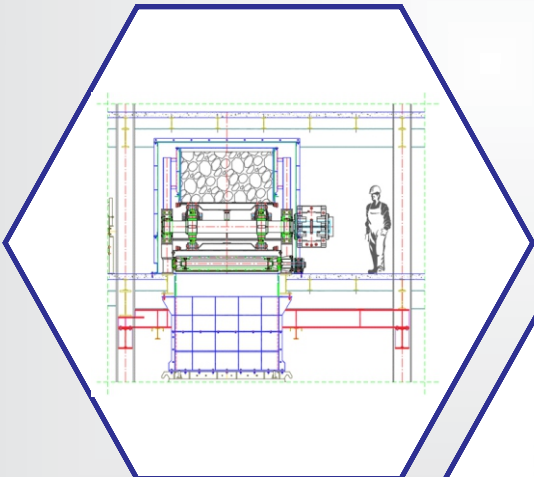

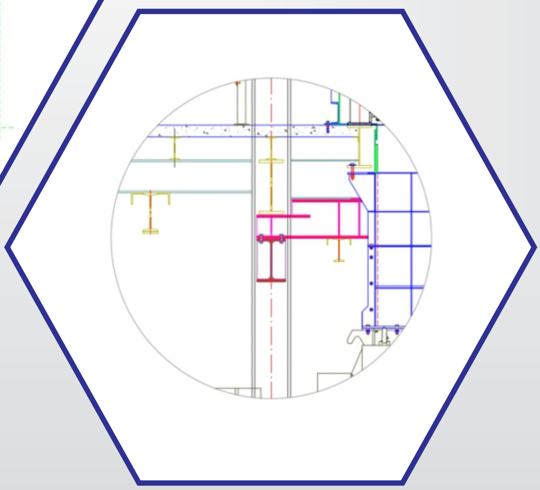

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*Miloš Živanović[*1], Aleksandar Doderović[*2], Ivan Stojičić[*3], Jovan Marković[*4], Jelena Stefanović[*5], Nikola Miljković[*6], Miloš Marković[*7]*

TECHNOLOGICAL AND STRUCTURAL DESIGN OF A CONVEYOR UNDERPASS FOR THE COMBINED COAL TRANSPORT SYSTEM FROM THE ROOF EXPLOITATION ZONE OF THE GACKO-CENTRAL FIELD OPEN PIT MINE[**]

[*1] E-mail: milos.zivanovic@irmbor.co.rs, Orcid: https://orcid.org/0009-0006-3331-4294
[*2] E-mail: aleksandar.doderovic@irmbor.co.rs, Orcid: https://orcid.org/0000-0003-3665-6784
[*3] E-mail: ivan.stojicic@irmbor.co.rs, Orcid: https://orcid.org/0009-0005-0571-1172
[*4] E-mail: jovan.markovic@irmbor.co.rs, Orcid: https://orcid.org/0000-0002-3084-068X
[*5] E-mail: jelena.stankovic@irmbor.co.rs, Orcid: https://orcid.org/0000-0001-6418-1814
[*6] E-mail: nikola.miljkovic@irmbor.co.rs, Orcid: https://orcid.org/0009-0009-2372-3942
[*7] E-mail: milos.markovic@irmbor.co.rs, Orcid: https://orcid.org/0009-0007-8392-0636

Abstract

This paper presents the technological and structural design solution of a tunnel-shaped underpass constructed for the coal conveyor belt of a combined transport system, serving the Roof Exploitation Zone of the Gacko – Central Field open-pit coal mine. The underpass has a clear opening of 6.1 meters in width and 2.5 meters in height and is positioned at an azimuth of 140 degrees. It is integrated beneath a haul road intended for ultra-heavy-duty mining trucks, specifically BELAZ trucks with a payload capacity of 110 tonnes, used for overburden transport. The underpass is equipped with wing walls on all sides, to ensure structural stability and seamless integration with the surrounding terrain. The solution ensures uninterrupted operation of the conveyor system while maintaining the safety and functionality of the haul road for continuous mining operations.

Keywords: *Gacko coal mine, coal transport, conveyor underpass, open-pit mining, construction*

1 INTRODUCTION

The exploitation of coal i.e. lignite, in surface mines is characterized by the use of both group of equipment, continuous and discontinuous. Specifically, in the surface mines of the Kolubara and Kostolac coal basins, but also in North Macedonia (Suvodo and Brod-Gneotino surface mines), Bosnia and Herzegovina (Raškovac, Gacko-Central Field, Dubrave surface mines), in Kosovo and Metohia (Sibovac surface mine) they use continuous equipment either completely or for overburden excavation. On the other hand, the mass application of discontinuous equipment is characteristic for the exploit-tation of coal in the surface mines of the Ugljevik and Pljevlja coal basins. The use of both group of equipment has its benefits and drawbacks, but it is cer-

[*] *Mining and Metallurgy Institute Bor, Alberta Ajnštajna 1, 19210 Bor, Serbia*
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tainly a decision of strategic importance, the decision which is made by analyzing a large number of important factors (morphological, geological, structural, hydrogeological, tectonic, logistical, organizational, etc.). The use of both types of mining and transport machinery is not uncommon and is used in situations where it is necessary to take advantage of the specific features of both types of equipment [1, 2] or within a single system - combined exploitation systems that use discontinuous equipment in one part and continuous equipment in the other. A common case is excavation with excavators and transport by trucks to the crusher, and continuous transport by conveyors and disposal by spreaders or depositing of mineral raw materials in a dump.

Position of transition from discontinuous to continuous part (and vice versa) or places of intersection of continuous and discontinuous transport routes, as a rule, imply certain infrastructure facilities (e.g. crusher foundations, bridges, tunnels, etc.), which is why they have a stationary character or they are in the same position for a longer period of time which is measured in years.

During the construction of these infrastructure facilities, the key issue is their positioning, considering the stationarity and influence on the process of mass transport, where the volume is measured in millions of cubics meters. The intersection of continuous and discontinuous transport routes is defined by the main directions and routes of movement of trucks (the main representatives of discontinuous transport equipment) and, to an even greater extent, belt conveyors (the main representatives of continuous transport equipment). A special problem is the dynamic nature of surface mining works, which is reflected in the changing position of the work site over time and the constant need to change, extend or shorten the network of roads and conveyor routes. When it comes to the transport of mineral raw materials, it is usual for its final destination to be a dump, a processing plant, or a place of loading into the customer's transport equipment, and these places are usually stationary. In the case of overburden and tailings transport, the most common case is that both the place of loading and the place of disposal change over time. This dynamic character of the works during the exploitation of mineral raw materials and excavation, transport and disposal of over and interbred has a significant influence on the definition of the intersection of discontinuous and continuous transport routes.

Such a characteristic case is present at the surface mine of lignite Gacko-Central Field open pit and thermal power plant Gacko. As part of the reconstruction of the combined system for coal transport, the economically and technologically favorable solution was chosen which includes the crossing of discontinuous and continuous transport routes, and it is necessary to solve the task of positioning the intersection and its technological and constructive solution.

2 TECHNOLOGICAL SOLUTION

The open pit Gacko-Central Field, which is located in the Gacko coal basin, uses both continuous and discontinuous mining and transport equipment, as well as their combination as part of two combined systems. One of the problems with the application of both types of equipment is the positioning of the equipment, that is, on the transport routes. The entire system and production organization should be organized in such a way that these two types of equipment cross in as few places as possible, but in practice it is often the case when this crossing cannot be avoided, either because of the positions of the excavation and depositing or disposal works themselves, or because their crossing has an economic justification (e.g. shortening of transport routes).

This problem is not unsolvable, but it requires the introduction of special infrastructure facilities whose position does not change for a long period of time and are practically stationary. The problem of crossing transport lines of discontinuous and continuous transport can be solved in two ways:

1. By creating transport bridges for the crossing of trucks over the belt conveyor corridor (Figure 1a).
2. By creating bridges for transporters with a lane across the road (Figure 1b).

Figure 1 *The method of crossing the routes of continuous and discontinuous equipment*

About the reasons for the relocation and extension of the Crusher-Belt Conveyor-Crusher (CCC) system, has been written in the author's previous publications [2, 3]. These publications explain the reasons, ways and benefits of extending the CCC system for coal transport, as well as its final form. Also, in the publication [2], the method of crossing connections with the bridge for the belt conveyor under which there is a one-way transport road for trucks Belaz 75135 is shown.

During the year 2025, the Investor changed the concept of the way of crossing the conveyor belt corridor and the transport road. A new way of solving this problem foresees the expansion of the corridor of the TU-3 belt conveyor and the formation of a bridge for trucks over the conveyor. Figure 2a shows the original crossover concept, while 2b shows the new crossover concept.

The new solution consists of the construction of an underpass intended for the passage of a conveyor belt for the transport of coal, which is located under the haulroad designed for the movement of mining trucks (eg BELAZ) with a capacity of 110 tons.

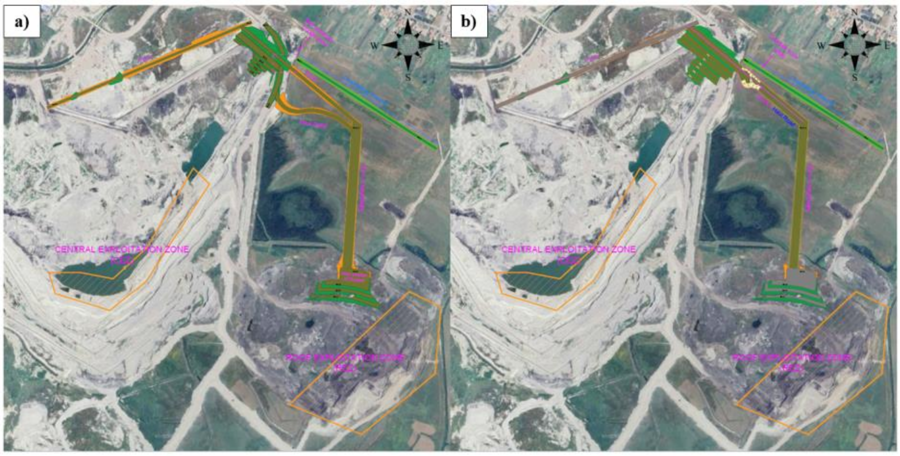


Figure 2 *Object position suggestions*

Both solutions have their positive and negative aspects. The advantages of the truck overpass described in this paper primarily lie in the fact that its maintenance and operation over time are significantly simpler. In addition, its construction ensures the integrity and complete compactness of the TU-3 conveyor embankment, even though significantly larger quantities of material are required for its formation. A third, but equally important aspect, relates to the water collector (marked as VS-C3). By constructing a unified embankment, there is potential for a significant increase in the active storage volume, as well as an expansion of the collector's flood zone. This is important not only for the functioning of the transport system but also for protecting the entire surface mine from water coming from the northern side.

