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Utility vehicle with hydraulic transmission and hybrid energy source

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Abstract:

Considering the EU's commitment to achieve climate neutrality by 2050, new tools and investments are needed to achieve this goal. Starting from this goal, the decision was made to develop a hybrid utility vehicle with a multifunctional role, which can also be used in closed spaces such as tunnels or underground parking lots or outside, contributing to the goal of zero carbon emsions. This machine will be the basis for the further development of an electric plug-in machine with increased autonomy. The machine will use a hybrid drive with a diesel engine and an electric motor coupled to a hydrostatic transmission in a closed circuit. The machine can work in heavy environments with a lot of dust, moisture or rugged terrain where the electric motors mounted in the wheel of the vehicle do not give very good results. The traction is done on all four wheels of the machine using wheel hydraulic motors with radial pistons. This type of engine ensures a high torque at low speeds, necessary for the types of work performed. The article presents the structure of this machine, the hydraulic scheme of the actuation, the configuration of the energy group powered by a LiFePO4 battery, through an inverter and the control system of the machine.

Keywords: utility vehicle, hybrid, electric drive, diesel, hydrostatic transmission

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1. Introduction

The main novelty brought by the machine is the proposed hybrid drive. Thus, it is proposed to use a hybrid drive with a diesel engine and an electric motor coupled to a hydrostatic transmission in a closed circuit. In recent years, a number of specialists have carried out research and developed solutions in the field of hybrid machinery. The works concerned the state and development trends, patents in the field and alternative powertrain systems [1-6]. Other authors have made simulations for heavy mobile machinery [7, 8].

Starting from the requirements imposed on the multi-functional machine with zero carbon emissions for working in closed spaces, the solution of a hydrostatic actuation system with a hybrid energy source was chosen, which allows the machine to be used even after discharging the batteries. The hydrostatic system can be driven, according to requirements, with the internal combustion engine or with an electric engine as the energy source. The main technical characteristics of the machine can be found in Table 1.

The machine can work in heavy environments with a lot of dust, moisture or rugged terrain where the electric motors mounted in the wheel of the vehicle do not give very good results. The traction is done on all four wheels of the machine using wheel hydraulic motors with radial pistons. This type of engine ensures a high torque at low speeds, necessary for the types of work performed. The steering is also done on all four wheels, thus ensuring very good maneuverability, necessary for fast maneuvering. Braking is hydrostatic by reducing the flow of the pump. The car is also equipped with a normally closed parking/emergency brake, also hydraulically operated.

At the front and at the back, the machine is equipped with hydraulic couplings that allow the attachment of different hydraulic equipment.

The machine can carry out snow removal, washing, cutting vegetation, spreading non-slip material etc. for concrete platforms, and can be equipped with equipment such as cleaning brush, arm for cutting vegetation, bucket, front loader etc.

Equipment assembly can be done very easily, the machine being equipped with a standardized front fixing plate according to SR EN 15432-1:2011 and with quick hydraulic couplings for connecting the hydraulic motors from these equipments.

Table 1. Technical data

Vehicle mass	6000 kg
Electric motor power	30 kW
Diesel engine power	50 kW
Fuel tank capacity	60 l
Battery pack capacity	30 kWh
Maximum speed – working regime	7 km/h
Maximum speed – travel regime	15 km/h
Maximum traction force	30 kN

2. The structure of the utility vehicle

Two identical pumps coupled with internal combustion engine and electric motor are used thus eliminating the need to use complicated mechanical transmissions. In the papers [9-12] the authors analyzed conversion and integration technologies based on hybrid power systems, the electrification of power trains for mobile and agricultural machinery and analyzed the design and performances of the electro-hydraulic hybrid transmission system.

In the Fig. 1 can be seen the main components of the new developed machine such as: pump driven by electric motor, pump driven by diesel engine, air/hydraulic fluid cooler, hydraulic fluid tank, fuel tank, vehile cabin and wheels with hydraulic motors inside.

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The hydraulically operated mechanisms of the machine are:

- the movement mechanism, which ensures the movement of the vehicle through the 4 rotary motors with radial pistons located in the wheels, these operating in a closed circuit;
- the steering mechanism (Fig. 2), consisting of a power steering, 4 hydraulic cylinders that act to change the position of the wheels according to the direction of the turn, and 2 directional valves with electric control, thus obtaining a very good maneuverability of the 4 wheels;
- removable equipment with hydraulic actuation, intended for various maintenance works (bucket, crane etc).

Fig. 3 shows the configuration of the car's hybrid drive system. By means of some electrohydraulic directional valves, the hydraulic circuits are switched to the pump driven by the electric motor or to the pump driven by the thermal engine.

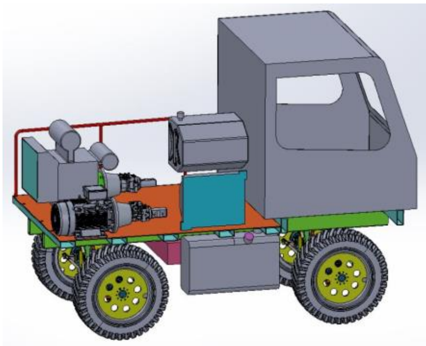

Fig. 1. 3D view with the layout of the main components of vehicle

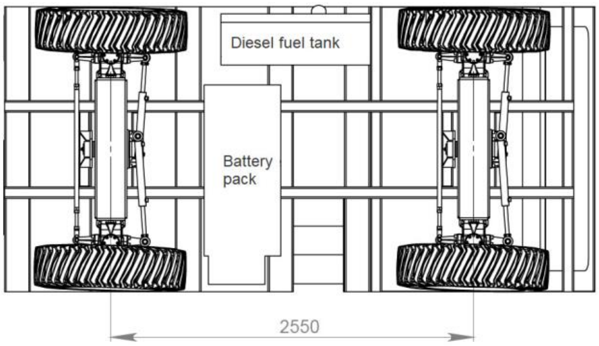

Fig. 2. Bottom view with the front and rear axles and steering mechanisms

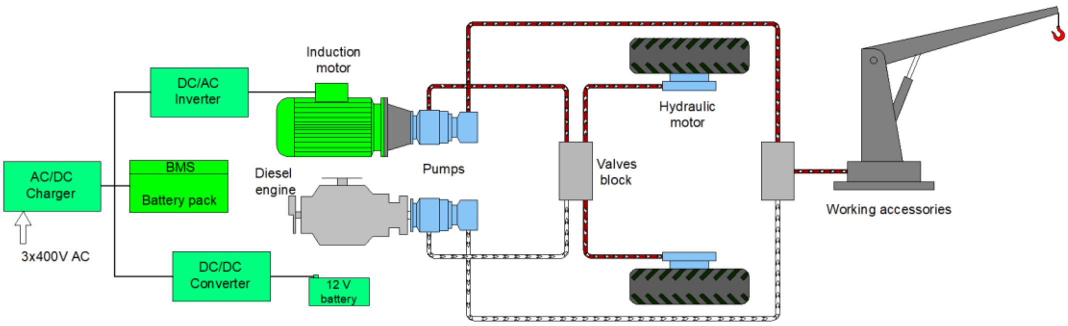

Fig. 3. The configuration of the machine hybrid drive system

3. Hydraulic drive system

The hydrostatic drive system can be activated, according to requirements, with the thermal engine or the electric engine as the energy source. Each energy group (Fig. 4) consists of: drive motor, which can be thermal – DIESEL, type Perkins 904J-E28t, N = 50 kW, or electric, N = 30 kW; pump with axial pistons (1) from Poclain company, equipped for operation in closed circuit.

The hydraulic diagram of the actuation system highlights the ease with which the two pumping groups, electrically or thermally actuated, can be coupled to the closed circuit of the rotary hydraulic motors that make the movement; each pumping group has in its component, apart from the pump with adjustable axial pistons, also a double pump (2) with toothed wheels mounted in tandem, which ensures the supply of power steering and auxiliary equipment that can be attached through quick couplings after they have been mounted on machinery.

The POCLAIN type axial piston pump is equipped to operate in a closed circuit. The closed circuit requires the existence of a valve to ensure the maintenance of the temperature and cleanliness of the oil within the recommended limits; the VS directional valve, hydraulically controlled, ensures the extraction of a quantity of hot oil from the low pressure branch which is sent to the auxiliary tank for cooling and filtering. To protect the environment in case of hydraulic fluid losses, biodegradable lubricant designed for hybrid vehicles can be used [13].

The auxiliary pump attached to the main pump (located in its casing) must ensure the necessary flow rate to compensate for the cooling and filtering fluid extracted by the VS directional valve, for internal or external losses from the devices and for feeding the control system, without exceeding the value of the allowed pressure.

The high-pressure valves ensure the pressure in the circuit at the required value; the check valves allow the charge flow to refill the low pressure line. The overpressure valves ensure the protection at transient high values of the high pressure loop of the circuit.

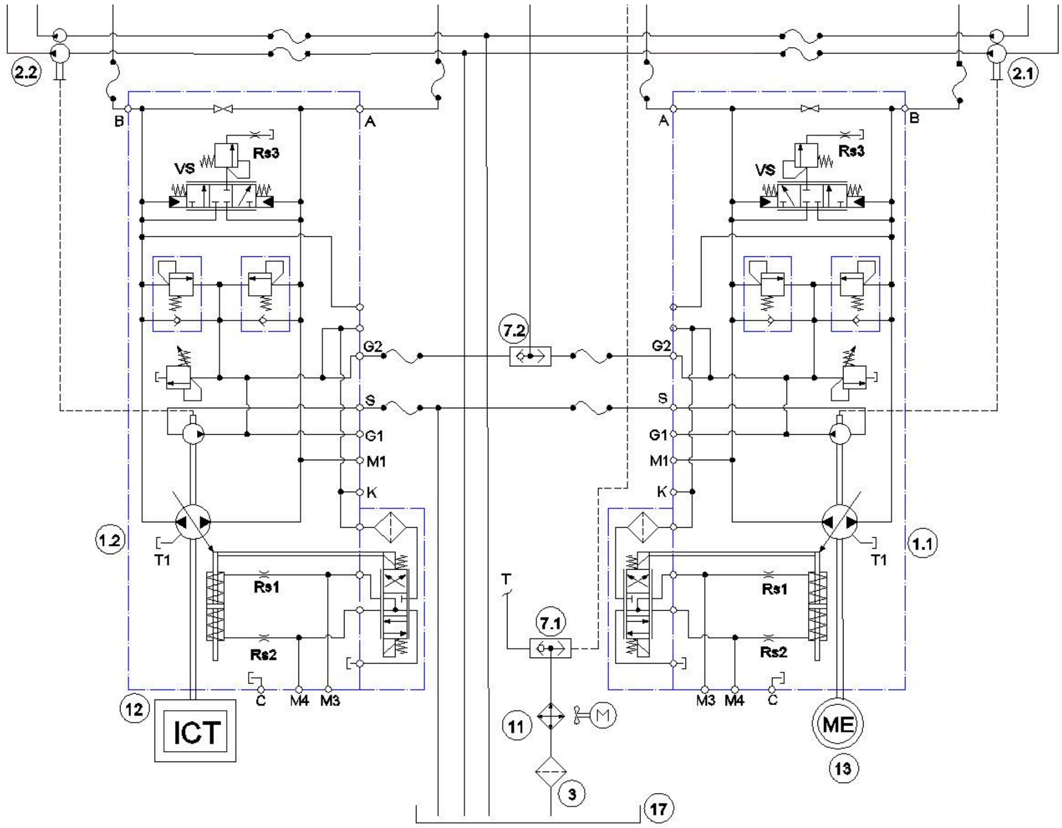

Fig. 4. Internal combustion and induction motor energy groups

These valves are not adjustable, but can be requested to be set. Flowing for a long period of time through these valves leads to excessive heating of the hydraulic fluid, which can cause damage. The related valve of the auxiliary pump ensures the loading pressure, and choosing the correct adjustment value ensures the maintenance of the pump's performance.

Adjusting the flow by changing the angle of inclination of the pump swash plate is done by applying a control current to the electro-proportional solenoids that control and adjust the pressure in the servo-control system. The flow direction depends on the activated solenoid. The reaction time can be controlled by ramps installed on the electronic control unit and by the restrictors Rs1 and Rs2 inserted between the servo control and the hydraulic servo piston. The feedback function is realized by a lever that connects the oscillating plate and the hydraulic servo piston. The presence of the two restrictors Rs1, Rs2 ensures the avoidance of sudden accelerations and stops.

In the hydraulic diagram in Fig. 4, there are also: the return filter (3), selection valves (7) which directs the flow depending on the supply source, the air-oil cooler (11), the thermal engine (12), the electric motor (13) and the hydraulic fluid tank (17).

In the Fig. 5 one can see the rotating hydraulic motors (5) mounted in the wheels of the type with radial pistons, from POCLAIN (MGE05-2-A04-101-1W20-EJ00), which can operate in two speed steps, corresponding to the two capacities, 374/749 cm^3/rot. The speed synchronization of the four rotary motors is obtained using a flow divider (4), type FD-M4-POCLAIN, which is a four-way flow divider that ensures the parallel operation of the wheels on the same axle or on different axle by dividing the debit. It can work in closed or open circuits. It is equipped with a by-pass with normal opening that can be controlled electrically, VS1 and VS2. The distribution of the flow is done in two stages; first in two equal parts and then each of them in two other, equal parts, obtaining the four equal supply flows of each hydraulic motor. The divider includes the safety valves of each direction of rotation as well as the capacity change command; its modification is ordered with the help of directional valves VS1 and VS2. The coupling of the used pumping group - thermal or electric - to the circuit of the rotary motors (5) is carried out with the help of directional valves (8) (8.1 for electric drive, 8.2 for internal combustion drive) for forward movement; for going backwards, changes the discharge direction of the pump so that on the path T - A circulates the flow necessary for the hydraulic motors to achieve the speed of going backwards, this being possible because the directional valves (8) allows a pressure of up to 350 bar on the T-A circuit.

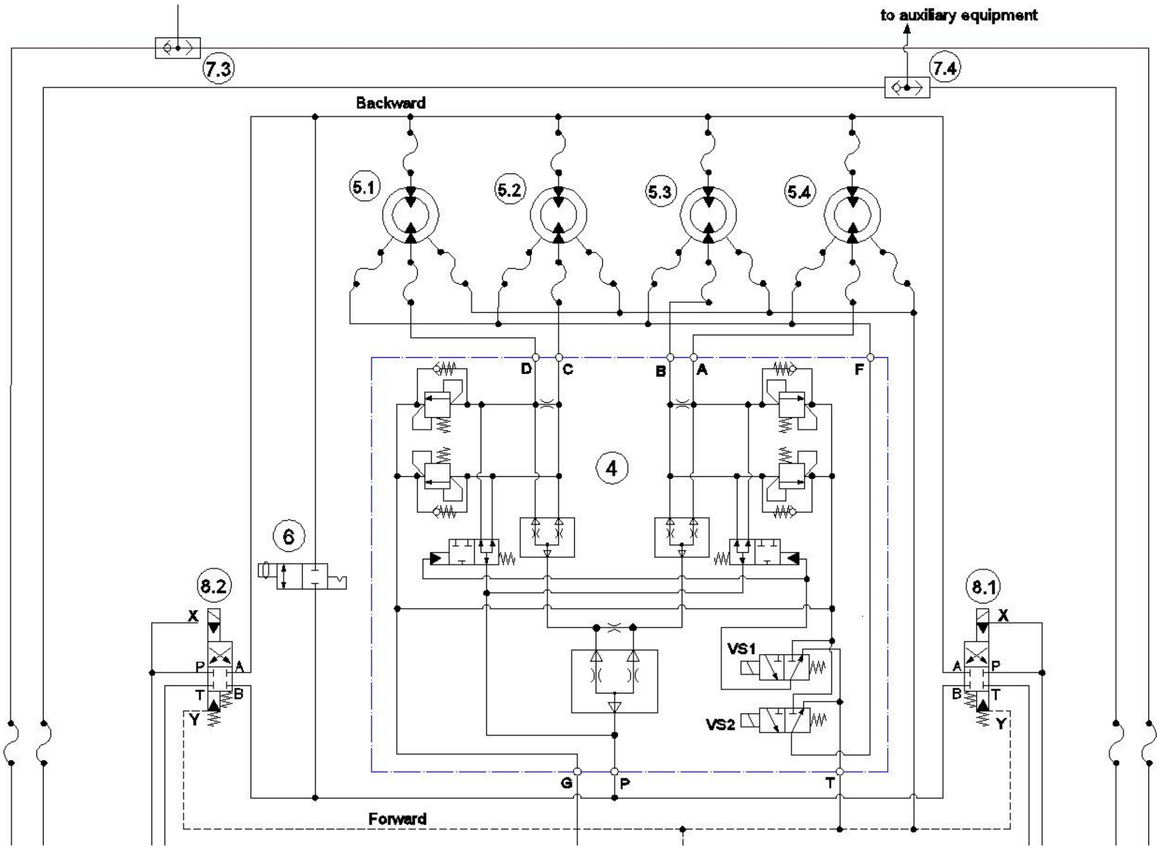

Fig. 5. Hydraulic scheme for driving hydraulic motors mounted inside wheels

In the Fig. 6 the directional valve (6) is used for emergency situations when the machine must be towed. The steering mechanism of the machine is made up of power steering (9), 4 hydraulic cylinders (10.1)÷(10.4) and two electrically controlled 4/2 directional valves (14), (15). For moving forward and turning with the two wheels from the front, power steering feeds cylinders (10.1) and (10.2); when you want to turn as small as possible, in which all 4 wheels of the machine are used, directional valve (14) is switched, and for sideway "crab walk" both directional valves, (14) and (15), are switched.

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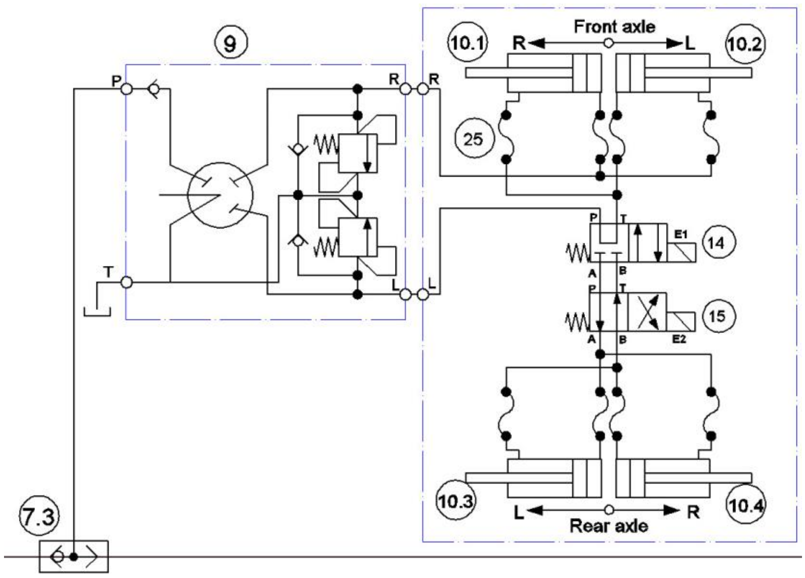

Fig. 6. Scheme of the power steering system

4. Electric drive system

The electric drive system of a hybrid utility vehicle uses a 30 kW electric motor powered by a 30 kWh battery pack through a motor controller. The electric motor drive a Poclain pump with axial pistons equipped for operation in closed circuit. The batteries can only be charged from the mains, and in case of discharge, the diesel engine is used until reaching the garage for recharging. The diesel engine can also be used in winter conditions when the capacity of the batteries is reduced due to low temperatures. The electric drive of the machine is made with a three-phase electric motor specially designed for power supply with inverters and which resists higher voltage spikes without insulation failure (Fig. 7).

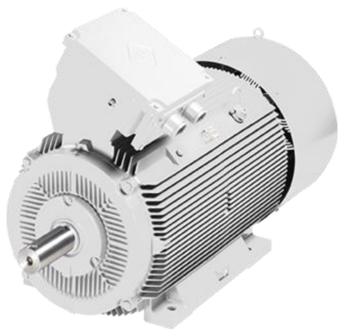

Fig. 7. Inverter fed induction motor

These motors are designed to handle lower speeds without overheating. In the case of this machine, there is no need to control the speed of the electric motor, which drives the hydraulic pumps, in a wide range, because the control of the machine's movement speed is done by the continuous variation of the pump flow rate.

The adoption of electrification and hybrid drives can contribute to increasing the energy efficiency of machinery [14]. An important problem with hybrid machinery is the energy storage systems and battery life [15, 16]. For machines that lift loads such as cranes or loaders or in the case of braking, energy recovery systems can be adopted [17, 18].

The charging of the battery pack (Fig. 8) is done by means of a charger on board (Fig. 9) which allows connection to the single-phase or three-phase electrical grid, and a DC/DC converter is used to charge the machine 12 V battery. The characteristics of the battery pack can be seen in the Table 2.

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Fig. 8. Battery pack for mobile machinery from Aliant

Fig. 9. On board battery pack charger

Aliant battery pack has the main Features:

- Embedded battery management system (Pegasus proprietary)
- Integrated data logger
- USB port for diagnostic
- Parameters communication
  - SoC – State of Charge
  - SoH – State of health
  - Imax – Maximum current
  - Vnom – Nominal voltage
- Dedicated temperature management system
- Cells protection
  - Overcharge
  - Deep discharge
  - Short circuit
  - Maximum current delivered
- Optional ventilation system IP54 / fanless IP65.

Table 2. Battery pack characteristics

Energy installed	Useful Energy 80% DoD	Nominal Voltage OCV	Continuous discharge current
37632 Wh	30100 Wh	358 V nominal 20-80% SoC	105 Amp
Continuous charging current	**Max charging current**	**Gross weight**	**Dimensions [mm]**
105 Amp up to 80% SoC	210 Amp @25°C 5 Min 315 Amp@25°C 30 Sec Depending on SoC and Temp	310 kg	540x1400x250
Peak Discharge 30s	**Energy Density**	**Temperature**	**Protection degree**
210 Amp	120 Wh/kg	Discharge -30°C/60°C Charge -30°C/55°C Storage -20°C/35°C	IP54/IP65

DoD – Deep of discharge

OCV – Open-circuit voltage

Powering the electric motor is done with a controller produced by the company Inmotion type ACH (Fig. 10).

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Fig. 10. Motor controller from *Inmotion*

The features of the motor controller are:

– Nominal voltage 350 / 650 V
– 4-quadrant, synchronous or asynchronous AC motor control, with speed, torque and DC voltage control modes
– Standard firmware with extensive configurability
– Application software can be configured
– Internal DC EMC filter with common mode and differential mode reduces high frequency electromagnetic interference and el iminates DC bus oscillations
– The DC EMC filter allows for free cable lengths and parallel operation of several ACH controllers and auxiliary equipment
– Vector control, adjustable for different motor types

Fig. 11 shows the block diagram of the machine's command and control system. The system uses a PLC for the management of all the car's electrical equipment. Through digital inputs, the PLC receives commands from the various buttons on the car's board to activate the solenoid valves of the hydraulic systems, to start the electric motor, activate the lights, etc. The digital outputs of the PLC effectively control, by means of relays, the solenoids of the hydraulic valves, the hydraulic fluid cooling fan, the indicator lamps, the solenoids of some relays of consumers on board etc. The pressure and temperature sensors in the hydraulic circuits, the voltage of the 12 V car battery and the control levels of the inverter and variable capacity pump controllers are monitored through the analog inputs.

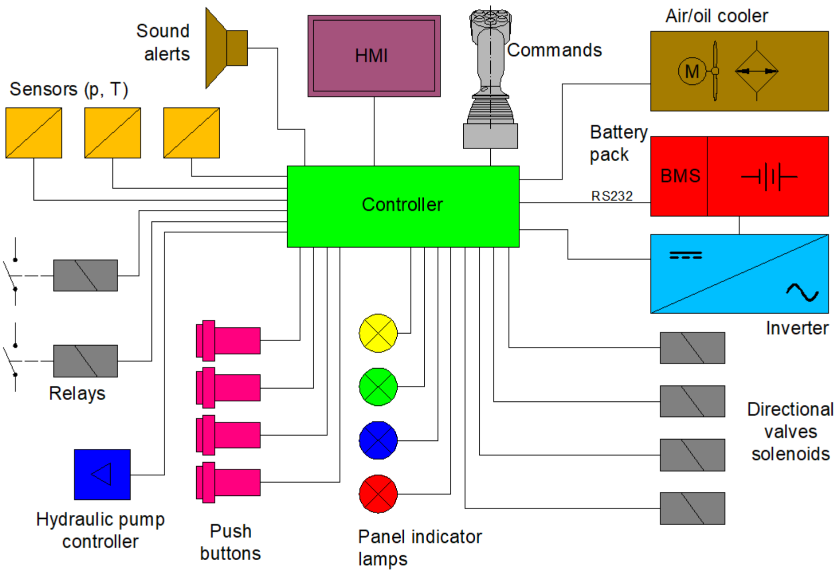

Fig. 11. The block diagram of the utility vehicle command and control system

Analogue outputs of the PLC, control the hydraulic pump controllers and the frequency of the inverter. Through a serial communication, information is received about the state of charge (SoC), voltage and temperature, as well as alerts from the battery management system (BMS) of the battery pack. Some information of interest is accessible to the driver, and others can only be visible when the machine's service mode is activated.

In works [19, 20], the authors studied and tested systems and strategies of control for hybrid machinery. Through the human-machine interface (HMI), the driver can view information, during the operation of the machine, regarding the status of the controls, the operating mode, the power used by the electric motor, the charging status of the battery and the temperatures of: ambient, electric motor, diesel engine, battery pack and hydraulic fluid. In the PLC program, a series of automations are also realized, for example hydraulic fluid thermostating, thresholds regarding audio and visual alerts related to temperatures, pressures, SoC etc. Interlocks are also implemented in the PLC so that some commands cannot be overlapped, which can lead to the failure of some equipment.

5. Summary

The vehicle can be supplied with power from an electric motor and an internal combustion engine, and the battery can only be charged from the grid.

The vehicle can be used in spaces where should not be polluting emissions such as tunnels without forced ventilation, underground parking lots or other areas.

The vehicle can be the basis for a further development of a full electric utility vehicle with greater autonomy.

Auxiliary equipment with hydraulic actuation can be mounted on the vehicle to carry out various works.

The electrical installation is modern, being based on a programmable controller that fulfills multiple functions.

Acknowledgements

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Just transition of post mining areas – technical, economic, environmental and social aspects

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Abstract:

The article is a review of papers, presentations, expert opinions concerning a just transition of post-mining areas in the light of technical, economic, ecological and social aspects, which were the subject-matter of the International Scientific-and-Technical Conference, organized by the KOMAG Institute of Mining Technology in Gliwice, Poland and the IHP Hydraulics and Pneumatics Research Institute in Bucarest, Romania. The Conference participants concentrated their discussions both on the social effects of transition, on the economic aspects of activities concerning a collaboration of circummining companies as well as on technical and technological challenges in the mines already closed down or in those which are currently subject to the closing-down processes. Some possibilities of a reorientation of the mining plants towards generating and storage of green energy were presented. It should be borne in mind that a transition of the European Economy in the direction of more green and climate friendly is one of the most important objectives determined by the European Union. In particular, it is a big challenge for mining regions such as Silesia in Poland. The transition process includes a liquidation of underground workings and of the surface infrastructure and a series of indispensable activities oriented onto a restoration of the natural environment and a protection of mining plants areas against hazards which may occur after a termination of their operation. The article is ended with some information concerning a role research institutes in the just transition of post-mining areas and a new strategy of KOMAG as GREEN INSTITUTE.

Keywords: just transition, post-mining areas, challenges, mines, closing-down process, green energy storage, green deal, green institute

1. Introduction

At present the world is tragically effected not only by a crisis of safety and security, but an energy, economic and ecological crisis as well. We live in a very sensitive, break-through moment. Representatives of science often exchange views on the role of research organizations, in particular research institutes in the transition processes. They are responsible for an intensive search of innovative technical and technological solutions, not forgetting about new organizational solutions. As research institutes are a sort of bridge between science and industry, so they are expected to create innovations in close collaboration with business partners oriented onto industrial, climatic, energy and IT challenges. The KOMAG Institute of Mining Technology organized the International Scientific-and-Technical Conference on the just transition of post-mining areas to create a forum enabling an exchange of knowledge and experience among scientists, researchers, politicians, businessmen, representatives of local authorities and of mining plants. During the conference there was also a possibility of taking advantage of several European countries' experience in the scope of reducing a production of electric energy from hard and brown coal, according to the guidelines of the Green Deal and according to the recommendations of the process stake-holders.