After the place of intersection of transport routes is chosen, they are tied to that point in area, so the further construction of transport routes must be planned in relation to the place of work, but also in relation to this place. This results in a lower degree of freedom in the construction of routes and their formation in the geological environment that is present on those routes. This factor particularly affects the scope of works and the cost of construction of transport routes, especially when dealing with materials with unfavorable physico-mechanical properties. In this particular case, the surface layer over the entire area is represented by Quaternary sediments, which consists of alluvial deposits made of clay, gravel and sand. Closer to the river lines, there is more clastic material. With distance from the river-beds, the share of gravel and sand decreases, so the sediments become almost entirely clayey. The thickness of these layers is from 0.5 to a maximum of 8 meters. From a hydrogeological point of view, this environment is a collector, and from an engineering-geological point of view, it is an environment with extremely low strength parameters [4,5].

Beneath the quaternary sediments there are different marls of Neogene age, namely marls of the high roof of the main coal seam, and for this issue it is important that they have very good geomechanical characteristics and that they represent a good base for transport routes with good carrying characteristics. In addition, there are roof clays and marls, which are the youngest stratigraphic member of the Neogene. This member is built of clay and clayey marls. From the hydrogeological aspect, they represent an insulator [6].

Figure 3 *Contact of Quaternary sediments and roof clays and marls (red) with the transport path formed in the marls*

The negative aspects of this solution lie in the fact that significantly larger quantities of material need to be excavated along the route of the conveyor corridor and the transport road. This aspect is directly related to the amount of material that needs to be integrated. Due to the characteristics of the materials on which the transport routes are formed in certain parts, where the Quaternary sediments are less thick, it is more convenient to completely dig them out and form the routes on a marl substrate. On parts of the route that are formed in Quaternary sediments, it is necessary to replace the material, that is, to form an embankment made of material with good geomechanical parameters. In the first case, although the volume of quaternary sediments that need to be excavated is somewhat larger, the cost of creating a transport communication is lower, considering the quality of the substrate, while in the second case, the volume of backfilling with suitable material is larger, but it has a favorable effect on the subsequent cost of road maintenance. In general, it is more convenient and economical to form tracks in places where the Quaternary sediments are less thick and to form tracks directly on marls. Based on that, an important factor for the selection of the intersection of continuous and discontinuous transport routes is the structural-geological, engineering-geological and hydrogeological properties of the wider area. As illustrated in Figure 4, a cross-section of the route is presented, showcasing the distribution of Quaternary and marl sediments at the zone where the construction of the crossing will be built.

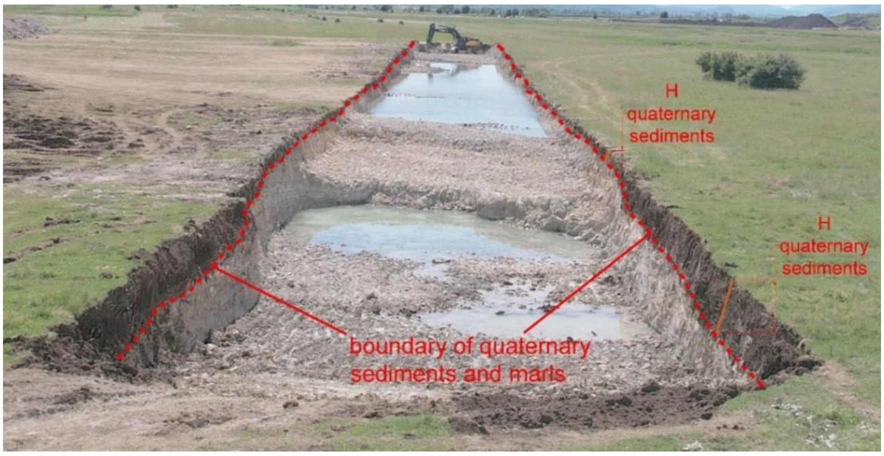


Figure 4 *Distribution of Quaternary and marly sediments at the zone where the construction of the crossing will be built*

By changing the position and manner of intersection between the two types of transport (trucks and conveyors), in this case—it is brought up to the surface level. This step results in increased noise emissions throughout the year, as well as a greater spread of dust emissions during dry months (summer period), especially considering the proximity of the settlement area. In this case the transport routes are positioned near settlements, negative impacts of transport on the environment are expected, primarily an increase in noise and dust concentration. In order to reduce these negative effects, it is planned to build a protective embankment with a green belt. The embankment would be formed from excavated Quaternary sediments suitable for reclamation and as a substrate for green belt plants. The position, dimensions and costs of creating a protective embankment are directly related to the excavated amount of quaternary sediments and the position where it is excavated, and is also a function of the choice of the position where transport routes crosses each other. Therefore, it can be concluded that the choice of the place where the routes cross depends on environmental factors, but also influences them.

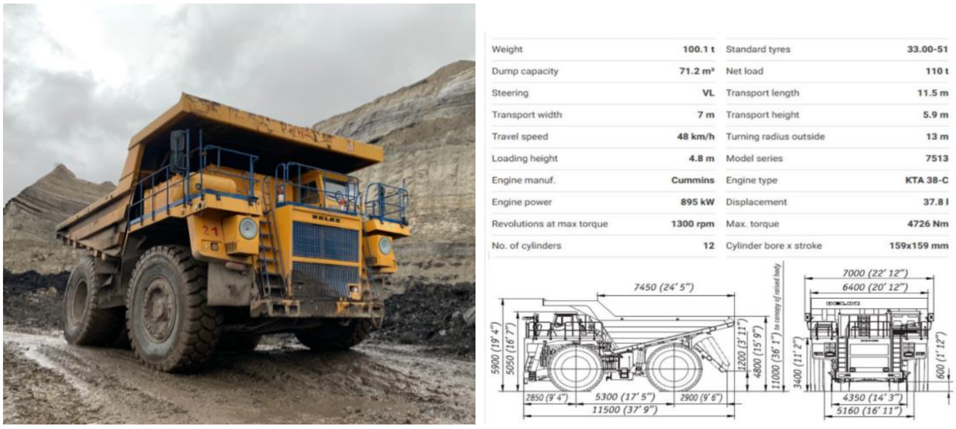
In addition to positioning, from the technological aspect of transporting over and interburden or mineral raw materials, whether it is a discontinuous or continuous transport, it is important to define the dimensions of the crossing points, which depend on the dimensions of the truck, the dimensions of the belt conveyor, the longitudinal slopes of the routes, the turning radius of the trucks and the dimensions of the water protect facilities of the transport routes. The dimensions and general geometry of the object of crossing routes is a function of the frequency of discontinuous transport, as well as the requirements that this object must meet in terms of the subsequent efficient and convenient maintenance of transport routes.

3 TUNNEL SHAPED UNDERPASS

The subject micro-location of the intersection of mining roads at the Gacko-Central Field open pit is shown in detail in Figure 5.

Figure 5 *Underpass location*

From a structural engineering standpoint, the underpass is designed as a rigid reinforced concrete frame system, capable of withstanding significant vertical and lateral force generated by heavy mining trucks (BELAZ, 110-ton payload). Technical characteristics of BELAZ truck are illustrated in Figure 6.



Weight	100.1 t	Standard tyres	33.00-51
Dump capacity	71.2 m³	Net load	110 t
Steering	VL	Transport length	11.5 m
Transport width	7 m	Transport height	5.9 m
Travel speed	48 km/h	Turning radius outside	13 m
Loading height	4.8 m	Model series	7513
Engine manuf.	Cummins	Engine type	KTA 38-C
Engine power	895 kW	Displacement	37.8 l
Revolutions at max torque	1300 rpm	Max. torque	4726 Nm
No. of cylinders	12	Cylinder bore x stroke	159x159 mm

Figure 6 *BELAZ heavy mining truck*

The clear dimensions of the tunnel are 6.1 meters in width and 2.5 meters in height, with a total length of 18.5 meters. The structural elements - including the base slab, side walls, and top slab - are all 40 cm thick, providing robust resistance to bending and shear stresses. Figure 7 represent microlocation.

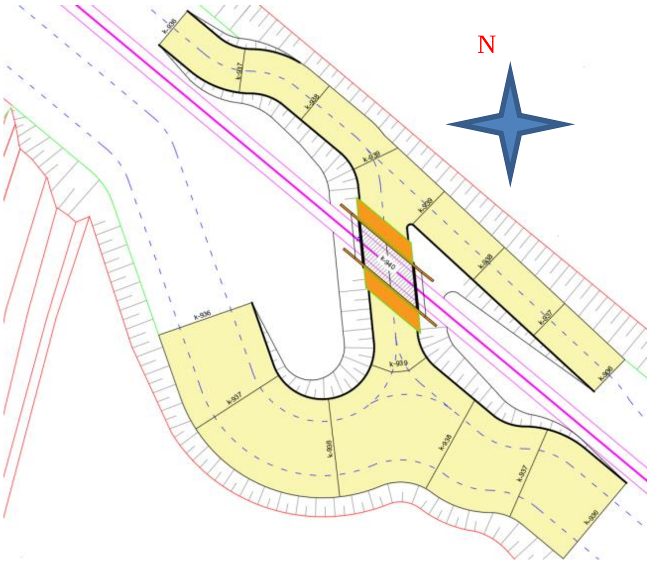


Figure 7 *Underpass microlocation*

To address stress concentration at the wall-slab junctions, especially under repetitive high-load wheel pressures, haunches (corbel-like reinforcements) have been introduced beneath the top slab. These haunches extend 1 meter horizontally and 0.5 meters vertically, effectively redistributing loads and improving the structural behavior at critical connection points. The structure is fully reinforced in accordance with rigid frame detailing principles, ensuring monolithic action and minimizing differential deformation. Additionally, reinforced concrete transition slabs measuring 14.5 × 4.5 meters and 30 cm in thickness are installed on both entry and exit sides of the underpass. These slabs facilitate the smooth transfer of wheel loads from the haul road onto the rigid structure while minimizing differential settlement and edge loading.