The papers, presentations and discussions concentrated on the following subjects:

- Social-and-economic aspects of just transition of post-mining areas.
- Principles of transition in the light of green deal requirements.
- Advantageous factors and barriers of just transition.
- Management of post-mining areas.
- Production of green energy, its storage and management.
- Generation of new work-places and a search of market niches.
- Management of just transition processes on local and regional levels.
- Determination of just transition principles and a formulation of recommendations for different groups of stake-holders to obtain a social approval of planned changes.
- Designing and construction of equipment for a protection of underground mine workings against hazards.
- Possibilities of mining technologies transfer to foreign markets.

It should be borne in mind that the mechanism of just transition is a key tool enabling to introduce climate neutral economy in an efficient, society and environment friendly way. Just transition creates chances for local and regional development, a chance for investments in renewable sources of energy, for gaining new markets connected with green power generation, energy storage or sustainable transport. It is also a chance for increasing economic potential of post-mining areas, for a remediation of damaged areas in the result of mining operations and for a reduction of a negative impact of industry on inhabitants of these areas. The Conference was oriented onto a presentation of the Silesian Region potential, in particular in the scope of industry, scientific and research institutions as well as human resources.

The presentations were based on several publications [1-4], concerning the state's energy policy in the direction of the energy and fuel sector development, the effect of energy transition on the labour market, a contextual understanding of regional energy transitions in Europe as well as decarbonization processes. The reclamation of post-mining areas as well as the restoration of abandoned land and post-industrial sites were the subject-matter of international discussions [5]. These processes consist of creating a new land use pattern and giving new functions to areas degraded by the industry. In the case of mine closure it is particularly important to create new work-places for ex-miners [6] as well as to analyze the potential of regions, where mining is concentrated, to adapt to closure given the regional assets [7]. As regards energy storage different systems were discussed [8-10]. In the following part of this article there will be some information about hazards which may occur in mines subject to closing down processes [11]. During the Conference a lot of attention was paid to the EU citizens' perception of renewable energy transition amidst the European Green Deal and to energy transition scenarios [12, 13]. It was interesting to get some information about the assessment of renewable energy sources (RES) in Poland against the world renewable energy sector [14, 15].

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2. Thematic scope of selected papers and presentations

2.1. Diversification of energy security – world megatrends

Mr. Piotr Pyzik, Under-Secretary of State in the Ministry of State Assets, Government Plenipotentiary for the Transformation of Energy Companies and Coal Mining Industry concentrated his presentation on geopolitical conditions, confirming the world megatrends in the scope of energy security. This phenomenon is closely connected with a dissemination of renewable energy sources, a creation of local energy societies and energy storage systems and more and more advanced systems of energy management, integrating the power generating sources on local levels. The Conference programme included the discussion panel "Poland – Africa – strategic cooperation between the mining sector and RES" which seems to be of particular importance in the light of the European Union policy. The European Commission signed a contract with the African Union, allocating 150 billion Euros for a support of EU countries participating in development projects in Africa. Minister Pyzik expressed his joy and satisfaction that KOMAG, as the first Polish institution, decided to join the European Association for Storage of Energy (EASE). In his opinion it is a new functional perspective not only for Silesia but for our country. He congratulated the KOMAG Management and Employees on the initiative of establishing the "Institute of Green Transition", integrating Silesian scientists and researchers. He wished further successes in an implementation of the fourth industrial revolution in mechanization, electrification, IT and automation of the ECONOMY 4.0. This presentation was finished with best wishes for all the Conference Participants. He wished them fruitful deliberations and interesting discussions enabling to find lingua franca.

2.2. EU policy of importance to the coal and lignite mining regions

Mr. Brian Ricketts, Secretary-General of the EURACOAL Association for Coal and Lignite represented members from fourteen countries, including many from Poland. He started his presentation with describing the situation for coal and lignite in Europe (Fig. 1). Then he discussed the production of hard coal in the EU over the years 1990-2021 (Fig. 2).

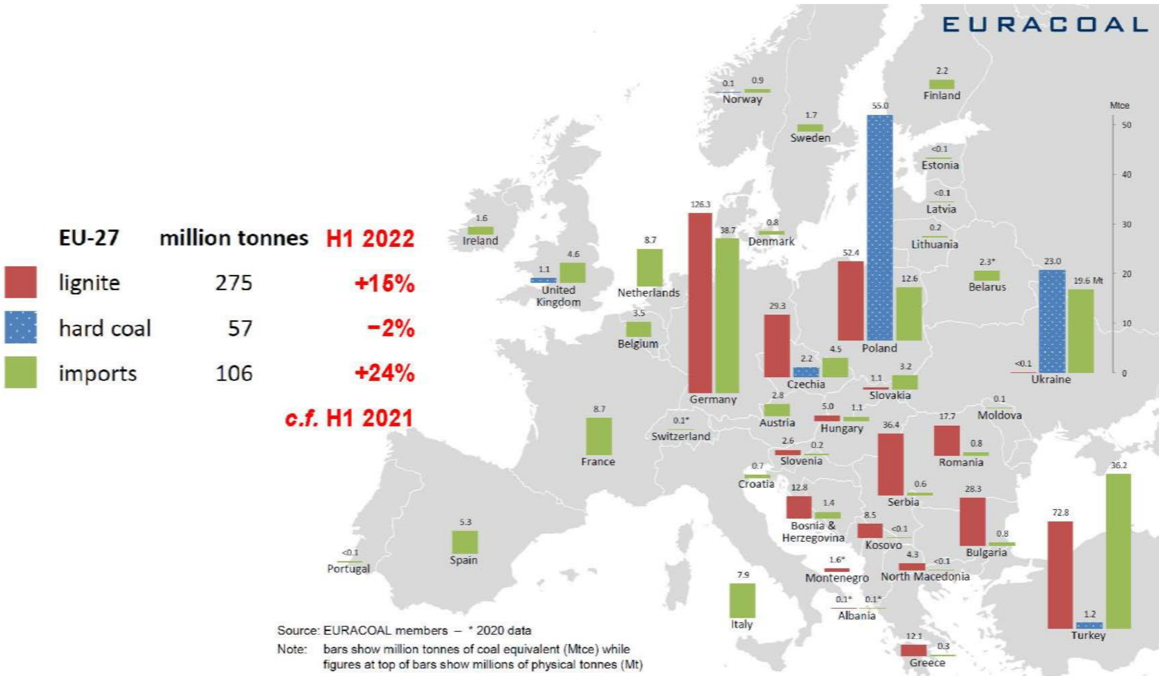

Fig. 1. Coal in Europe 2021 – lignite production, hard coal production and imports

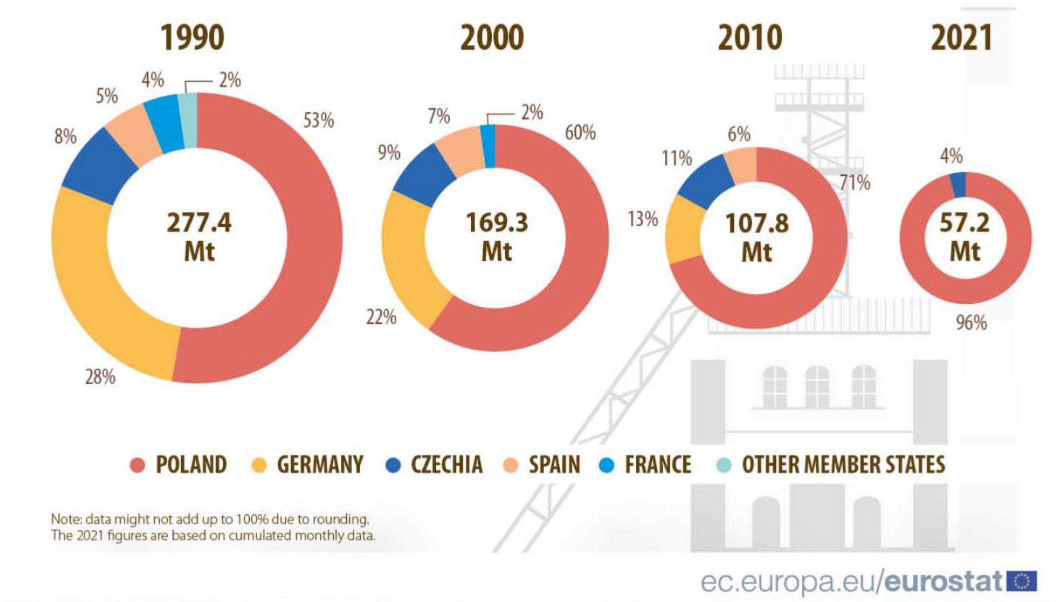

Fig. 2. Production of hard coal in the EU over the years 1990-2021 (million tonnes)

The European Commission remains committed to the European Green Deal and the 55% GHG emission reduction target for 2030 as laid down in the European Climate Law which came into force in July last year. The so-called Fit-for-55 package has yet to be adopted. It should be highlighted that the share of coal and lignite in power generation was around 17% in 2019, way less than the global average of 38% (Fig. 3).

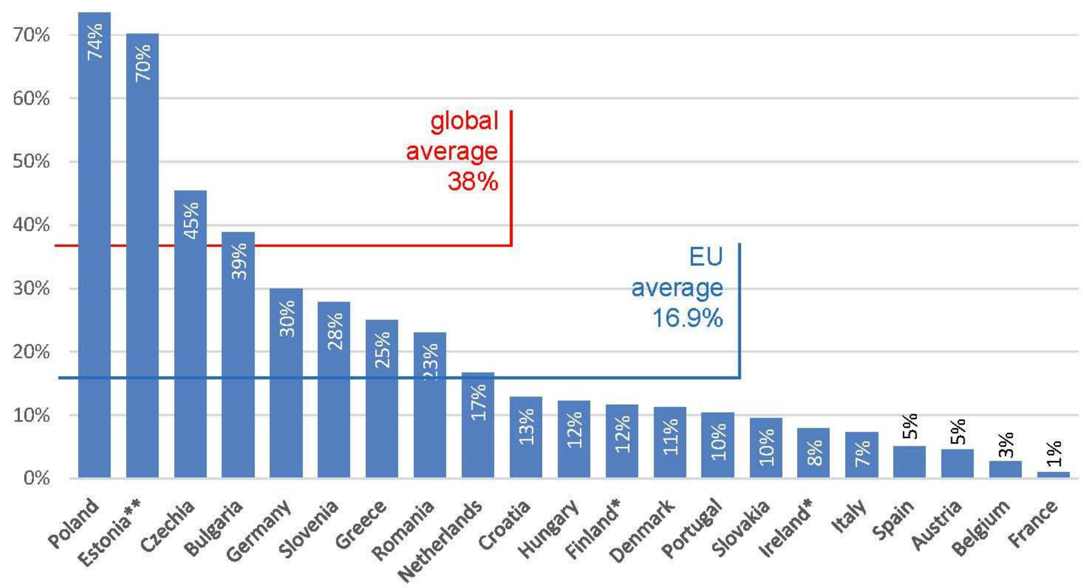

Fig. 3. Coal in EU electricity generation, 2019

The historic trend of declining coal production in Europe will not change (Fig. 4). The graph shows the evolution of coal as it powered the Industrial Revolution in Europe with some global events that changed the course of an otherwise perfect bell-shaped “Hubbert curve” – the symmetrical, logistic distribution curve for the production of any finite resource exploited in a free market economy.

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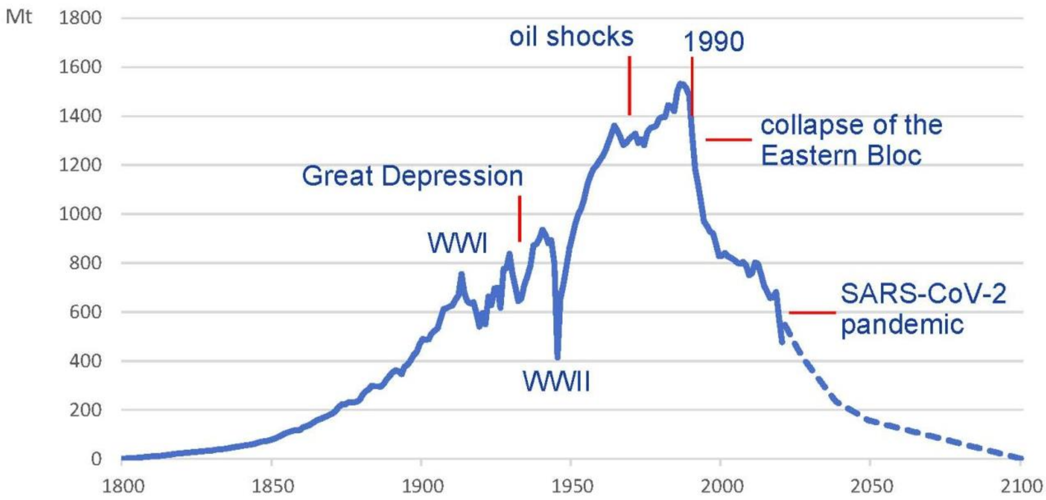

Fig. 4. European coal production 1800-2020 and forecast to 2100

Under the Green Deal, the European Commission offers a "just transition" for coal miners. The Just Transition Fund is a useful first step but nobody knows what will happen after 2027 – the end of the current EU budget. PGG, the Polish Mining Group, alone would need about 40 billion EUR to complete the transformation of its business activities to capitalise on the value chains in the coal regions.

Mr. Ricketts mentioned the EU Research Fund for Coal and Steel. It is a solid source of funding for coal-related research projects.

In conclusion he said that the coal industry was doing everything possible to guarantee Europe's energy security at a price citizens could afford.

2.3. Transition of post-mining areas on the example of the Ruhr Region

The presentation, given by Dr. Krzysztof Tajduś from the Institute of Rock Mechanics of the Polish Academy of Sciences, was oriented onto the decarbonization processes undertaken in Germany over the years 1957-2018. The following four maps show the changes in detail (Fig. 5, 6. 7, 8).