A 1-meter-thick crushed stone (graded aggregate) overburden is placed above the tunnel structure. This load distribution layer serves to disperse wheel loads from the mining trucks more evenly across the upper slab of the underpass, thereby reducing point load intensity and improving overall structural longevity. Figure 8 represent an underpass cross section.

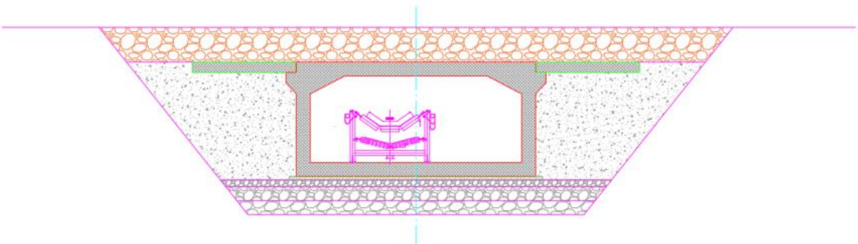


Figure 8 *Underpass cross section*

A longitudinal gradient of 0.5% has been incorporated into the base slab to facilitate drainage and prevent water accumulation inside the underpass. This solution not only guarantees structural stability and durability under extreme operational conditions but also serves as a protective housing for the coal conveyor system passing underneath the haul road. Figure 9 represent an underpass longitudinal section.

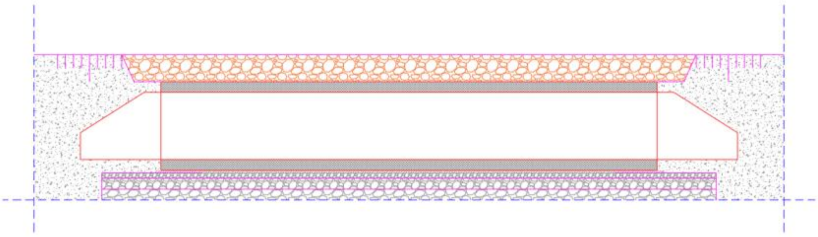


Figure 9 *Underpass longitudinal section*

4 CONCLUSION

The adopted tunnel-shaped underpass solution offers several practical and economic advantages over a potential bridge structure that could have been used to carry the haul road over the coal conveyor. The tunnel (underpass) requires a relatively short construction period, minimal permitting procedures, and lower overall investment costs. It is structurally compact and integrates well with the terrain, with wing walls ensuring slope stability and proper load transfer from the haul road above.

In contrast, a bridge alternative - particularly one capable of supporting ultra-heavy mining trucks such as BELAZ (110-tonne payload) - would have required a significantly more complex and costly design. This would likely involve deep pile foundations, post-tensioned cables, or a composite steel-concrete superstructure to achieve the required load-bearing capacity and durability. Moreover, such a solution would necessitate extensive geotechnical investigations, detailed permitting processes with local authorities, and a longer construction timeline including structural testing and future maintenance protocols.

While a bridge may offer marginally easier access beneath the structure and reduced risk of flooding under extreme weather conditions, the tunnel-shaped underpass was selected as the optimal solution due to its cost-effectiveness, faster implementation, and sufficient load-bearing performance within the specific operational and geological conditions of the Gacko open-pit mine.

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Original Scientific Paper
Energy

Dragan Milošević[*1], *Jasmina Nešković*[*2], *Jelena Isailović*[*3]

EVALUATION OF COAL USE IN THE ENERGY SECTOR

[1] E-mail: dragan.milosevic@ribeograd.ac.rs, Orcid: https://orcid.org/0000-0003-3714-1950
[2] E-mail: jasmina.neskovic@ribeograd.ac.rs, Orcid: https://orcid.org/0000-0002-1798-1656
[3] E-mail: jelena.isailovic@ribeograd.ac.rs, Orcid: https://orcid.org/0000-0003-2544-0080

Abstract

In many countries, coal plays a primary role in ensuring energy supply security. As a competitive fuel, it directly affects the economic value in the production of steel, cement, and, most importantly, in the generation of electricity and heat. A diverse energy mix with controlled use of coal can be part of a strategy that reduces risk and supports sustainable economic growth. Conventional energy generation in thermal power plants, including nuclear, coal, lignite, and gas-fired plants, requires sustainability and will remain necessary in the future.

Today, new renewable energy sources, primarily wind turbines and solar photovoltaic systems, are gaining importance, but they still require reliable backup from conventional sources. Space is increasingly being created for the integration of renewable energy sources, given the flexibility and reliability of coal and lignite-based power generation. A key prerequisite for future electricity production in Europe lies in utilizing a broad spectrum of energy sources to minimize supply risks, maximize reliability, and achieve further progress in environmental and climate protection.

***Keywords**: coal, energy, stability, supply*

1 INTRODUCTION

Coal has been a key energy source worldwide for decades, particularly in thermal power plants for electricity generation. Although it remains important in many countries, its role is diminishing due to climate change, environmental standards, and the transition to renewable energy sources. Coal has been used because of its high energy value, reliability of supply, as well as availability and low cost-especially in countries with large reserves (e.g., China, India, the USA, and Russia). In some developing countries, coal still accounts for more than 50% of total electricity generation [1].

The European energy sector faces significant challenges in ensuring the reliability of energy supply and investing in new energy infrastructure. Conventional thermal energy production, including nuclear, coal, lignite, and gas power plants, will still be necessary in the coming period. A key condition for energy supply stability in Europe is competitiveness.

Energy at affordable and transparent prices helps maintain the overall competitiveness of European industry. Risk management in energy supply has been an integral part of the Energy Union strategy since 2015. [1]. Two essential elements of a

[*] *Mining Institute, Batajnički put 2, 11080 Beograd – Zemun, Serbia*

secure energy system are the diversity of energy sources and energy technologies. An energy mix consisting of domestic and imported energy sources-including hard coal and lignite-helps control supply risks.

The use of high-efficiency, low-emission technologies, including coal upgrading, advanced combustion technologies, pollution control measures, and the application of carbon capture and storage (CCS) technologies, can improve the sustainability of coal use [1].

2 GLOBAL ENERGY TRENDS

Electricity is no longer produced solely from conventional hydropower, coal, gas, and nuclear energy. New renewable energy sources, primarily wind turbines and solar photovoltaic systems, are becoming increasingly important, but they still require reliable backup from conventional sources-at least until large-scale energy storage options become available. Analyzing the flexibility and reliability of coal-based electricity generation reveals significant potential for maximizing the use of renewable energy sources.

The key to future electricity production in Europe lies in a wide variety of energy sources. Supply risks are minimized, ensuring maximum reliability by utilizing available electricity generation sources and achieving further progress in environmental and climate protection towards net-zero emissions by 2050.

Globally, the number of coal-fired power plants has been declining during the period from 2014 to 2024, as shown in Figure 1 [2]. Many governments are increasing efforts to reduce funding for new high-emission fuel sources. Coal, as the most polluting fossil fuel, remains a major energy source, especially in rapidly growing economies.

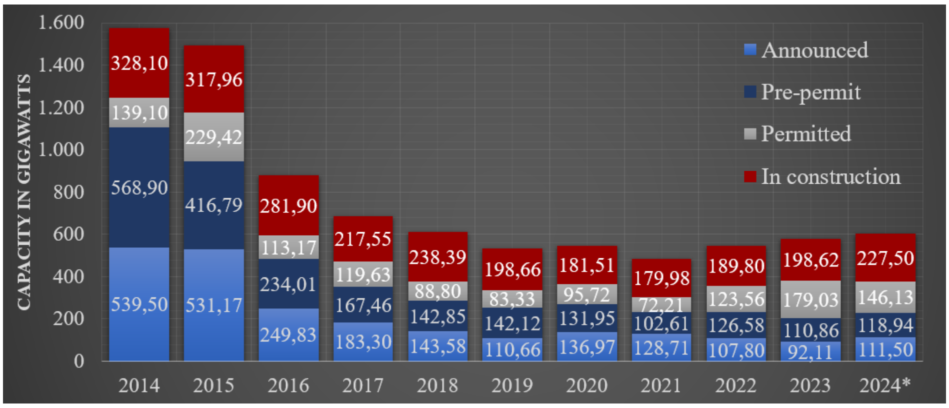

Figure 1 *Capacity of coal-fired power plants from 2014 to 2024 [2]*

The total global primary energy supply in 2022 amounted to 20,609 million tons of coal equivalent (Mtce), of which 26.7% came from coal, which is of particular importance for electricity generation, as shown in Figure 2 [2].

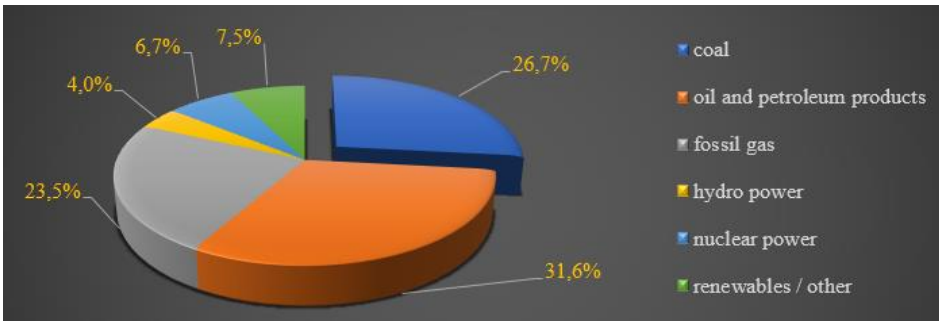

Figure 2 *Total world primary energy supply by fuel type, 2022 [3]*

Over one third, or 35.4%, of global electricity production and 17.1% of electricity production in the EU in 2022 were based on coal, as shown in Figure 3 [3].

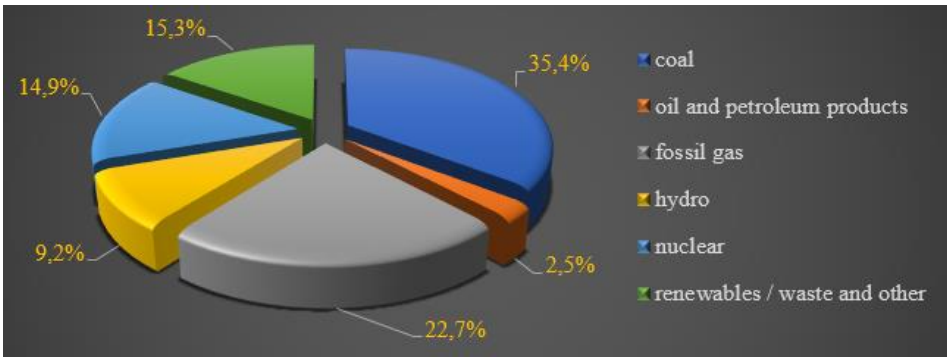

Figure 3 *World electricity production by fuel type, 2022 [3]*

Global coal consumption strongly recovered after a sharp decline at the peak of the pandemic [4, 5]. It is projected to reach a record 8.77 billion tons in 2024. However, demand is expected to remain close to this level until 2027. In China, which consumes 30% more coal than the rest of the world combined, coal consumption is expected to stabilize due to the massive expansion of renewable energy sources alongside strong growth in electricity demand [5].

In most developed economies, coal demand has already peaked and is expected to continue declining until 2027. Meanwhile, coal demand continues to grow in some developing economies where electricity demand is rapidly increasing alongside economic and population growth, such as India, Indonesia, and Vietnam. In developing economies, growth is mainly driven by coal demand from the power sector, although industrial use is also increasing, as shown in Figure 4 [6].

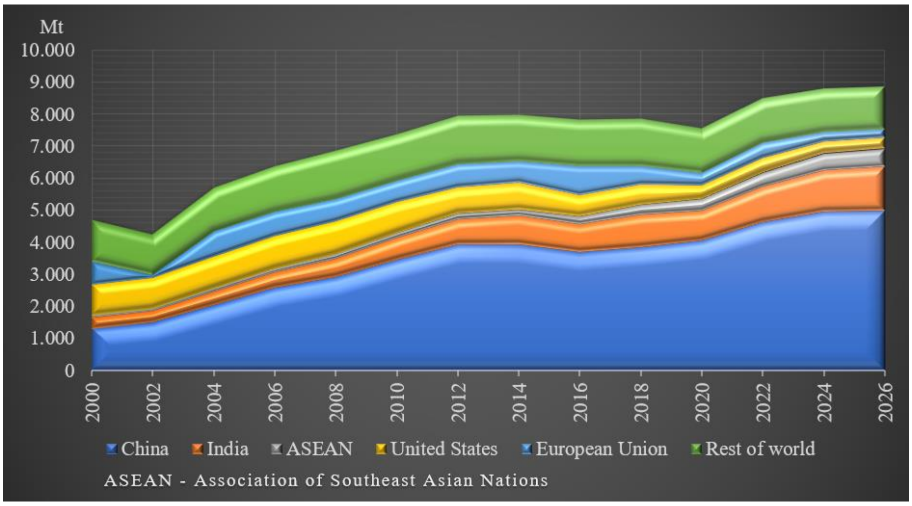

Figure 4 *Global coal consumption 2000 – 2026 [6]*

The International Energy Agency (IEA) report shows that global energy demand grew by 2.2% last year - lower than GDP growth of 3.2%, but significantly faster than the average annual demand growth of 1.3% between 2013 and 2023. Developed and developing countries accounted for over 80% of the global energy demand increase in 2024. The sharp rise in global electricity consumption was driven by record-high global temperatures, which increased cooling demand in many countries, as well as growing industrial consumption, transport electrification, and the expansion of data centers and artificial intelligence [6].

The growing supply of low-emission sources covered most of the increase in global electricity demand in 2024. As a result, 80% of the global electricity production growth in 2024 was provided by renewables and nuclear power, which together accounted for 40% of total production. Additionally, to meet rising electricity demand, natural gas saw the largest increase in demand among fossil fuels in 2024 [6].

Meanwhile, oil demand grew more slowly, causing the oil share in total energy demand to fall below 30%. Electric vehicle sales increased by over 25% last year, with electric models making up 20% of all cars sold worldwide. This significantly contributed to the decline in oil demand in road transport, while consumption of oil for aviation and petrochemicals increased [6].

3 ENERGY SECTOR INPUTS IN SERBIA

In the Central Balkan region, Serbia is favorably positioned for services and trade. The Morava Valley is the easiest land route from Europe to Turkey and beyond. Regarding energy, Serbia relies on lignite and small amounts of imported coal. Energy production in the country is largely based on lignite, accounting for 64.07%, as shown in Table 1 and Table 2. However, in the process of EU accession, the Republic of Serbia will be obliged to achieve an appropriate share of renewable energy sources in primary energy consumption [7].

On the other hand, existing low productivity, both in the mining sector and in electricity production in coal-fired thermal power plants, seriously calls into question the viability of maintaining existing capacities as well as the justification for building new ones [8]. To raise Serbia’s development level to a higher stage, energy development must be faster and more market-oriented than it is today [9].

Compliance with economic parameters is inevitable, without diminishing the importance of environmental protection.

Table 1 *Primary energy production (%) [3]*

Description / Year	2018	2019	2020	2021	2022	Average
Coal	65,37	66,22	65,11	61,58	62,05	64,07
Hydroelectric power	9,69	8,51	7,16	9,51	7,72	8,52
Solar photovoltaic power	0,01	0,01	0,01	0,01	0,01	0,01
Wind power	0,13	0,75	0,77	0,91	0,85	0,68
Crude oil and natural gas liquids	9,52	9,03	8,38	8,65	9,03	8,92
Firewood, wood chips and residues[1)]	11,08	11,39	14,83	15,67	16,77	13,95
Natural gas	3,93	3,76	3,33	3,14	3,01	3,43
Geothermal power	,05	0,05	0,05	0,01	0,02	0,04
Biogas	0,22	0,28	0,36	0,52	0,54	0,38

[1)] Final biomass consumption was taken from the Ministry of Mining and Energy of the Republic Serbia

Table 2 *Primary energy production (TJ) [3]*

Description / Year	2018	2019	2020	2021	2022	Average
Coal	276.720	285.772	295.647	263.034	250.324	274.299
Hydroelectric power	41.015	36.714	32.524	40.624	31.135	36.402
Solar photovoltaic power	47	49	48	49	57	50
Wind power	542	3.234	3.512	3.904	3.418	2.922
Crude oil and natural gas liquids	40.310	38.990	38.030	36.967	36.432	38.146
Firewood, wood chips and residues[1)]	46.931	49.151	67.334	66.938	67.640	59.599
Natural gas	16.653	16.247	15.133	13.414	12.145	14.718
Geothermal power	219	220	212	63	64	156
Biogas	939	1.190	1.624	2.221	2.193	1.633

[1)] Final biomass consumption was taken from the Ministry of Mining and Energy of the Republic Serbia

Coal is by far the most used fossil fuel in the Western Balkans and Ukraine [10]. In Europe, only Germany and Turkey have larger reserves. Deposits are located in two main coal basins, Kolubara and Kostolac, as shown in Figure 5. In 2022, Serbia mined 35.1 million tons of coal, but imported an additional 2.2 million tons of lignite. Lignite reserves amount to 7,112 million tons, with total resources of 20,186 million tons. Imports of hard coal amounted to 204 thousand tons. Hard coal reserves stand at 402 million tons, with total resources of 855 million tons [11**]**.

Production, processing, and transport of coal, electricity generation, distribution system operation, renewable energy production, and steam and hot water generation in cogeneration plants are carried out by Elektroprivreda Srbije (EPS). The total gross electricity production in 2022 was 36 TWh, net imports amounted to 2.6 TWh, while total supply was 34.9 TWh. Net electricity production from hard coal was 0.7 TWh, from lignite 21.5 TWh, while the net capacity for electricity production from hard coal was 486 MW and from lignite 5,661 MW [11].

Directly in lignite-based electricity production, 16,700 employees work, while the total number of employees in the mining sector is shown in the following table. Based on the presented data, it can be seen that about 1.3% of the total workforce is employed in the mining sector [12].