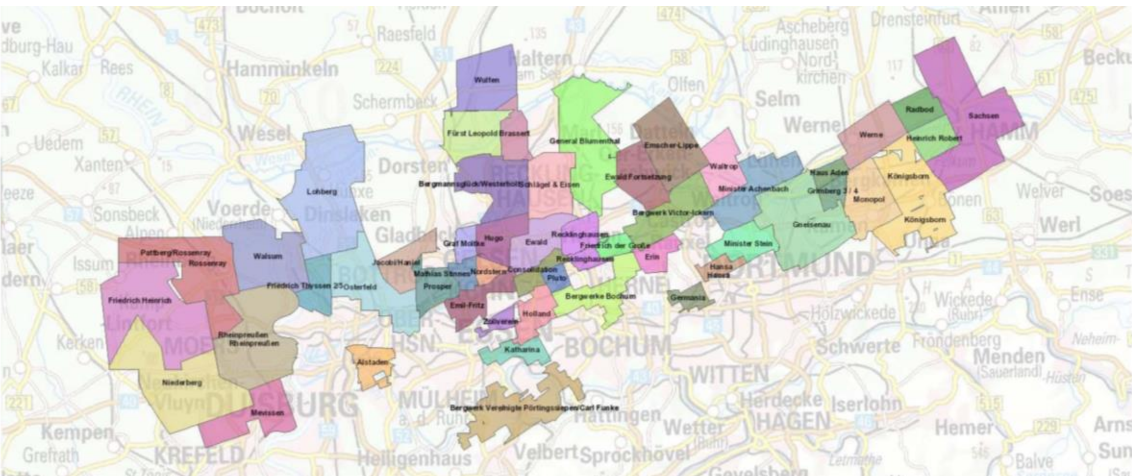

Fig. 5. Active coal mines in Germany in 1969 (Source: Prof. Anton Sroka's presentation at the meeting of the Mining Committee of the Polish Academy of Sciences)

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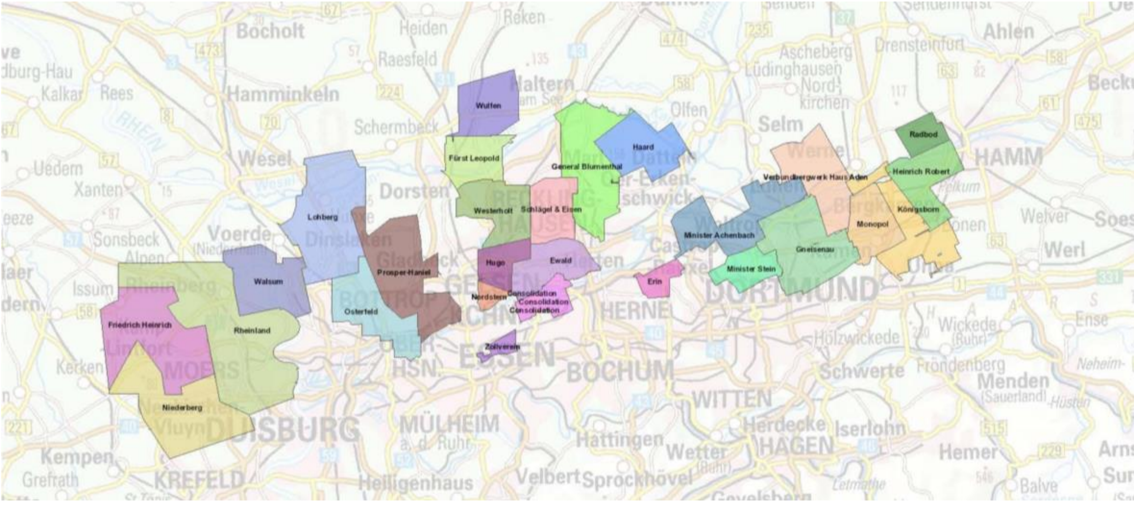

Fig. 6. Active coal mines in Germany in 1980 (Source: Prof. Anton Sroka's presentation at the meeting of the Mining Committee of the Polish Academy of Sciences)

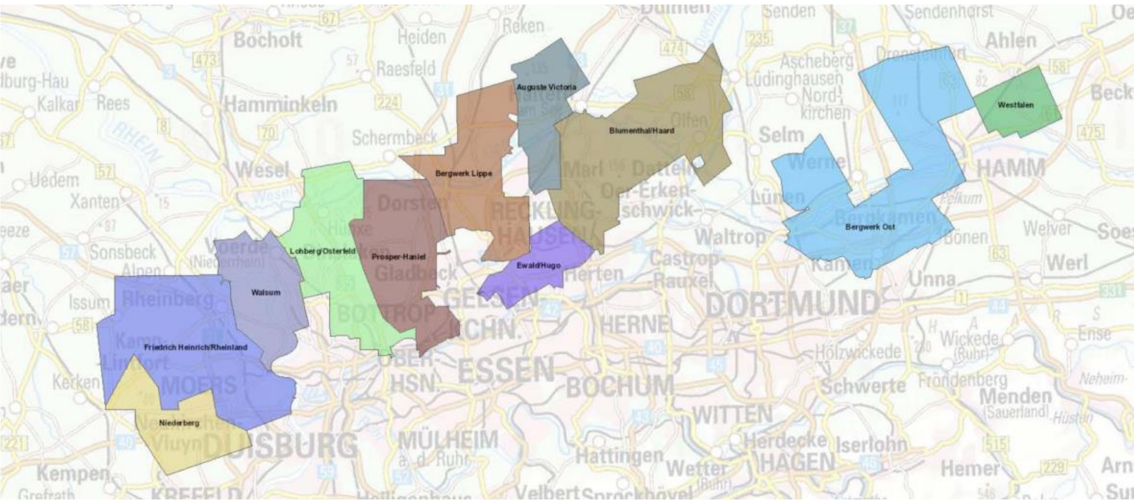

Fig. 7. Active coal mines in Germany in 2000 (Source: Prof. Anton Sroka's presentation at the meeting of the Mining Committee of the Polish Academy of Sciences)

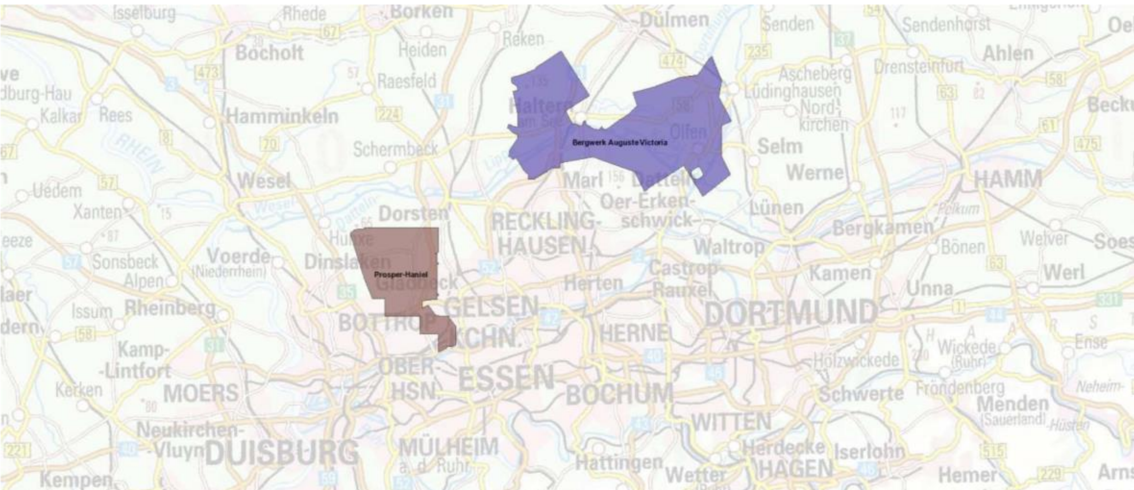

Fig. 8. Active coal mines in Germany in 2015 (Source: Prof. Anton Sroka's presentation at the meeting of the Mining Committee of the Polish Academy of Sciences)

It should be highlighted that in 1957 there were 173 active mines, employing 607.3 thousand people, producing 149 million tonnes of coal; whereas in 1970 – 69 active mines employing 253 thousand people, producing 111 million tonnes; in 1980 – 39 active mines, employing 186.8 people, producing 87.9 million tonnes; in 2000 – 12 active mines, employing 58.1 thousand people, producing 34.3 million tonnes and in 2015 – 3 active mines, employing 9.6 thousand people and producing 6.4 million tonnes (Fig. 9).

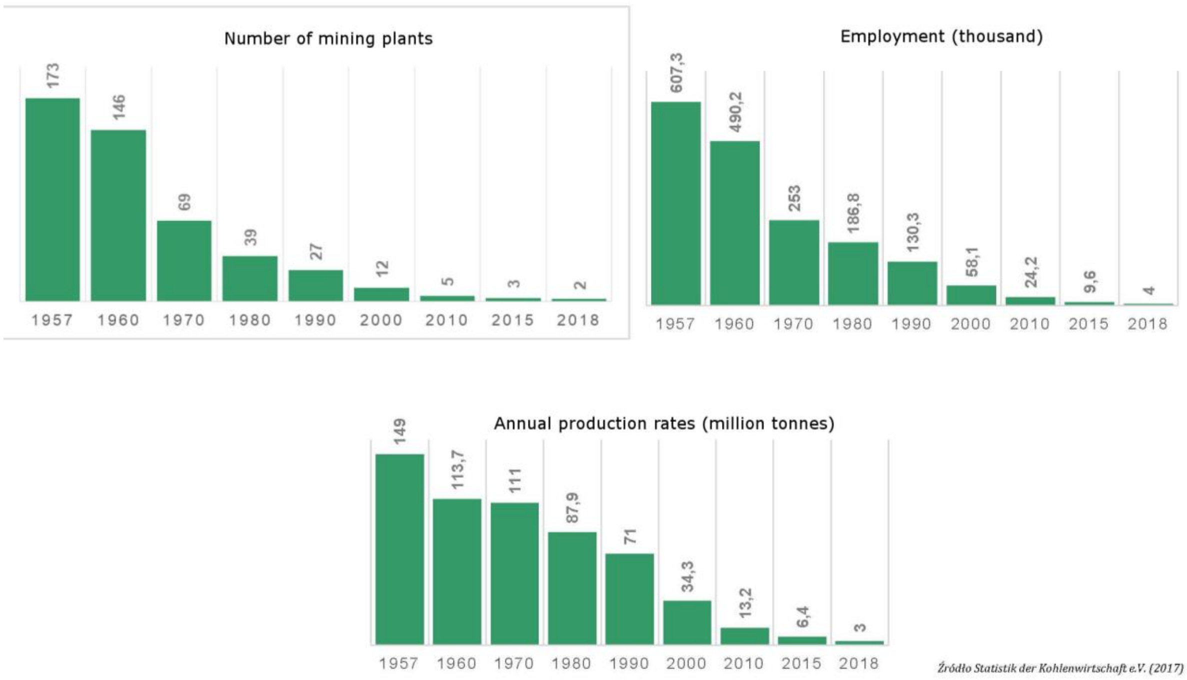

Fig. 9. Transition of the German mining industry over the years 1957-2018 (Source: Statistik der Kohlenwirtschaft e.V. 2017)

All the transition processes were planned and conducted by the RAG (Ruhrgebiet Aktiengesellschaft) established in 1960. In 2018 the subsidies for the mining processes ended and in 2019 the post-mining era started. All the RAG development stages are shown in Fig. 10.

Fig. 10. Development of RAG and its role in the transition processes (Source: RAG)

Since 2016 RAG has started the transition process from the production phase over the years 2016-2018, through the extinction phase over the years 2019-2021 to the eternity phase since 2022, (which is shown in Fig. 11).

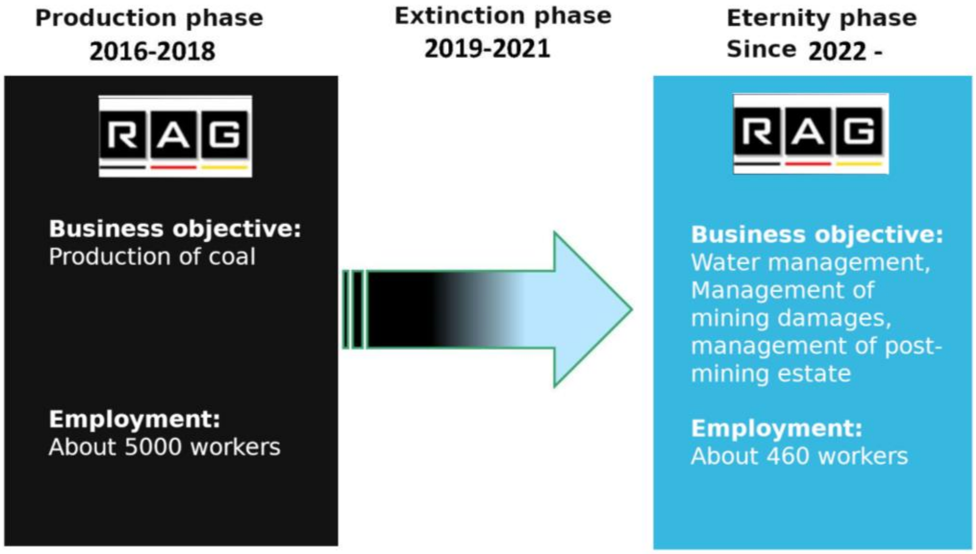

Fig. 11. Schematic diagram of transition processes conducted by RAG since 2016 up till the present time (Source: Krzysztof Tajduś's presentation at the Conference)

Analyzing the transition processes, undertaken in the German mining industry, it is worth specifying the milestones which are as follows:

- Innovativeness consisting in interdisciplinary use of the potential of universities and scientific institutions.
- A realization of programmes supporting a creation and development of the state-of-the-art technologies.
- A support of different branches and domains such as health, transport, energy and logistics.
- A use of highly developed infrastructural network such as motorways, railway systems and airports.
- An implementation of new production methods.
- A use of mining infrastructure for a development of state-of-the-art power generation technologies including photovoltaic installations on mine waste dumps, heat recovery from mine water, wind turbines on mine dumps, energy from methane, biomass, pumped-storage power stations, geotherms.

A realization of the above mentioned milestones required a reorientation of the structural policy to achieve the following objectives:

- An increase of the local identity.
- A use of mine estate for cultural institutions such as museums, centres of culture etc.
- An improvement of inhabitants' standard of living.
- A use of multi-national potential for international contacts.
- A preparation of highly-qualified personnel enabling to meet the requirements of new enterprises in the region.
- A maintenance of development unity of all the communes in the post-mining areas – the union of Ruhr Basin.

The presentation was ended with a case study concerning the Ewald mine.

2.4. Social-and-economic conditions of the transition in the Polish coal regions

Prof. Adam Drobniak from the University of Economics in Katowice concentrated on five aspects of transition: social, economic, infrastructural, environmental and institutional. He highlighted the importance and significance of interdisciplinary collaboration oriented onto focusing knowledge and resources on a creation of new value chains. He suggested two levels of this collaboration:

– A vertical one: local – regional – state – European,
– A horizontal one: representatives of territorial administration non-governmental organizations, trade unions, research institutions, institutions of business environment, sector of education and companies.

Prof. Drobniak carried out detailed analyses of transitions of coal regions in Poland in the territorial, economic technological and institutional as well as environmental contexts (Fig. 12, 13, 14 and 15 respectively).

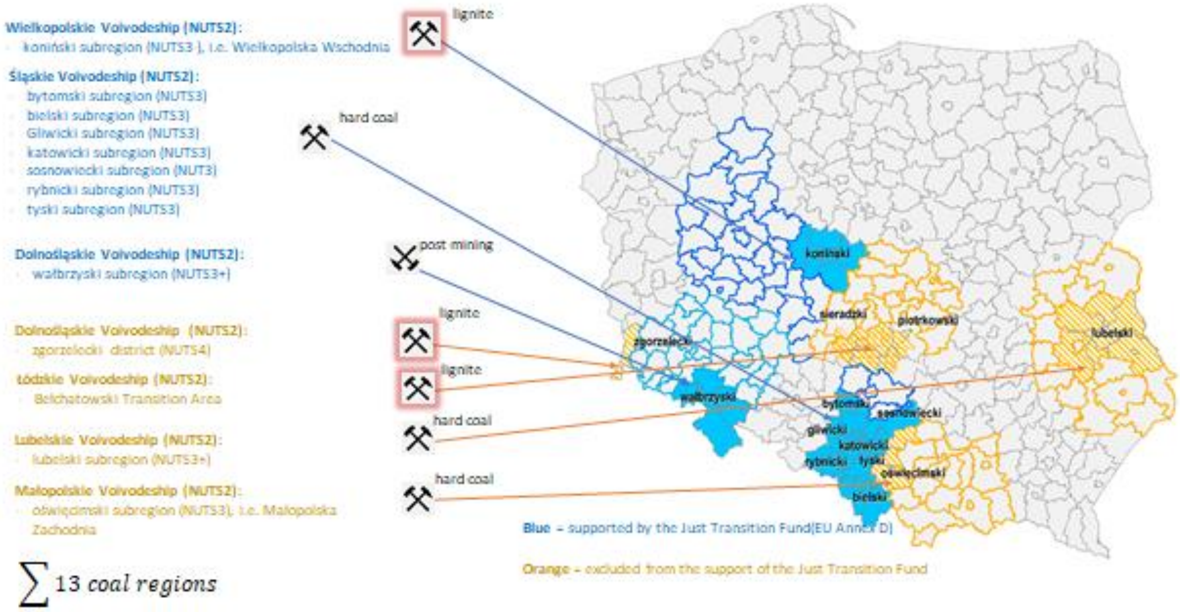

Fig. 12. Transition of coal regions in Poland in the territorial context (Source: KPST – November 2021)

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Coal regions	Number of economic subjects and their dynamics 2010=100(2019)	Employment (2019)	Employment in the mining industry (2019)	Employment in related activities* (2019)
wałbrzyski	75 748 (104)	193 772	0	0
zgorzelecki	8 713 (100)	19 405	3 500	4 235
bielski	79 831 (110)	279 450	1 746	2 113
bytomski	44 328 (109)	134 318	2 784	3 369
gliwicki	51 306 (107)	191 498	7 542	9 126
katowicki	**88 295 (107)**	**353 716**	15 333	18 553
rybnicki	51 796 (107)	208 740	22,113	26 757
sosnowiecki	70 942 (99)	234 182	3 486	4 218
tyski	41 404 (112)	168 975	19 009	23 001
lubelski	76 051 (117)	311 090	5 653	6 840
bełchatowski	44 505 (107)	166 413	4 728	5 721
Zachodnia Małopolska	57 358 (107)	189 868	3 998	4 838
Wschodnia Wielkopolska	65 865 (117)	137 322	6 689	8 094

Fig. 13. Transition of coal regions in Poland in the economic context (Source: KPST – November 2021)

Coal regions	Domination level of traditional industries	Type of economic structure	Potential of institutions supporting business
walbrzyski	low	weakened post-industrial	average
zgorzelecki	high	excessive specialization	low
bielski	low	mix of industries and services	high
bytomski	high	weakened post-industrial	average
gliwicki	low	mix of industries and services	high
katowicki	low	mix of industries and services	high
rybnicki	high	excessive specialization	average
sosnowiecki	low	mix of industries and services	average
tyski	average	zrównoważona	average
lubelski	high	excessive specialization	low
bełchatowski	high	excessive specialization	low
Zachodnia Małopolska	low	mix of industries and services	average
Wschodnia Wielkopolska	high	excessive specialization	average

Fig. 14. Transition of coal regions in Poland in the technological context (Source: KPST – November 2021)

Coal region	Extraction grounds [ha]	Industry and production [ha]	Share in the region surface [%]
wałbrzyski	1 643.61	2 456.42	0.90
zgorzelecki	3 026.07	265.84	**3.93**
bielski	158.23	1 782.10	0.82
bytomski	165.78	2 364.03	1.60
gliwicki	17.79	2 815.05	**3.22**
katowicki	8.62	2 919.33	**7.70**
rybnicki	334.13	2 006.29	1.73
sosnowiecki	856.42	4 491.50	**2.97**
tyski	96.02	2 255.58	**2.49**
lubelski	945.87	1 313.76	0.28
bełchatowski	5 770.00	2 001.27	**2.12**
Zachodnia Małopolska	595.02	2 347.36	1.44
Wschodnia Wielkopolska	5 031.89	942.85	1.35

Fig. 15. Transition of coal regions in Poland in the environmental context (Source: KPST – November 2021)

Looking at the economic context, it is easy to notice a significant share of direct and indirect employment figures in traditional branches of industry, whereas in the case of the technological and institutional context a significant share of traditional branches of industry (big and medium size enterprises in the mining sector as well as in the circum-mining branches, conventional power plants, metallurgy and coking industry) can be seen. There is a deficit of the institutions supporting business. Another issue concerns a big technological sensitivity to changes and a big number of post-industrial and industrial areas including contaminated grounds.

2.5. Silesia in transformation – European Funds for Silesia for the years 2021-2027

Just transition is a process of systematic changes, oriented onto basing the economy on environmentally neutral industry. The most important element of the just transition concerns social costs of economic changes. Just transition is a chance for a development of Silesia due to the following activities:

- Investments in renewable energy sources.
- A creation of new markets connected with green energy and sustainable transport.
- A development of geographic areas and branches neglected in the result of coal exploitation.
- A remediation of urban and natural areas.
- A reparation of damages caused by an intensive coal exploitation.

All the above mentioned activities are included in the Territorial Plan of Just Transition of the Silesian Voivodeship 2030, covering the Economy – budget of 920 million EUR, the Environment – budget 763.4 million EUR and the Society – 300 million EUR. As far as the Economy is concerned, there are tree fields of activity:

- Innovative economy of mining sub-regions.
- Diversified economy of mining sub-regions enabling to save resources and save energy.
- Strong entrepreneurship of mining sub-regions.

In the scope of the Environment two fields of activity are regarded to be top priority:

- Balanced dissipation of power engineering in mining sub-regions oriented onto a dissemination of solutions based on renewable energy sources (production of energy, its distribution and storage).

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- Efficient use of post-industrial areas in mining sub-regions for economic, environmental and social purposes.

Presenting the activities of just transition, the third aspect, related to the society, should be highlighted:
- Attraction and efficient education and an improvement of qualifications in mining sub-regions.
- Complex system of social support to make inhabitants of mining sub-regions more active and open to changes.

It should be borne in mind that the Mechanism of Just Transition is a key tool enabling an efficient transformation of the economy in the way which is environmentally neutral and has no negative impact on the society. The Silesian Voivodeship is the biggest mining region in the European Union at present. The transition processes of different intensity have been realized here for more than 30 years. However, till the year 2050 the Polish mining industry will face colossal changes, resulting from the European Green Deal requirements. The transition will embrace 3 thousand hectares of grounds, nearly 5 thousand buildings and more than 6 thousand of other structures, including 30 shafts. For Silesia, whose economy has been based on mining coal for centuries, an inevitable withdrawal from this industry constitutes a unique challenge and a great development chance.

2.6. KOMAG Institute of Green Transition – 2030 as an example of changes in the scientific sector supporting the Just Transition of Post-Mining Areas

For 72 years KOMAG has been realizing the mission of automation, mechanization and electrification of industrial processes in Silesia but within less than a decade it intends to become very active in implementing breakthrough technologies in the scope of electromobility, energy storage, cybersecurity of industrial systems and a transition of urban ecosystems in the direction of the closed loop economy. The primary objectives, till the year 2030, include a transformation into the INSTITUTE of GREEN TRANSITION and an achievement of the status of the European leading research institution, having highly specialized staff and laboratories equipped with the state-of-the-art testing facilities.

ITG KOMAG, as the Institute of Green Transition, realizes the mission of becoming soon a European scientific-and-research partner, increasing efficiency, quality and security of key economic processes of its clients. The mission, defined in such a way, shapes the new strategy of the Institute for the years 2023-2030, in which a development of scientific and design activity is perceived through the business context, enabling a maintenance and an enlargement of the research and competence potential.

The strategy is based on the awareness that the KOMAG research activity plays a key role in a development of our country and of Europe and it is inseparably connected with social responsibility.

The strategy determines new areas of activity such as:
- An efficiency increase of research-and-development as well as of educational activity.
- A maximization of the Institute's present research possibilities.
- A use of the present scientific and research potential for attracting new business partners.
- An increase of using state-of-the-art development technologies.
- An increase of efficiency, competences and a change of the present organizational system.
- A development of scientific and engineering staff.

The Institute's new strategy is focused on the following fields of activity:
- Power systems sustainable climatically and economically.
- A transition of post-mining areas and power transition.
- A use of the potential of underground infrastructure and of post-mining areas.
- New technologies in the scope of energy management, generation and storage.
- A decarbonization of economy.
- Solutions for means of defence.

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– A transfer of mining technologies in the aspect of occupational safety issues and a use of innovative techniques and technologies.

One of KOMAG's ambitions includes strengthening of the Institute's position on the domestic and international arenas in the scope of basic and applied research.

3. Conclusions

– The International Scientific and Technical Conference was a successful forum of knowledge and professional experience exchange among scientists, researchers, representatives of local and regional administration as well as industrialists.
– Interdisciplinary presentations and panel discussions enabled the conference participants to concentrate on varied issues experienced during a transition of post-mining areas in the light of technical, economic, ecological and social aspects.
– One of the most important Conference objectives consisted in taking advantage of the European countries in the scope of reducing energy generation from hard coal and lignite according to the European Green Deal requirements.
– Special attention was paid to a determination of the transition process principles and a formulation of guidelines for different groups of stakeholders.
– Panel discussions also concerned the most important factors favourable for the just transition of post-mining areas and barriers experienced by different groups of stakeholders.
– A role of scientists and researchers in the process of the just transition of post-mining areas was highlighted and an example of the KOMAG Institute's of Mining Technology transformation into the Institute of Green Transition – 2030 was presented and discussed.

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Energy storage using compressed air

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Abstract:

The climate change is probably the greatest challenge humanity is facing today. In order to protect future generations from the catastrophic effects of the process, actions to achieve climate neutrality are being taken worldwide. These actions include development of renewable energy sources. Renewable energy depends on weather conditions, which results in a mismatch between supply and demand for energy. Use of energy storage is the technical solution to minimize this issue. The paper presents topics related to the potential storing of surplus electricity produced from renewable energy sources (RES) in the form of compressed air. The article also shows worldwide solutions for energy storage using compressed air. As part of the work, three variants of a warehouse consisting of standardly available pneumatic units were considered. The conducted analyzes made it possible to determine the energy efficiency of such a system. It can be observed that greater efficiency is achieved by using large flow compressors and the operation of the pneumatic motor at a higher supply pressure. In addition, it can also be said that the greatest losses are associated with the operation of the compressor, which generates large amounts of heat during operation. Increasing the efficiency of the energy storage system can be achieved by utilizing the heat generated in the compression process.

Keywords: energy storage, pneumatic storage, Compressed Air Energy Storage (CAES), Renewable Energy Sources (RES)

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1. Introduction

According to the Green Deal, a strategy for climate neutrality planned as a goal for 2050 [1], reducing CO_2 emissions can be achieved by increasing the share of renewable energy sources (RES) in the energy mix. Due to the cyclical and unpredictable nature of energy production from RES, their cooperation with energy storage facilities significantly increases efficiency of the energy system and enables matching energy supply and demand. This cyclicality is especially observed in the case of photovoltaic farms, where electricity is produced during the day, and the installation is unproductive at night, moreover, in the annual cycle insolation changes (Fig. 1) [2-4].

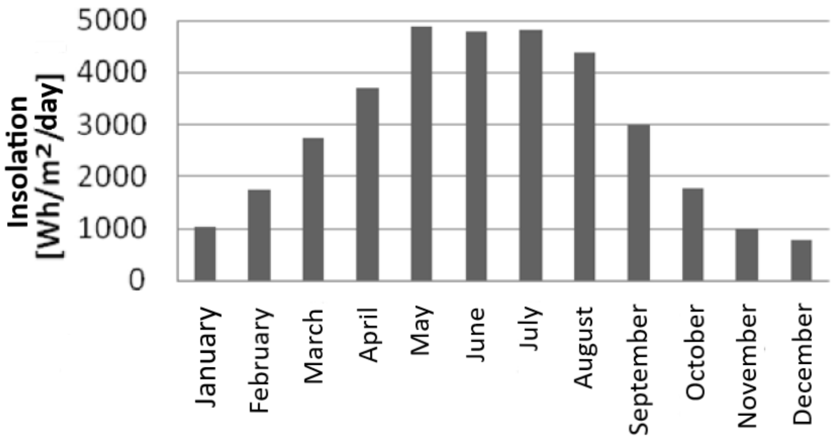

Fig. 1. Average daily insolation during the year [3]

The cyclical operation of RES sources creates the risk of unstable operation of transmission and distribution networks. RES production unpredictability can be compensated by energy storage. Regarding the RES installation, the share of energy storage is increased under the government program "My Electricity", which in its fourth edition allows for support for home energy storage solutions, thus increasing self-use of produced energy [5].

Energy storage facilities are divided according to their size (domestic and industrial) and due to the technologies used, such as: electrochemical batteries, pumped-storage power plants, supercapacitors, fuel cells, superconducting energy storage, kinetic and pneumatic energy storage, liquefied air, reservoirs using heat pumps and hydrogen storage. The most effective, and at the same time the most popular in recent times, are electrochemical battery storage units. These storage units were first used in cooperation with domestic and medium-sized RES installations. It is assumed that the capacity of produced battery energy storage will increase from less than 30 GWh in 2021 to 362 GWh in 2025 [6]. Forecasts for major battery cell manufacturers are shown in Fig. 2.