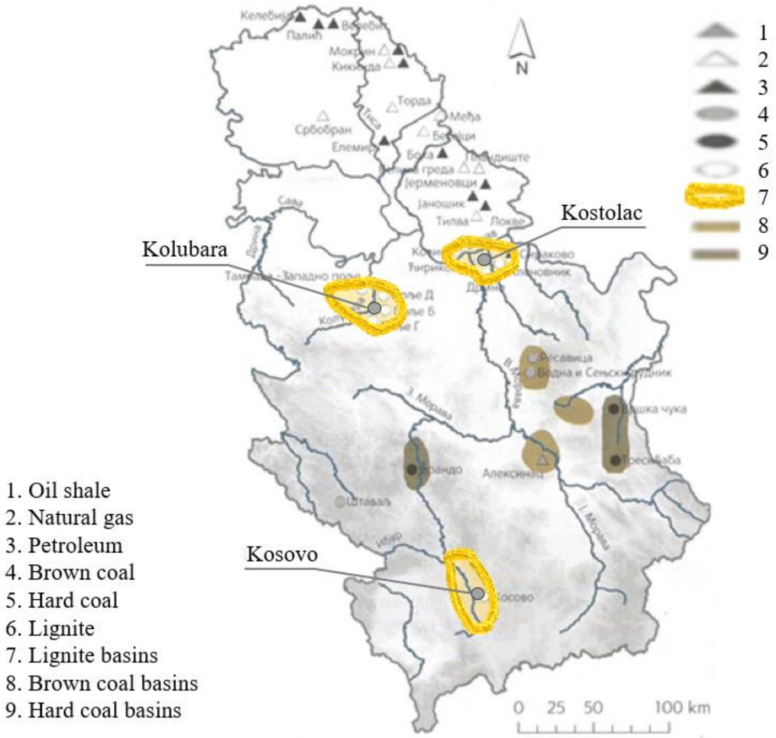

Figure 5 *Non-renewable energy sources - lignite coal in Serbia [12]*

Table 3 *Registered employment, 2020-2024 [3]* *annual average*

Description / Year	2020	2021	2022	2023	2024
Total number of employees	2.149.099	2.212.631	2.253.473	2.306.955	2.319.535
Mining	28.969	27.286	29.124	30.275	30.783

The mining sector in Serbia plays a significant role in the country's overall economic development. Thanks to its natural resources, it forms the basis of industrial development in the country and holds an important role in regional development. One of the indicators of the impact of the energy and mining sectors on economic growth is presented in the Table 3 and Table 4 [3].

Table 4 *Basic indices of industrial production by purpose and sectors, 2019-2023. [3] 2021=100*

Description / Year	2019	2020	2021	2022	2023
Industry - total	93,9	93,8	100,0	101,9	104,6
Energy	96,2	98,5	100,0	98,6	102,8
Intermediate products, except energy	89,7	88,5	100,0	104,2	104,0
Capital products	93,4	89,2	100,0	107,4	115,6
Durable consumer goods	98,7	103,0	100,0	9,38	91,8
Non-durable consumer goods	96,5	96,3	100,0	101,0	103,5
Mining	74,8	77,8	100,0	125,9	126,0
Manufacturing	94,9	94,2	100,0	101,4	102,4
Electricity, gas, steam and air conditioning supply	98,3	99,3	100,0	92,9	104,6

Based on data on the consumption of hazardous chemicals, Table 5 (covering the sectors: Mining, Manufacturing Industry, Electricity, Gas and Steam Supply, Water Supply and Wastewater Management), the negative effects of the energy and mining sectors are also presented in Table 6 [3].

Table 5 *Consumption of hazardous chemicals [3]* *thousand tons*

Description / Year	2022	2023
Dangerous to health	1.096	1.098
Dangerous to the environment	904	935

Table 6 *Waste generated by sectors KD1) and from households [3]* *thousand tons*

Description[1)] / Year	2022	2023[2)]
Total	176.879	182.319
— Hazardous	29.862	39.670
— Non-Hazardous	147.017	142.649
Agriculture	88	92
Mining	164.903	170.974
Manufacturing	1.072	1.086
Electricity, gas and steam supply	6.531	6.016
Water supply and wastewater management	970	1.088
Construction	630	503
Services[3)]	459	394
Household waste[4)]	2.225	2.167

1) Classification of activities
2) Data not final
3) Sectors covered by G-S KD
4) Estimate

4 DISCUSSION OF THE RESULTS

Coal still plays a significant role in many energy systems, but its use is increasingly limited due to environmental and economic reasons. Evaluation of its use shows that the costs and environmental impacts are high, and trends indicate the need for a faster transition to cleaner and more sustainable energy sources, Table 7.

Table 7 *The role of coal application*

Aspects	Importance	+	-	Comment
Economic Evaluation	Low production cost per kWh	●		
	Well-developed infrastructure in existing thermal power plants	●		
	Employment of a large number of workers (especially in mining and thermal energy sectors)	●		
	Rising CO_2 emission costs (e.g., EU ETS)		●	
	Costs of plant modernization due to pollution regulations		●	
	Reduced attractiveness to investors		●	
Aspects	**Importance**	**+**	**-**	**Comment**
Environmental Impacts	Greenhouse gas emissions (CO_2, CH_4)		●	For these reasons, many countries are implementing decarbonization strategies and plans to close coal-fired power plants
	Air pollution (SO_2, NO_x, particulate matter)		●	
	Water and soil contamination (waste ash and slag)		●	
	Land degradation due to surface mining		●	
Technical Improvement Possibilities	CCS technologies (carbon capture and storage)	●		However, these requirements often demand large investments that are not cost-effective compared to transitioning to renewables
	Cofiring – burning coal together with biomass	●		
	Modernization of plants to increase efficiency and reduce emissions	●		
Replacing Coal in the Energy Mix	Solar and wind power	●		EU countries and other developed countries are increasingly using alternative options
	Hydropower and nuclear energy	●		
	Natural gas as a transitional fuel	●		

The conservation of mineral resources, including coal, plays a significant role in the sustainable management of natural resources and long-term planning for the development of the energy sector. Although it is one of the key sources of energy in industry, the power industry and households, its use is declining due to environmental reasons and the global transition to cleaner energy sources.

Investing in the rational use and preservation of coal deposits allows countries to provide a backup source of energy in situations when other energy systems are unstable or unavailable (in emergency conditions, energy crises, disruptions in gas or oil supply), coal remains a reliable support). Such planning contributes to long-term sustainability and the reduction of negative environmental impact. In some regions, coal is still an important factor in local development — it provides jobs, supports metallurgy, the chemical industry, and other supporting industries.

Preserving coal resources allows for a gradual and controlled transition to alternative sectors, without a sudden economic downturn. Although coal is considered the most polluting fossil fuel, conserving the deposit also has an ecological dimension: the size and structure of mineral reserves are preserved, which allows for more precise planning of rehabilitation and reclamation, uncontrolled exploitation is prevented, which can lead to collapse, erosion and contamination of soil and water and allows for the gradual closure of mines with a reclamation plan that is aligned with natural processes.

Conserving mineral resources allows countries to gradually replace coal with renewable energy sources, without sudden disruptions to supply and the economy. Controlled and planned exploitation represents an important bridge to the energy transition.

5 CONCLUSION

Under its emissions reduction strategy, Serbia is expected to comply with the EU Carbon Border Adjustment Mechanism (CBAM), which will be gradually introduced starting January 1, 2026. To meet EU environmental standards, Elektroprivreda Srbije has recently invested in the modernization of power plants and environmental protection projects, particularly in its thermal power plants, where projects for flue gas desulfurization, electrostatic precipitators, ash and slag transport, and wastewater treatment have been completed.

Serbia still produces around 65–70% of its electricity from coal but is developing energy transition strategies. According to the draft National Energy and Climate Plan, Serbia will increase the share of renewable energy sources in electricity production, which will require new capacities. In any case, the production and utilization of electricity from wind, solar, and biomass should be developed to the greatest extent possible, while maintaining hydropower potential and using imported gas to the extent it is available at a favorable price.

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Stevica Jankov[*1], *Borivoj Novaković*[**2], *Goran Ivanov*[***3], *Luka Đorđević*[**4]

OPTIMIZATION OF OIL PRODUCTION USING RECIPROCATING PUMPS THROUGH CORRECTIVE ADJUSTMENT OF OPERATING PARAMETERS

[1] E-mail: stevica.jankov@nis.rs, Orcid: 1) https://orcid.org/0009-0000-6503-8200;
[2] E-mail: borivoj.novakovic@tfzr.rs, Orcid: https://orcid.org/0000-0003-2816-3584;
[3] E-mail: luka.djordjevic@tfzr.rs , Orcid: https://orcid.org/0009-0001-2004-4567
[4] E-mail: press-serbia@draexlmaier.com, Orcid: https://orcid.org/0000-0003-4578-9060

Abstract

This paper examines the optimization of oil production using reciprocating pumps through corrective adjustment of operating parameters. Considering the challenges posed by Industry 4.0, such as increased demand and the need for more efficient resource use, the study highlights the importance of applying modern technologies and methods for improving production processes. It focuses on the implementation of smart sucker rod pumps (SRP) equipped with Internet of Things (IoT) technologies that enable real-time data collection and analysis. Through the analysis of several wells, the study demonstrates how changes in pump speed affect production dynamics, volumetric efficiency, and energy consumption. The results showed that reducing the number of pump strokes led to improved efficiency and lower energy costs, further increasing the sustainability and profitability of oil production.

Keywords*: production optimization, reciprocating pumps, Industry 4.0, dynamic fluid level, volumetric efficiency, energy consumption*

1 INTRODUCTION

A key component in industries, it is used to maintain industrial sustainability and stability within Industry 4.0, as well as to improve process optimization and resource availability [1]. Various methods for process optimization have drawn the attention of researchers in the field of production management. The concept of process optimization has increasingly focused on improving the efficiency of production operations. Several methods are currently applied for process optimization in industries, including lean manufacturing, smart manufacturing, the Internet of Things, and artificial intelligence. The process optimization approach is a dominant strategy in Industry 4.0, applied to improve productivity and resource utilization [2]. In addition, this approach is used to meet customer demand regarding products, as it increases productivity by eliminating waste to achieve industrial objectives.