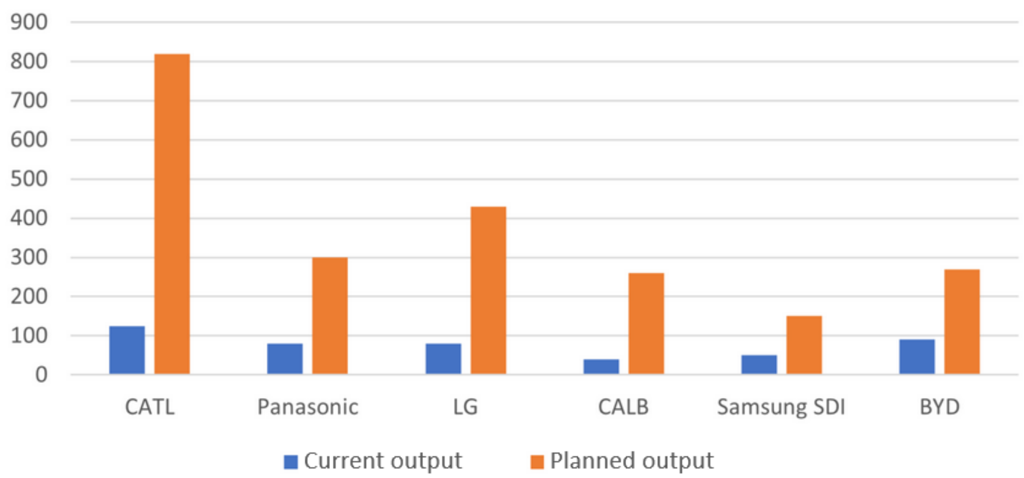

Fig. 2. Annual battery production of selected manufacturers in 2021 and planned for 2030 [6]

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The increase in the demand for batteries will entail an increase in the demand for raw materials, which will ultimately translate into an increase in the cost of such storage units. In the energy sector, pumped-storage power plants PHS - Pumped Hydroelectric Storage are in the lead, accounting for over 96% of global electricity storage capacity (Fig. 3).

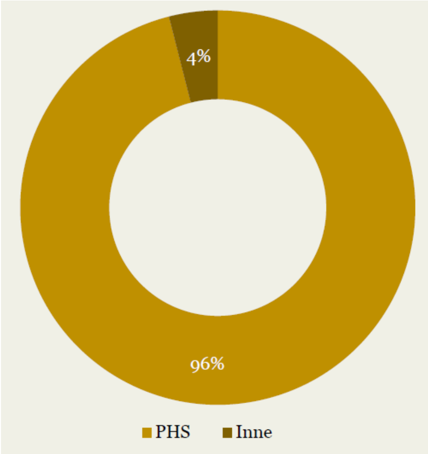

Fig. 3. Global share of energy storage [7]

Other storage technologies are also being developed, including the technology of energy accumulation in compressed air CAES - Compressed Air Energy Storage.

Currently, there are only a few such installations in the world, the most recognizable of which are: McIntosh in the US state of Alabama and Huntorf in Germany.

2. Research methods

2.1. Gas power plants using compressed air storage

The Huntorf power plant (Fig. 4, Table 1) in Germany was put into operation in 1978 [8]. At that time, it was the world's first commercial power plant with a compressed air energy storage facility. Originally, it was designed to absorb excess energy produced from the nearby nuclear power plant and serve as an emergency source of electricity. Increase in the share of RES in production of electricity meant that the power plant with an underground storage began to play an increasingly important role.

a) b)

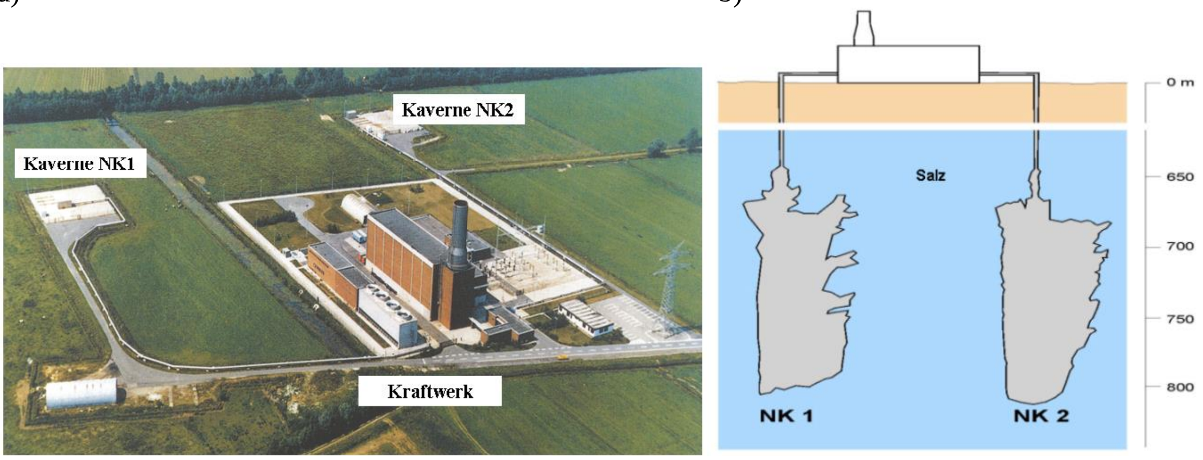

Fig. 4. Huntorf power plant: a) general view, b) location of caverns [9, 10]

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Table 1. Technical data of the Huntorf power plant [11]

Power	
Gas turbine	290 MW (≤3 hrs)
Compressor turbine	60 MW (≤12 hrs)
Air flow rate	
Gas turbine	417 kg/s
Compressor turbine	108 kg/s
Storage capacity	310 000 m^3 (140 000 m^3 + 170 000 m^3)
Storage air pressure	
Minimum permissible	1 bar
Minimum operational (exceptional)	20 bar
Minimum operational (regular)	43 bar
Maximum permissible and operational	70 bar

The underground part of the power plant consists of two salt caverns with a total capacity of approx. 310 m^3, for which the working pressure range is 50-70 bar. Huntorf power plant deliberately resigned from recuperators (although this would increase efficiency) to minimize start-up time of the system. Reliability of the power plant over the 30-year period of operation amounted to approx 99%. The energy efficiency of the power plant is 42%. In 2006, the power plant underwent modernization and its capacity was increased from 290 MW to 321 MW [8].

Fig. 5 shows the main components of the installation. Compressed air in the storage unit powers the gas turbines of a power plant. In classic gas turbines, about 2/3 of the power is used to compress the air entering the combustion chamber (100 MW net power + 200 MW compressor operation = 300 MW gross power). In the CAES power plant, air delivered to the turbine is already compressed and thus. the turbine generates full power (300 MW instead of 100 MW).

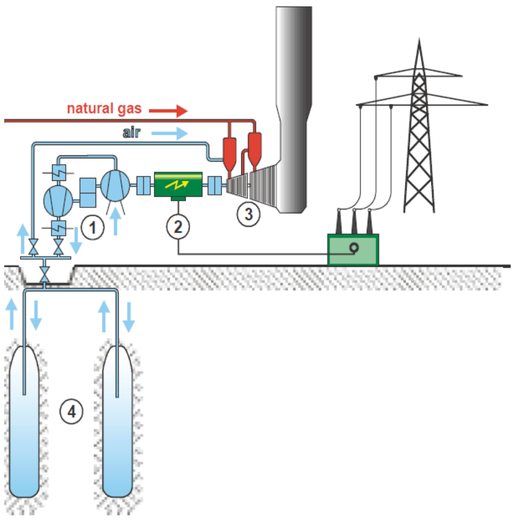

Fig. 5. Main components of the installation: 1) compressor unit, 2) motor-generator unit, 3) gas turbine, 4) underground compressed air storage unit [11]

Another CEAS storage solution is the 110 MW McIntosh power plant, which was built in the salt mines of the USA, in southwest Alabama. Air is compressed in one cavern with a volume of 560,000 m^3 to a working pressure of 45-74 bar. Full power operation can be maintained for more than 26 hours. Technological solutions (Fig. 6, Fig. 7) and operating parameters such as: pressure, temperature, etc., uses the experience of the Huntorf power plant, however, a heat recuperator was used here, allowing to reduce fuel consumption by approx. 22%. A combustion chamber for two types of fuel - natural gas and fuel oil was used [12].

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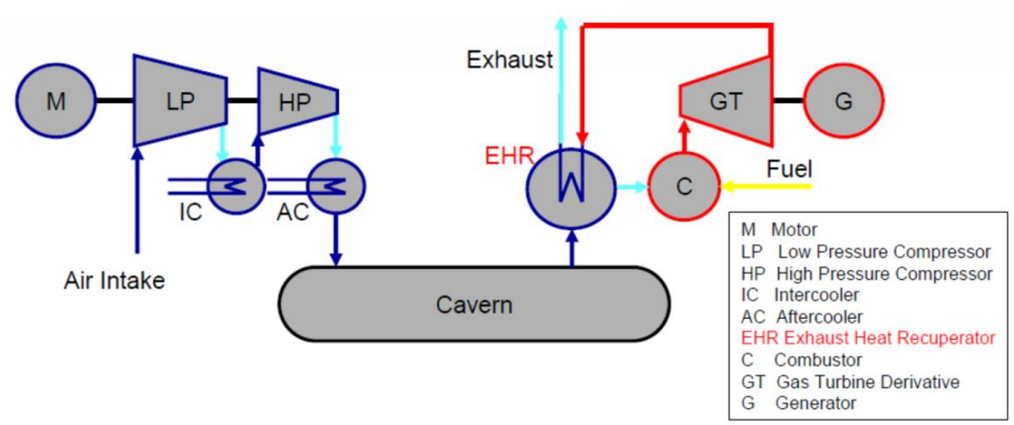

Fig. 6. Diagram of CAES with heat recuperator [10]

a)  b) 

Fig. 7. McIntosh power plant machine room: a) McIntosh compressor system, b) turbine [12]

2.2. Pneumatic storage unit integrated with thermal energy storage unit

In order to increase energy efficiency of the compressed air storage unit, a research work is being carried out to recover the heat energy lost to during its compression (Fig. 8). This problem was resolved in the AA-CAES (Advanced Adiabatic Compressed Air Energy Storage) project.

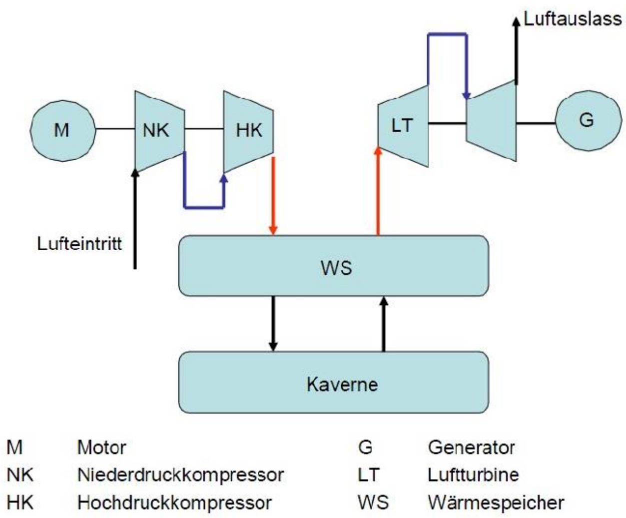

Fig. 8. Diagram of compressed air storage with heat storage [13]

Project uses a horizontal mine roadway approx. 120 m long and approx. 5 m high, which was sealed with concrete plugs and a steel door. Thermal energy storage unit was placed inside a separate roadway (Fig. 9) and consisted of a rock storage (sensible heat) with a capacity of 12 MWh and a PCM storage (latent heat) with a capacity of 0.171 MWh. The heat storage units reached a temperature of 560°C.

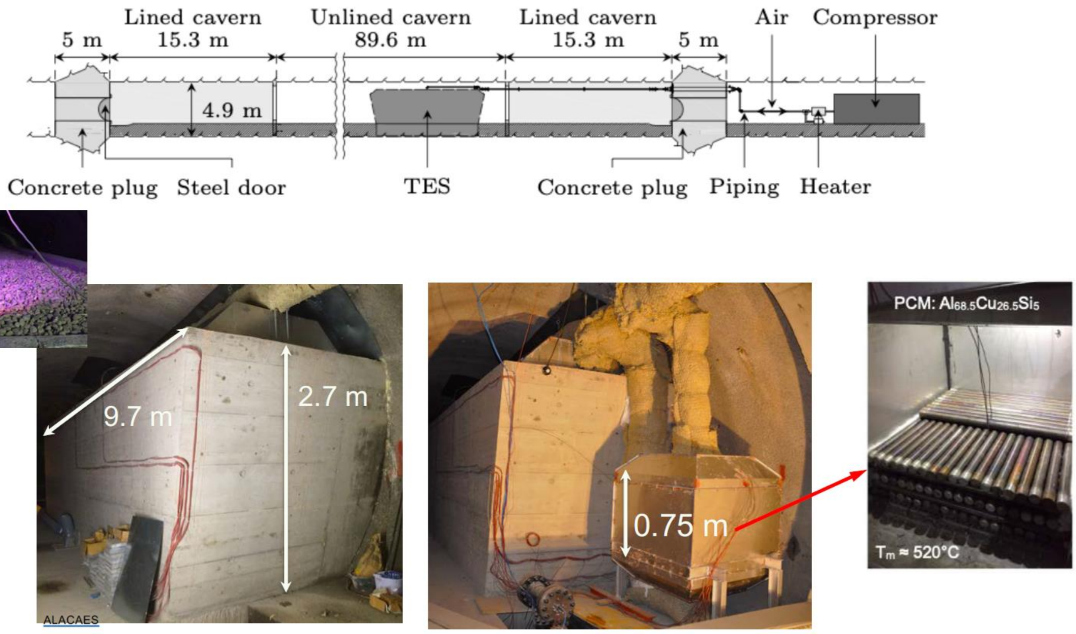

Fig. 9. AA-CAES (Advanced Adiabatic Compressed Air Energy Storage) [14]

Efficiency of the pilot installation made under the AA-CAES project was estimated at 65-75%. The turbine and generator were not manufactured within the project, and their efficiencies were assumed in the simulations to be 0.85 and 0.97, respectively [14].

2.3. Hydrostor's A-CAES plant

In 2019, Hydrostor launched an A-CAES storage unit in Goderich, Ontario (Fig. 10). It is a solution that uses an underground air tank and heat storage unit. Installation has a power of 1.75 MW, while the charging power is 2.2 MW, and the energy storage capacity is 10 MWh [15]. In addition to the project in Goderich, the company has three more A-CAES installations in its portfolio, which it intends to launch in the future.

Fig. 10. A-CAES storage facility in Goderich, Ontario, Canada [16]

3. Results - evaluation of using the standard pneumatic devices for compressed air energy storage

Examples of installations using compressed air as energy storage are presented above. These solutions are mostly the components of commercial power plants in which dedicated turbine designs were used. In the further part of the article, the authors presented a technical and energy analysis of the system based on commonly available pneumatic devices. Such an approach to the issue would popularize the use of pneumatic storage units. In the system, air is compressed with an industrial compressor, air is stored in steel tanks, and pneumatic motors are used to generate the torque driving the electricity generator (Fig. 11).

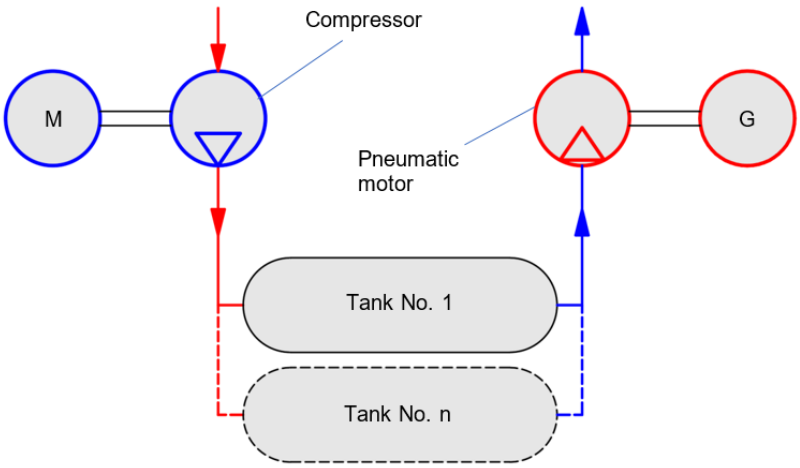

Fig. 11. Schematic diagram of compressed air storage unit

Three variants of the unit were analyzed.

Variant 1

Variant 1 uses a screw displacement compressor. Currently, it is the most common type of compressors in the industry (93.5%) [17]. Compressing air is a very energy-intensive process and it is assumed that about 80% of the energy supplied to the compressor is converted into heat, and only 20% is the compressed air energy (whereby the energy consumption for displacement compressors should be in the range of 0.09-0.13 kWh/m^3) [18].

A CompAir L250 screw compressor was suggested (Fig. 12).

Model sprężarki	Max. ciśnienie robocze [bar g]	Silnik napędowy [kW]	Wydajność[1] [m³/min]	Poziom hałasu[2] [dB(A)]	Ciężar [kg]	Wymiary dł. x szer. x wys. [mm]
L160	7,5	160	32,04	76	4186	2907 x 2071 x 2193
	10	160	28,20	76	4186	2907 x 2071 x 2193
	13	160	23,91	76	4186	2907 x 2071 x 2193
L200	7,5	200	39,23	77	4415	2907 x 2071 x 2193
	10	200	34,85	77	4415	2907 x 2071 x 2193
	13	200	29,38	77	4415	2907 x 2071 x 2193
L250	7,5	250	42,03	78	4625	2907 x 2071 x 2193
	10	250	37,01	78	4625	2907 x 2071 x 2193
	13	250	32,64	78	4625	2907 x 2071 x 2193
L290	7,5	250	47,10	79	4650	2907 x 2071 x 2193
	10	250	41,53	79	4650	2907 x 2071 x 2193
	13	250	36,44	79	4650	2907 x 2071 x 2193

Fig. 12. CompAir Screw compressor [19]

The Dusterloch DMO 15 gear motor was suggested as the pneumatic motor (Fig. 13). The air consumption characteristics of the pneumatic motor is shown in Fig. 14.

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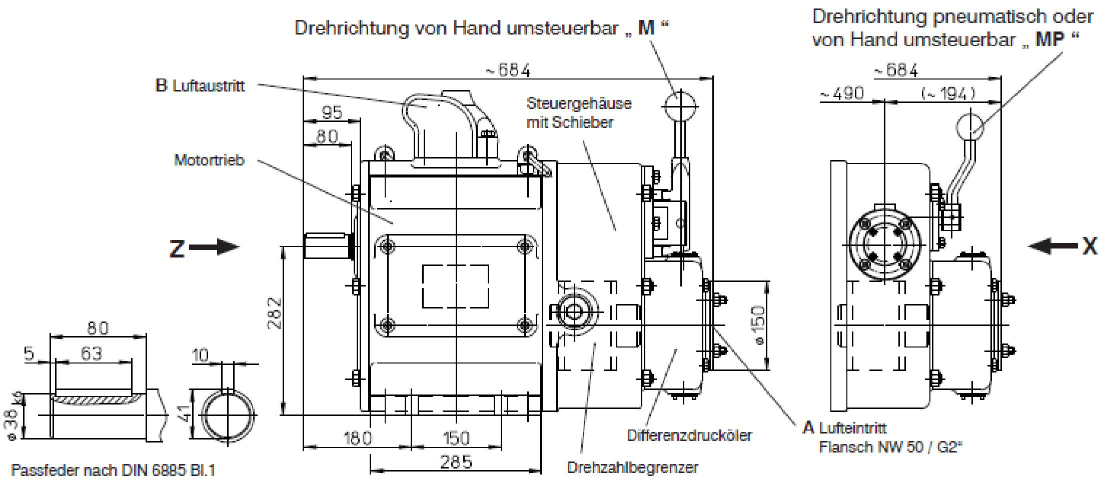
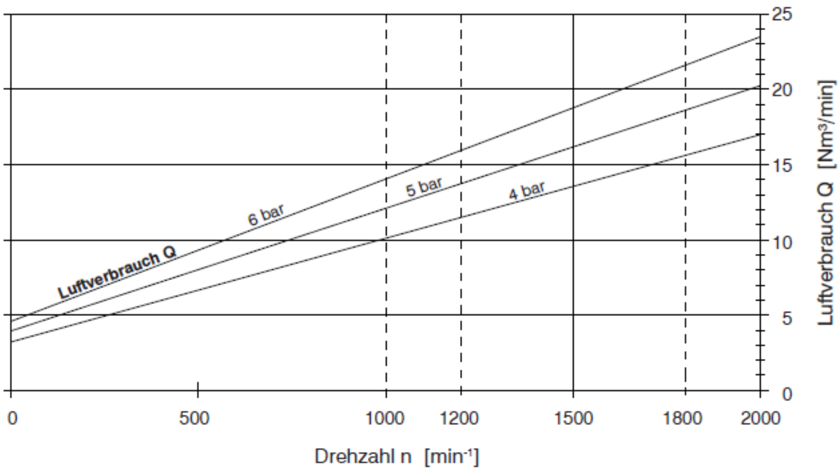


Fig. 13. Dimensions of the DMO 15 motor [20]



Typ	Betriebsdruck		Drehzahlbereich		Daten bei Nenndrehzahl und 6 bar Überdruck			
					Drehmoment		Leistung	Luft-verbrauch
	dauer p [bar]	max. p [bar]	Nenndr. n [min^{-1}]	Leerlauf n [min^{-1}]	Start T [min/max Nm]	Nenn T [Nm]	P [kW]	Q [Nm^3/min]
DMO 8/10	6	8	1000	ca. 1200	62 - 71	60	6,3	9
DMO 8/12	6	8	1200	ca. 1400	62 - 71	59	7,4	10
DMO 8/15	6	8	1500	ca. 1680	62 - 71	57	9,0	12
DMO 8/18	6	8	1800	ca. 1950	62 - 71	55	10,4	14
DMO 8/20	6	8	2000	ca. 2150	62 - 71	54	11,3	15
DMO 15/10	6	8	1000	ca. 1200	115 - 131	111	11,6	14
DMO 15/12	6	8	1200	ca. 1400	115 - 131	109	13,7	16
DMO 15/15	6	8	1500	ca. 1680	115 - 131	104	16,3	19
DMO 15/18	6	8	1800	ca. 1950	115 - 131	102	19,2	23
DMO 15/20	6	8	2000	ca. 2150	115 - 131	99	20,7	24

Fig. 14. Characteristics of the DMO 15 motor operation and its main technical parameters [20]

Due to the operating parameters of the compressor and pneumatic motor, it was assumed that the compressor would supply the air tanks in the range from 6 bar (due to the motor's operating pressure) to 13 bar (due to the compressor's operation). Currently in industrial pneumatic systems, the pressure in the mains is reduced to increase economic efficiency [21].

Variant 2

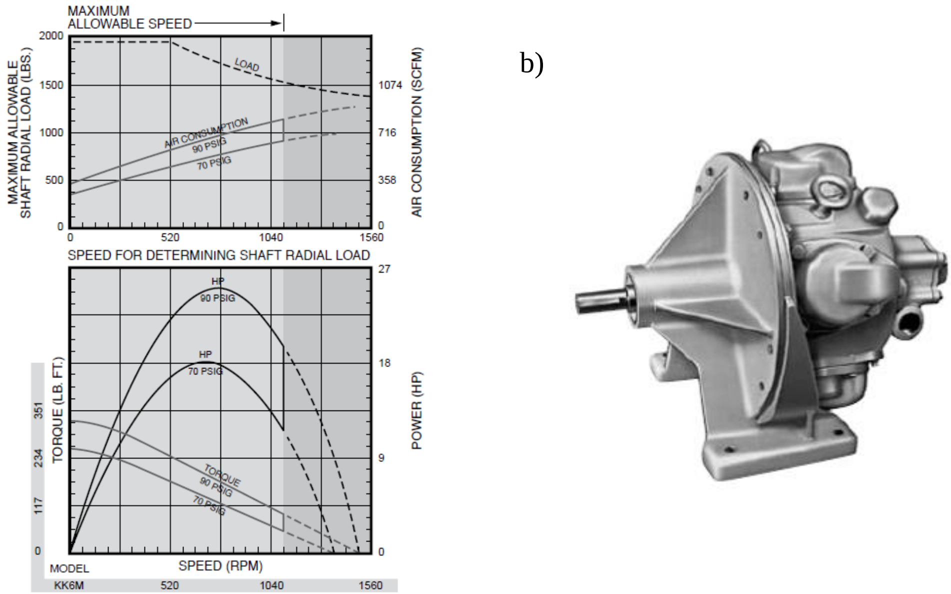
Variant 2 uses an Atlas Copco ZH 560 three-stage centrifugal flow compressor (Fig. 15). The same motor was used as in Variant 1.

Fig. 15. Atlas Copco ZH centrifugal flow compressor [22]

Variant 3

In variant 3, the same compressor was adopted as in variant 2, and the use of a KK6M pneumatic piston motor from the Ingersoll Rand catalog was planned (Fig. 16).

a)



c)

Model	Max. Power		Speed at Max. Power	Free Speed▲	Starting Torque		Stall Torque		Air Consumption at Max. Power		Weight	
	hp	kw	rpm	rpm	lb.-ft.	Nm	lb.-ft.	Nm	scfm	m³/m	lb.	kg
Direct Drive Reversible												
CCM	2.05	1.53	1075	2140	13.2	17.9	18.8	25.5	97	2.7	135	61.2
DD6M	2.6	1.94	750	1490	24	32.5	34.2	46.4	79	2.2	135	61.2
EEM	4.4	3.28	735	1450	41	55.6	59	80	137	3.9	200	90.7
EE5M	7.8	5.82	950	1875	60	81.4	80.5	109.2	220	6.2	210	95.3
HHM	11.3	8.43	730	1450	106	144	152	206	270	7.6	235	107
HH5M	15.2	11.33	750	1500	146	198	195	264	400	11.3	250	113
KK6M	25	18.64	755	1500	260	353	325	441	680	19.3	475	216
Geared Drive Reversible												
EE3G	5	3.73	275	560	122	165	175	237	155	4.4	200	90.7
EE53G	6.8	5.07	305	600	154	209	205	278	220	6.2	220	99.8
EE9G	4.7	3.51	92	190	357	484	510	692	155	4.4	210	95.3
EE59G	6.5	4.85	100	200	450	610	600	814	220	6.2	230	104

▲ ALL models must be operated with sufficient load to prevent speed from exceeding maximum allowable speed shown on performance curve.
All of the above motors are furnished less valve and piping as standard.
Performance figures are at 90 psig (620 kPa) air pressure.

Fig. 16. Pneumatic piston motor: a) parameters of the KK6M motor, b) view of the pneumatic motor, c) technical data of the Ingersoll Rand pneumatic piston motors [23]

Results of the analyzes are presented in Table 2.

Table 2. Results of analysis of the suggested variants

			Variant		
			W1	**W1**	**W3**
Compressor					
Compressor power	P_spr	kW	250	560	
Maximum working pressure	p_max	bar	13	13	
Output					
(ISO 5389 (1 bar, 35°C, humidity 60%)	$g\_spr_{(5289)}$	m^3/min FAD	-	81.06	
(ISO 1217 (1 bar, 20°C, humidity 0%)	g_spr		32.64	100.2	
Average daily working time	t_spr	hours	6	6	
Daily volume of compressed air	G(FAD)	m^3	11750.4	36072	
Daily energy consumption	E_in	kWh	1500	3360	
Motor					
Pneumatic motor power	P_sil	kW	16.3		18.64
Supply pressure	p_sil	bar	6		6.2
Air consumption					
(ISO 1343 (1 bar, 0°C, humidity 0%)	g_sil	Nm^3/min	19		19.3
(ISO 1217 (1 bar, 20°C, humidity 0%)	g_sil	m^3/min FAD	20.51		20.51
Engine operating time	t_sil	min	572.91	1758.75	1758.75
		h	9.55	29.31	29.31
Storage					
Compressed air volume (ISO 1217 (1 bar, 20°C, humidity 0%)	G(13bar)	m^3	903.88	2774.77	
Assumed tank capacity	V	m^3	9.00		
Number of tanks	n	pc.	100	308	
Electricity (from generator)	Eout	kWh	149.42	463.46	524.53
Efficiency of the power generator		-	0.96		
Energy efficiency [E_{out}/E_{in} x 100%]	SprE	%	9.96	13.79	15.61

Based on results of analysis of the variants described above, a relatively low efficiency of the system can be observed, amounting to a maximum of about 15%, which means that ultimately 15% of electricity from such a storage unit is stored. Legitimacy of using the compressed air storage units described in the first part of the article results from their cooperation with gas turbines, work of which, in the first phase consists in compressing the inlet air to the combustion chamber. This process is energy-intensive, therefore air compression was excluded from the turbine operation and shifted in time so that it took place at a time when electricity is cheap and there is an excess of it in the power grid.