Working toward this goal also provides several other benefits, such as reducing production time and improving the quality of manufacturing processes, leading to

[*] *NAFTAGAS – Oil Services LLC, Novi Sad, Serbia*
[**] *University of Novi Sad, Technical Faculty "Mihajlo Pupin", Zrenjanin, Serbia*
[***] *DRÄXLMAIER GROUP|DAD, Dräxlmaier Automotive d.o.o. Zrenjanin, Serbia*

higher customer satisfaction with products [3]. According to [4], process optimization methods are applied to increase production efficiency. The main advantages of the process optimization approach in Industry 4.0 are as follows:

1. Achieving a sustainable production management system;
2. Maximizing the production rate and flexibility within the limits of available resources;
3. Improving flexibility, agility, adaptability, and responsiveness in Industry 4.0;
4. Simplifying the implementation of Industry 4.0 technologies in production facilities for industry professionals;

Researchers have proposed several process optimization methodologies aimed at ensuring industrial sustainability in complex environments. Such environments include various operating conditions, unexpected demand, overload, lack of production space, continuous operation, and nonstandardized work processes. Waste-free manufacturing, smart manufacturing, the Internet of Things, and artificial intelligence are process optimization approaches implemented to eliminate waste. Waste refers to unnecessary activities performed in production that do not add value to the product [5]. Waste is classified into eight categories: overprocessing, overproduction, transport, unnecessary movement, waiting, defects, and unused skills [6].

The process optimization approach is generally preferred in Industry 4.0 because it can achieve production improvements with limited resources on automated production lines and serves the purpose of optimizing processes [7,8].

2 METHODOLOGY

Today, many oil and gas fields are equipped with advanced instrumentation and control platforms that can be used to collect digital operating data from field equipment. Another characteristic of smart fields is that they are networked; data generated from multiple sites are transmitted to a central data center that can be located miles away. A team of specialists working in the data center monitors information received from several fields and makes decisions to simplify and optimize field operations [9]. Industry 4.0 focuses on the use of advanced technologies such as integrated sensors and actuators, which enable products to be designed or redesigned to improve operational efficiency and support business growth while reducing risks. The trend toward automation and other major Industry 4.0 technologies such as artificial intelligence, the Internet of Things, 3D printing, big data, cloud technology, and digital twin systems has shown measurable business value that helps improve performance while maintaining customer satisfaction in actual drilling processes. Many oil and gas companies have adopted and implemented some of these technologies, developing their own hardware and software tools to increase operational accuracy and improve decision-making for maintaining asset sustainability [10,11].

Mechanical lift systems are used to increase pressure in oil wells to improve hydrocarbon production. Globally, around 95% of wells use mechanical lift systems, and most of these employ sucker rod pumps. These pumps are among the oldest and most commonly used artificial lift systems in the oil and gas industry, representing about 45% of mechanical lift systems used worldwide [9]. Their simple design, ease of use, low installation and operating costs, and wide production range make them a popular choice. Although reciprocating pumps are reliable and relatively efficient systems, a lack of proper technical management and maintenance can cause recurring failures that reduce system lifespan. Regular monitoring and maintenance are therefore necessary to ensure safe and optimal operation of the equipment. With advances in automation and instrumentation, it is now possible to equip field systems with various sensors and use sensor data for monitoring and optimal control.

This study examines smart sucker rod pumps (SRP) with integration of advanced technologies such as the Industrial Internet of Things (IoT). The Industrial Internet of Things, as one of the smart technologies, has proven beneficial for improving efficiency in oil and gas production activities. Sensors collect data that are stored in the cloud, where analysis is then performed. Big data analytics transform the collected data into knowledge, creating business value. The oil production system based on reciprocating pumps is equipped with multiple sensors and actuators that provide insight into the pump's operating conditions. Dynamic charts and real-time data are generated and can be used to monitor pump performance. The intelligent design of the control system allows users to replicate different field conditions and perform adjustments under various experimental setups that can be used to optimize oil production.

2.1 Fundamentals of the reciprocating pump oil production system and data collection

The main components of oil wells that use reciprocating pumps include the prime mover, the walking beam, the sucker rod string, and the reciprocating pump. The walking beam converts the rotary motion of the prime mover into the reciprocating motion required for pump operation [12]. The sucker rod string connects the reciprocating pump to the walking beam. The pump operates on the positive displacement principle and consists of a cylinder and a plunger. The plunger contains a traveling valve, while the cylinder houses a standing valve. Both valves operate on a ball-and-seat mechanism and function as check valves [13]. The advantages of sucker rod pumping systems include operational simplicity, low maintenance costs, equipment durability, a wide range of operating flow rates and depths, good energy efficiency, and the ability to handle fluids of varying composition [14,15]. The basic components of an oil well using reciprocating pumps are shown in Figure 1.

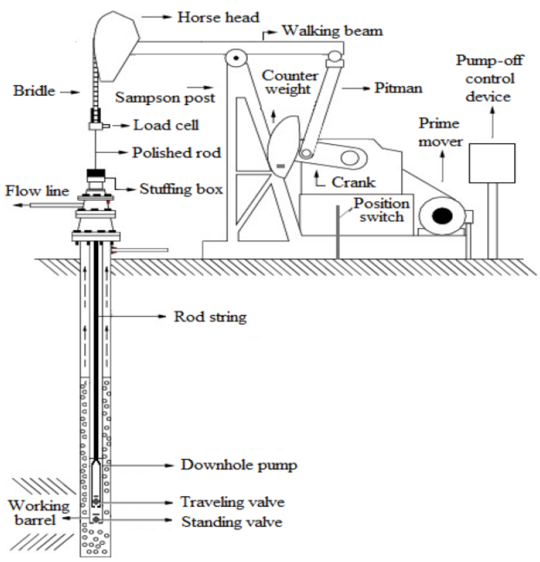

Figure 1 *Basic components of the reciprocating pump oil production system [12]*

2.2 Frequency regulator

Modern technology requires variable speeds in many applications that use electric motors. Electric motors that rely on traditional control methods generally have two states: stopped and operating at maximum speed. In most motor installations, motors are sized to deliver the maximum required power. When the rotational speed remains constant at its maximum value to provide the highest designed load, the power input to the motor also stays at its maximum. However, when the load decreases, significant energy savings can be achieved by reducing the motor speed to match the load requirements [16].

Most motors operate at full speed only for short periods. As a result, many systems run inefficiently for extended durations, causing notable energy losses over time. Reducing these losses can be accomplished by installing variable speed drive (VSD) systems that adjust motor speed according to the actual load. VSDs have become widely used due to their advantages over traditional control methods. Using a VSD, the speed of a motor or generator can be controlled and adjusted to any desired level. In addition to speed adjustment, a VSD can maintain a constant motor speed even under varying load conditions [17].

Several terms are used to describe devices capable of controlling motor speed [16]:

1. Variable frequency drive (VFD) – uses power electronics components to control motor speed by changing the frequency of the input power.
2. Variable speed drive (VSD) – controls the speed of the motor or the equipment it drives (fan, pump, compressor, etc.); it may be electrical or mechanical.
3. Adjustable speed drive (ASD) – uses both mechanical and electrical means to control motor speed.

VSD and VFD are electronic devices that align motor speed with the required speed of the application. The output voltage and frequency depend on the motor's input power. Most motors can benefit from a VSD to provide variable frequency outputs, whether the drive speed is set manually by an operator or automatically by a control system. VSDs are an efficient and economical upgrade option suitable for systems requiring variable speed. They allow motor speed to vary according to real operating conditions instead of continuously running at full speed. Adjusting speed in this way ensures a better match between motor operation and changing load requirements [16].

2.3 Data collection, data processing, and decision-making

SCADA systems are highly distributed control systems used to manage geographically dispersed assets, often spread over thousands of square kilometers, where centralized data collection and control are essential for system operation. They are applied in distribution networks such as water supply and wastewater systems, oil and gas pipelines, power grids, and railway transport systems. The SCADA control center provides centralized monitoring and control of field locations through long-distance communication networks, including alarm monitoring and status data processing. Based on information received from remote stations, automated or operator-guided supervisory commands can be sent to remote control units, commonly referred to as field devices. These field devices control local operations such as opening and closing valves and switches, collecting sensor data, and monitoring the local environment for alarm conditions. Figure 2 shows the basic components of a SCADA system for data collection, transmission, and archiving [18].

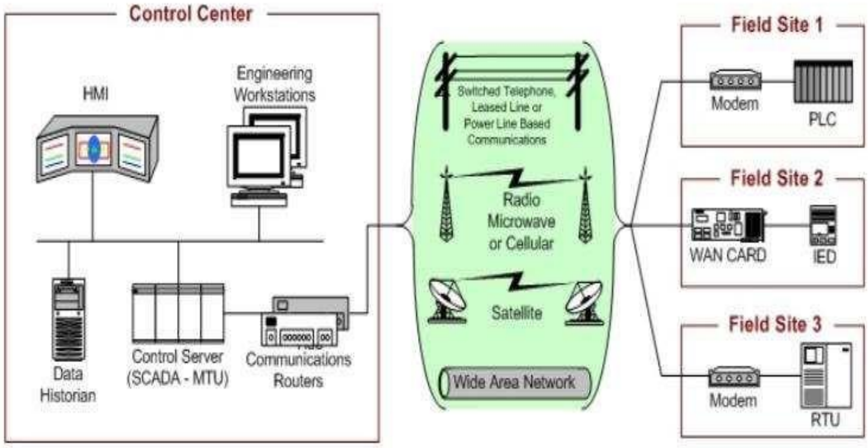

Figure 2 *Basic components of the SCADA system [18]*

2.4 Dynamic fluid level and its determination

With the progress of digital oilfield development, automated collection and analysis of dynamic fluid level parameters in oil wells have become important tasks that directly affect production increase, energy reduction, and overall economic performance [19,20]. Adjusting the operating speed of the pumping unit in real time based on the dynamic fluid level depth can significantly improve production efficiency. When the dynamic fluid level depth decreases, it indicates sufficient fluid supply in the reservoir, and increasing the pumping speed can raise production per unit of time. Conversely, when the level depth increases, it signals a decrease in fluid supply capacity. In such cases, reducing the operating speed or temporarily stopping the machine can maintain production while lowering energy consumption per unit of time [21]. Real-time monitoring and accurate measurement of dynamic fluid level depth in oil wells are therefore highly important [22].

The data used for analyzing the impact of dynamic fluid levels were obtained using an automatic recorder based on the acoustic wave method for measuring the depth of the dynamic fluid level in oil wells. This method relies on the principle of acoustic range measurement. The acoustic wave generator at the wellhead emits a signal that propagates downward through the annular space. When the wave encounters a tubing joint, a small portion of the wave is reflected and received by a sensor at the wellhead. Most of the wave continues to propagate downward, gradually losing energy and reducing in intensity. Eventually, a portion of the wave reaches the fluid level, and the resulting reflection, known as the fluid level wave, is received by the sensor. This fluid level wave differs significantly from the transmitted wellhead wave and the tubing joint reflections in both the time and frequency domains [23 - 25].

Based on this principle, an equation was derived and used to calculate the dynamic fluid level depth [23]:

$$H = \frac{vt}{2} \quad (1)$$

Where: H is the dynamic level (m), v is the sound velocity in the gas within the annular space (m/s), and t is the time required for the sound to travel from the sound generator to the dynamic fluid level and back to the receiver (s).

Figure 3 shows the model of sound wave propagation through the annular space.

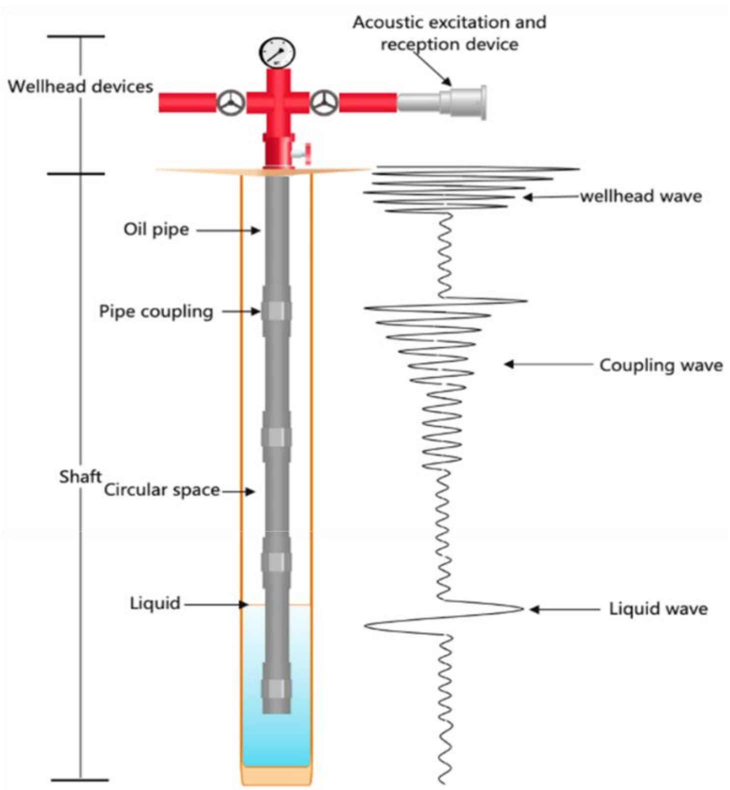

Figure 3 *Model of sound wave propagation through the annular space [23]*

Figure 4 presents the acoustic wave forms and the positions of different echoes.

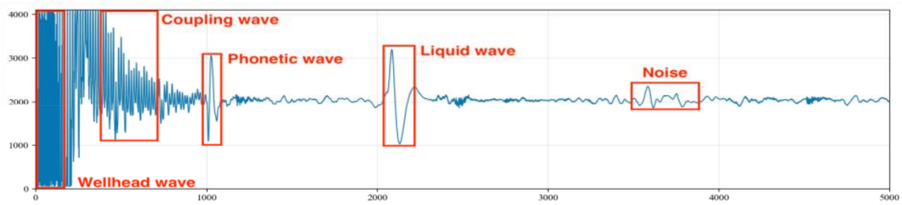

Figure 4 *Acoustic waveforms and the positions of different echoes*

2.5 System load and dynamometer card recording

To understand the basic patterns of surface dynamometer cards produced by conventional dynamometers, the cards under standard operating conditions must first be examined. The relationship between the polished rod load and its position is represented as the parallelogram 1, 2, 3, and 4 in Figure 5 [26].

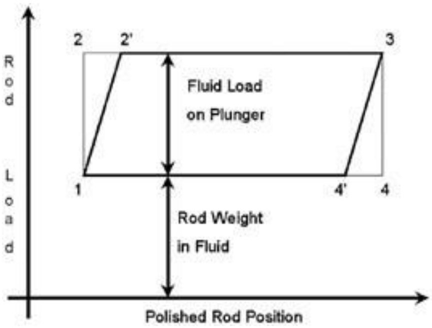

Figure 5 *Theoretical shape of a dynamometer card*

At point 1, the upward stroke begins, leading to the immediate closure of the traveling valve. The load on the polished rod, corresponding to the floating weight of the rod string at point 1, rapidly increases to the value marked as point 2 when the fluid load transfers from the standing valve to the traveling valve. The plunger, along with the polished rod, continues to move upward to point 3, maintaining nearly constant load during this phase. At point 3, the upward motion ends, marking the start of the downward stroke, which corresponds to the rapid opening of the traveling valve. The rod load then sharply drops to point 4 because the fluid load no longer supports the traveling valve. Between points 4 and 3, with the traveling valve open, the rod string descends through the fluid, and the load on the polished rod reflects the floating weight of the rod string. Point 1 marks the beginning of the next cycle [26].

Figure 6 illustrates the loads that occur during one complete pumping cycle.

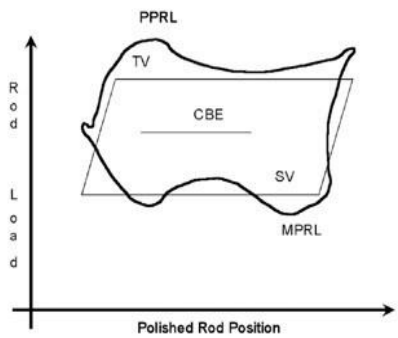

Figure 6 *Representation of loads on a dynamometer card*

The peak polished rod load (PPRL), shown in Equation (2), represents the maximum load occurring during the pumping cycle. It reflects the traveling valve (TV) load combined with the peak dynamic forces that arise during the upward stroke:

$$PPRL = W_{rf} + \left(\frac{F_1}{Sk_r}\right) x \, Sk_r \quad (2)$$

The minimum polished rod load (MPRL), calculated using Equation (3), represents the load on the standing valve (SV) reduced by the maximum dynamic load during the downward stroke. This value is identified on the dynamometer card as the minimum load observed during the pumping cycle (3):

$$MPRL = W_{rf} + \left(\frac{F_1}{Sk_r}\right) x \, Sk_r \quad (3)$$

where:

Wrf - weight of the sucker rod string (kg)

F_1/S_{kr} and F_2/S_{kr} - functions obtained from charts in the standard [27]

CBE - represents the counterbalance equivalent, which is the force acting on the polished rod, determined by the maximum counterbalance moment.

The fluid load (F_o) is obtained as the difference between the traveling valve load (W_{tv}) and the standing valve load (W_{sv}):

$$F_o = W_{tv} - W_{sv} \quad (4)$$

If the specific gravity of the produced fluid mixture in the tubing can be estimated, the depth to the working fluid level can be calculated as follows (5):

$$\boldsymbol{L_N} = \frac{F_O}{0{,}433 \, x \, \Upsilon_L \, x A_p} \quad (5)$$

where:

L_N - working or net fluid level from the surface (m)

F_o - fluid load (kg)

Υ_L - specific gravity of the produced fluid

A_p - plunger area (m^2)

This depth should correspond to the one obtained by fluid level measurement conducted simultaneously with dynamometer recording.

The previous calculations assume that the fluid column gradient is estimated based on the density of the produced fluids; they do not account for the possible presence of free gas in the fluid mixture. Figure 7 shows a dynamometer card indicating well operation issues caused by a low dynamic fluid level.

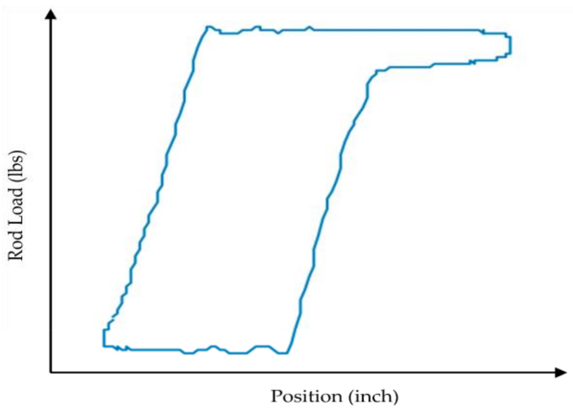

Figure 7 *Dynamometer card showing low dynamic fluid level in the well*

2.6 Optimization of oil production by adjusting pumping speed

The optimal stroke speed is determined using the pump dynamometer card. There are two common types of dynamometer cards used for computerized diagnosis of pumping units: the surface dynamometer card and the pump dynamometer card [28]. The surface dynamometer card represents the load–displacement curve at the polished rod suspension point during the full stroke cycle, but it is often difficult to interpret the downhole pump performance solely from this type of card [29,30].

The pump dynamometer card, on the other hand, represents the load–displacement curve at the downhole pump throughout the stroke cycle. It can be used to diagnose operating conditions of the pumping unit, including pump performance, tubing issues, valve leakage, and produced fluid volume [31]. The area of the pump dynamometer card is one of the most important indicators for determining the effective work applied by the downhole pump and the fluid output of the pumping unit [31,32]. Therefore, the optimal stroke speed can be determined by maximizing the area of the pump dynamometer card.

3 RESULTS AND DISCUSSION

The research was conducted on five wells (V-001, V-002, V-003, V-004, and V-005). All wells showed similar results, and the overall conclusion was consistent across all of them. The results are presented in detail through parameters and operational diagrams of well V-003.

The reciprocating pump was installed at a depth of h = 1439.7 m. From the time the well began operation, the dynamic fluid level remained relatively stable, ranging between L_N = 1213–1310 m, and the pump was a radial type with a volumetric efficiency between 57 – 67 %. Volumetric efficiency represents the ratio between the plunger stroke length and the effective plunger stroke. Due to reduced fluid inflow into the wellbore, the dynamic level decreased to L_N = 1432 m, which is approximately equal to the pump installation depth. The volumetric efficiency dropped to 28%, and fluid production decreased from Q_f = 13.3 m³/day to Q_f = 6.5 m³/day.

By monitoring the well operation in real time, a decision was made to reduce the frequency by 5 Hz, decreasing the rotational speed from 5.3 o/min to 4.7 o/min remotely through the monitoring and control systems (SCADA and AVEVA). The issue was identified through changes in the dynamometer card and by comparing real-time dynamometer recordings. After optimizing the operation by reducing the pumping speed, the volumetric efficiency increased to 70%, while fluid production rose to Q_f = 13.3 m³/day. The dynamic level increased to L_N = 1394 m.

Figure 8 shows the dynamometer card of the pump when the level dropped to L_N = 1432 m. The effective plunger stroke length is visibly reduced, as well as the area of the dynamometer card, which indicates a lack of fluid supply within the wellbore.

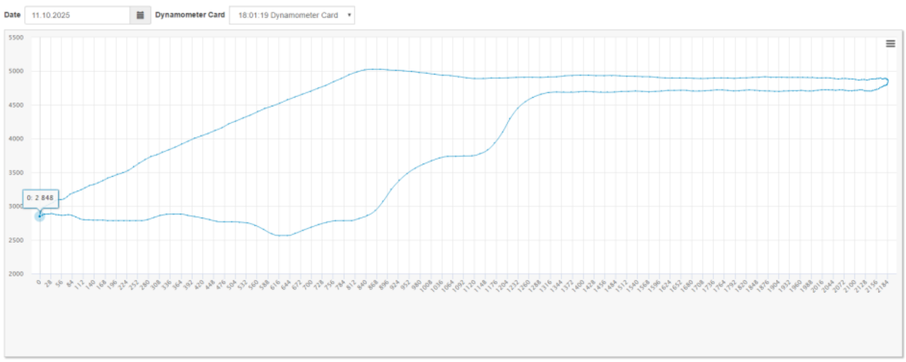

Figure 8 *Dynamometer card recorded before reducing the stroke rate on well V-003*

Figure 9. Dynamometer card recorded after reducing the stroke rate, with the dynamic level rising to L_N = 1394 m.

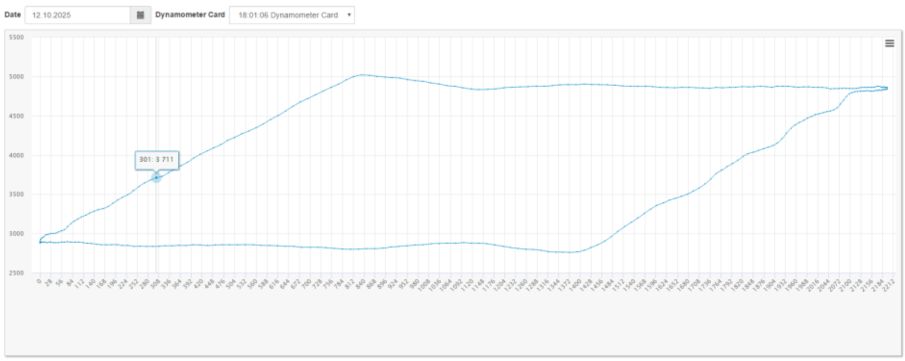

Figure 9 *Dynamometer card recorded after reducing the stroke rate on well V-003*

By reducing the pump stroke rate and frequency, the electrical energy consumption also decreased. Measurements of power consumption before and after parameter adjustment were performed in the field using a PAC 3220 measuring device, and the results were retrieved from the SCADA platform. Table 1 presents the energy consumption before and after the change in stroke rate.

Table 1 *Electrical energy consumption before and after reducing the stroke rate*

	Before		After		Savings	
Well	**Power (kW)**	**Consumption (kWh)**	**Power (kW)**	**Consumption (kWh)**	**kWh/day**	**%**
V-001	2.5	61.2	2.3	55.3	5.9	10%
V-002	2.8	65.0	2.4	57.0	8.0	12%
V-003	1.9	41.0	1.7	38.0	3.0	7%
V-004	3.1	71.3	2.7	65.8	5.5	8%
V-005	3.5	88.0	3.1	81.0	7.0	8%
					Avarage	9%

In Figure 10, a comparative graph of electrical energy consumption for all tested wells is presented.

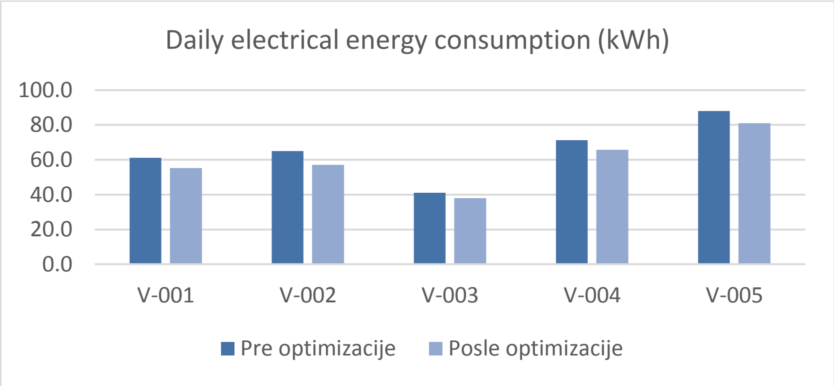

Figure 10 *Comparative chart of daily electrical energy consumption for the tested wells*

Table 2 *Well operating parameters before and after optimization*

	Before				After				Energy savings
	Stroke rate (o/min)	Production (m^3)	Level (m)	Volumetric efficiency	Stroke rate (o/min)	Production (m^3)	Level (m)	Volumetric efficiency	
V-001	4.2	11.4	1210	67%	3.2	10.2	1125	81%	10%
V-002	6.1	16.4	1192	63%	5.6	13.2	1085	75%	12%
V-003	5.3	6.5	1432	28%	4.7	13.3	1394	70%	7%
V-004	3.6	9.5	1120	78%	3.1	12.8	1098	92%	8%
V-005	4.4	11.2	854	62%	3.4	9.4	801	73%	9%

In Table 2, well operating parameters before and after optimization is given and in Figure 11, a comparative graph of daily fluid production for all tested wells is presented.

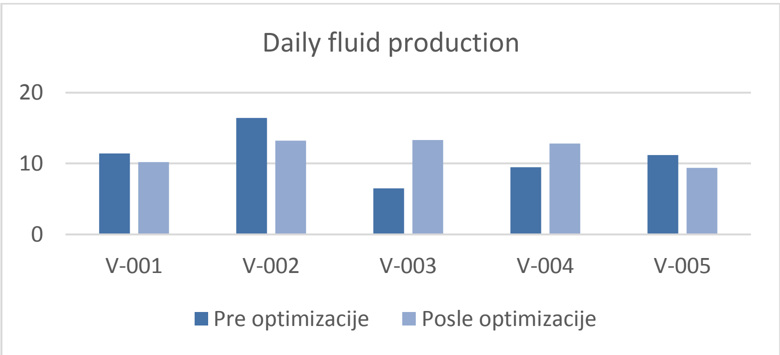

Figure 11 *Comparative chart of daily fluid production for the tested wells*

The results show that all wells achieved measurable energy savings after the stroke rate reduction. The average energy savings among the tested wells were 9 %.

For wells V-003 and V-004, fluid production per day increased even though the stroke rate was reduced. This indicates that volumetric efficiency in these wells significantly improved, meaning that the fluid level rose after the optimization and reached above the pump installation depth.

In wells V-001, V-002, and V-005, daily fluid production decreased by about 15 % on average, but these wells recorded the highest reduction in electrical energy consumption.

All wells demonstrated an increase in volumetric efficiency. After optimization, the pumps operated with a much higher degree of fill, which reduced friction between the plunger and cylinder, extending the service life of the equipment.

4 CONCLUSION

The findings of this research on optimizing oil production using reciprocating pumps through corrective adjustments of operating parameters indicate significant benefits achievable through the application of advanced technologies and methodologies within Industry 4.0. The study analyzed five wells, and the results demonstrated similar trends in efficiency improvement after the implementation of optimization strategies.

One of the main aspects of optimization was the real-time adjustment of pump operating speeds based on the analysis of the dynamic fluid level in wells. Reducing the pump frequency and rotation speed resulted in increased volumetric efficiency and improved fluid production. For example, well V-003, which initially had a problem with a reduced dynamic fluid level, showed a substantial improvement in efficiency after the pump speed was reduced from 5.3 o/min to 4.7 o/min. This corrective action raised volumetric efficiency from 28% to 70%, while production increased from 6.5 m^3/day to 13.3 m^3/day.

The research also revealed a notable reduction in electrical energy consumption. Lowering the stroke rate of the pumps resulted in an average energy savings of 9% across all tested wells, which is significant for maintaining the economic sustainability of oil production operations. Even in cases where fluid production decreased, such as in wells V-001, V-002, and V-005, the energy savings were considerable, demonstrating an overall improvement in operational efficiency.

From a technical management perspective, the results highlight the importance of regular monitoring and maintenance. Automation and the integration of smart technologies allow for faster and more accurate adjustments of operating parameters. The use of SCADA systems and data analytics supports informed decision-making and optimization of working conditions.

Overall, the study confirms that corrective changes in the operating parameters of reciprocating pumps are effective strategies for optimizing oil production. These strategies not only enhance productivity and efficiency but also contribute to reducing operational costs and extending equipment lifespan. Further research and development of new methodologies are recommended to enable greater integration of Industry 4.0 technologies into production processes, leading to improved sustainability and competitiveness in the oil and gas sector.

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