In order to identify the weakest point in the three analyzed variants, the indexes Wspr = P_spr / g_spr and W_sil = P_sil / g_sil expressed in kW/(m^3/min) FAD (Table 3) were used. These indexes apply to the air stream in normal conditions (includes the actual operating parameters: pressure, air humidity, temperature).

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Table 3. Comparison of energy storage variants

	Variant 1	Variant 2	Variant 3
Compressor W_spr, kW/(m^3/min) FAD	7.65	5.58	5.58
Motor W_sil, kW/(m^3/min) FAD	0.79	0.79	0.9

Based on the presented indicators, it can be observed that the compressor and the air compression process are the weakest elements of the system. According to the compressor manufacturers information, the L250 compressor generates about 190 kWc of heat when operating at power 250 kWe. This is confirmed by the objectives of the research work on CAES, focused on the recovery energy lost in the compression process. Storing as much air as in the analysis would require a large number of tanks, which is not justified due to the cost of the installation. CAES operating worldwide are based on underground sources.

4. Conclusions

To avoid irretrievable loss of energy surplus from RES installations, energy storage units should be used. Pumped storage hydroelectricity plants are currently, the most common energy storage facilities in the world (they account for over 90% of stored energy). However, other solutions are also available, including compressed air energy storage (CAES). Pneumatic storage systems currently operating in the world cooperate with gas turbines and are a source of compressed air, thus increasing the efficiency of the turbine (no need to compress the turbine intake air). In these storage units, mining underground workings or caverns (salt workings) are used as air reservoirs.

As part of this work, three variants of a storage units, consisting of a compressor, air tank and pneumatic motors, were considered. Analysis of the systems based on commonly available pneumatic devices shows that their energy efficiency ranges from approx. 10 to approx. 15%. It can be observed that greater efficiency is achieved with the use of large flow compressors and motor operation at a higher supply pressure. In addition, it can also be said that the greatest losses are associated with the operation of the compressor, which generates large amounts of heat during operation. Increasing the efficiency of the energy storage system can be achieved by recovering the heat generated in the compression process. The resulting heat could be used, for example, for heating purposes. However, discrepancy between demand and supply for such energy is a noticeable problem. In the summer, with high productivity of PV farms, the demand for thermal energy is low, therefore the possibilities of heat storage should be analysed. Another alternative is to use the heat to warm up air supplied from the storage unit to the air motor by increasing its enthalpy, or to use the heat to warm up the motor body. In this way, the efficiency of the system could be increased (a pneumatic motor would have the characteristics of a heat engine). selection or development of the appropriate type of thermal storage bed that would allow for the effective collection of heat, and then quickly distributing it to the air supplying the motor or heating its body is a technical problem.

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The concept of a household low-speed kinetic energy storage

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Sebastian JANAS [1*]

Abstract:

This paper presents a concept of mechanical design, for a slow-speed kinetic energy storage device. It is an attempt to present the problem of using the device to cooperate with small-scale household RES. Calculations allowing for selection of rotating mass along with determination of effective revolutions of the rotating mass are presented. The 3D model gives an overview of the main structural nodes of the device in the mechanical part. Due to large axial load resulting from the mass of the rotor and other components and subassemblies, a simple FEM simulation of the structure base was performed. Preliminary calculations of the magnetic bearing, acting as an axial bearing, were also carried out.

Keywords: kinetic energy storage, household RES, renewable energy, just transition

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1. Introduction

In the era of diversification of energy production using RES, there is a need to store excess amounts of it. Stabilization of the generated voltage is also an important aspect. RES commonly used in households (in terms of electricity generation) are photovoltaic panels. Household wind farms are less common. However, such systems do not always work properly, especially when the receiving power grid is overloaded while giving electricity to the power system. Also, such systems do not produce electricity in a ready-to-consume form. In such a situation, energy storage facilities collecting the excess electricity for a short time, compensate for temporary voltage spikes, and then, also in a short time, recharge the receiving grid. This energy can be stored in the form of heat or kinetic energy. In the event of a shortage of power from the energy system or renewable energy sources, the stored energy can be used and converted back into electricity.

2. Materials review – examples of FESS

There are many solutions for kinetic energy storage used primarily in industry and in RES power plants. These are complex systems with a capacity of at least several hundred kWh. Smaller systems are used in the automotive industry. In Volvo (Fig. 1), the use of a flywheel-based energy storage reduced fuel consumption by up to 25% [1, 2]. The system is installed on the rear axle. During deceleration, braking energy causes the flywheel to spin at 60,000 rpm. When moving off, the rotation of the flywheel is transferred to the rear drive wheels via a special gear. Energy from the wheel can be used to accelerate the vehicle or to move off again. With this solution, the car is best suited to urban driving, where there is a high number of braking and starting cycles.

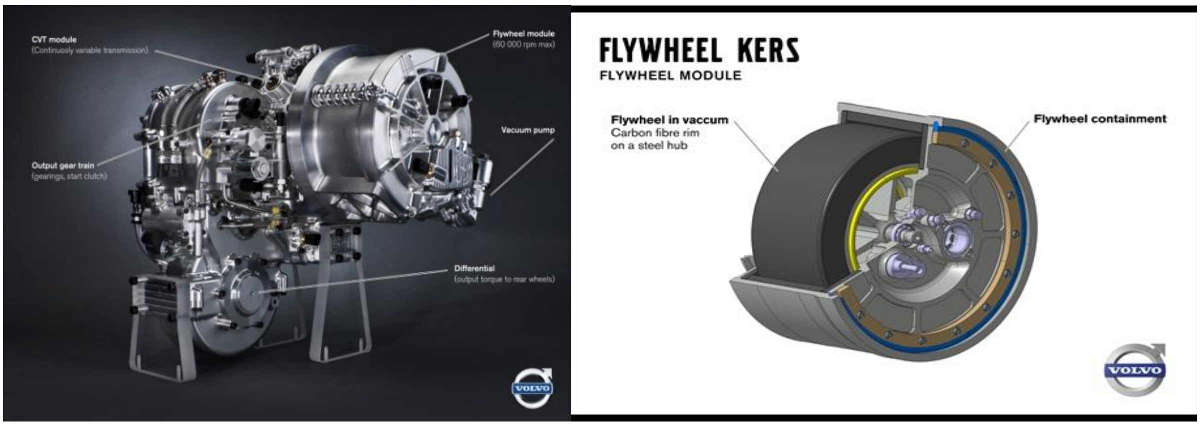

Fig. 1. Example of kinetic energy storage used in a Volvo S60 [1]

Flywheel systems acting as energy storages are used in Electric Multiple Units (EMU) or light-weight locomotives. Energy savings when using a flywheel reach 31%. Operation of such an energy storage is based on receiving braking energy and transferring it to the flywheel. Then, when moving off or driving up a hill, the energy stored in the flywheel is recovered [3]. In heavy long-distance locomotives, such systems did not prove to be useful. This is due to the very large weight of the locomotive, and thus the high energy demand when moving, and the very low frequency of braking. Another example of using FESS can be found on one of the Los Angeles underground lines. The VYCON company installed a train braking energy recovery system at the underground station. Originally, during braking, the energy generated was dissipated via third rail and converted into heat in the braking resistors. Currently, the same energy is converted by an electric machine into kinetic energy of the HSFESS flywheel. When the EMU is moving, the system is switched and the train receives energy through the third rail. In the peak hours of EMU traffic in the underground, the savings reach even 20%. As for Polish solutions, the company MEGATECH TECHNOLOGY Sp. z o.o. on its website informs about the project entitled: "Development of a high-speed PM BLDC motor as a kinetic energy storage device, along with infrastructure ensuring storage recharging and quick energy recovery and transforming it into a form and parameters that allow for effective use by the standard devices" (POIR.01.02. 00-00-0326/16 of September 29, 2017) [4].

3. Results

3.1. Preliminary calculations

Due to the introduction of kinetic energy storage systems in the industrial area, the possibility of using this type of system in households was analyzed. Initially, two cases of FESS were considered. Low Speed Flywheel Energy Storage System (LSFESS) with the rotational speed of the rotating mass up to 10,000 rpm and High Speed Flywheel Energy Storage System (HSFESS) with the speed range from around 10,000 rpm to even more than 100,000 rpm. Design of LSFESS is much simpler, and thus its cost is significantly lower compared to HSFESS. Also, HSFESS units are usually five times more expensive than low-speed energy storages [5, 6].

In order to identify the basic parameters for the selection of the energy storage system, a series of characteristics were defined, which were used to determine the maximum rotational speed of the rotor in relation to its mass and diameter.

The difference in energy of the storage system at the beginning and at the end was used to determine the speed range of the rotating mass:

$$\Delta E = E_1 - E_2 \quad (1)$$

where:

E_1 – initial energy of the storage, Ws,

E_2 – final energy of the storage, Ws.

After substituting the formula for kinetic energy derived from angular velocities into relationship (1), we obtain:

$$\Delta E = \frac{I \cdot \omega_1^2}{2} - \frac{I \cdot \omega_2^2}{2} \quad (2)$$

where:

I – moment of inertia of a rotating body, $kg \cdot m^2$,

ω_1 – initial angular velocity of the rotating body, $rad \cdot s^{-1}$,

ω_2 – final angular velocity of the rotating body, $rad \cdot s^{-1}$.

In order to determine rotational speed at which the rotating mass will accumulate maximum energy, the relationship was determined on the basis of the previously presented formula for kinetic energy and the relationship for the moment of inertia *I* of the rotating body:

$$I = \frac{m \cdot R^2}{2} \quad (3)$$

where:

m – mass of a rotating body, kg,

R – radius of a rotating body, m,

and angular velocity of a rotating body:

$$\omega = 2 \cdot \pi \cdot n \quad (4)$$

where:

n – rotational speed of a body, $rev \cdot s^{-1}$.

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After applying the relationships (3) and (4) in the formula for the kinetic energy of the rotating mass, the rotational speed [rev·s^{-1}] of the body, at which the rotating mass will accumulate the maximum amount of energy, was determined:

$$n_1 = \sqrt{\frac{E_1}{m \cdot (\pi \cdot R)^2}} \quad (5)$$

where:

E_1 – initial (stored) kinetic energy, Ws,
m – mass of a rotating body, kg,
R – radius of a rotating body, m.

In order to determine the area in which the optimal input parameters should be sought, the ranges of variables were adopted for the creation of characteristics listed in Table 1.

Table 1. Range of variables defining the selection area of basic parameters for energy storage

Parameter	Unit	Value
The amount of energy released, ΔE	kWh	2 ÷ 6
Considered range of masses of a rotating body, m	kg	100 ÷ 1000
Diameter range of a rotating body, R	mm	100 ÷ 800

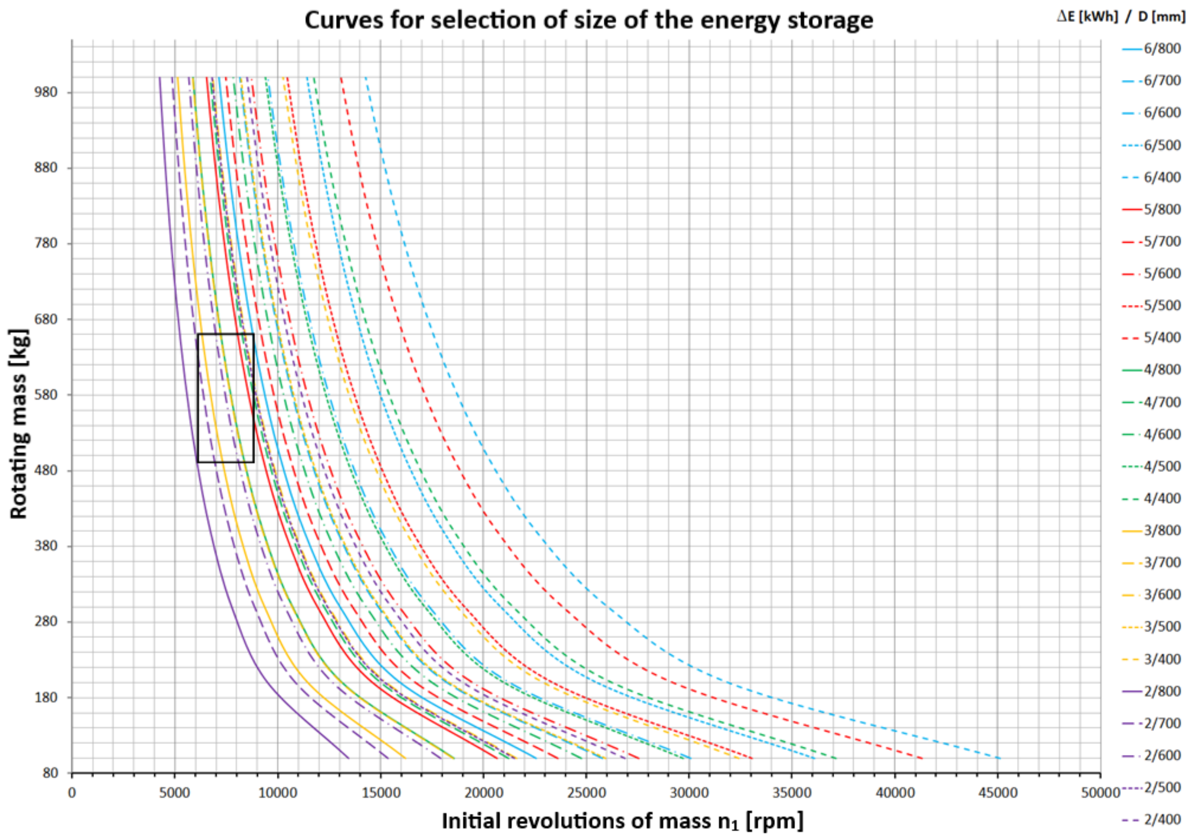


Fig. 2. Selection curves of basic parameters for kinetic energy storage in full range of adopted values

Fig. 2 presents a set of parameters illustrating the mass of storage rotor as a function of rotations for each energy storage capacity and rotating mass diameter. Assuming that the energy storage should be simple in its form and design and that it is meant to be a low-speed storage and it should store the amount of energy in the range of 2÷6 kWh, the range in which selection of basic parameters will take place was determined. For ΔE = 6 kWh and minimum revolutions of the mass n_2 = 1,550 rpm, the selection area of the storage parameters was determined, as shown in Fig. 3. Maximum revolutions n_1 = 8,650 rpm, diameter D = 800 mm and rotor mass m = 680 kg were selected for these boundary conditions.

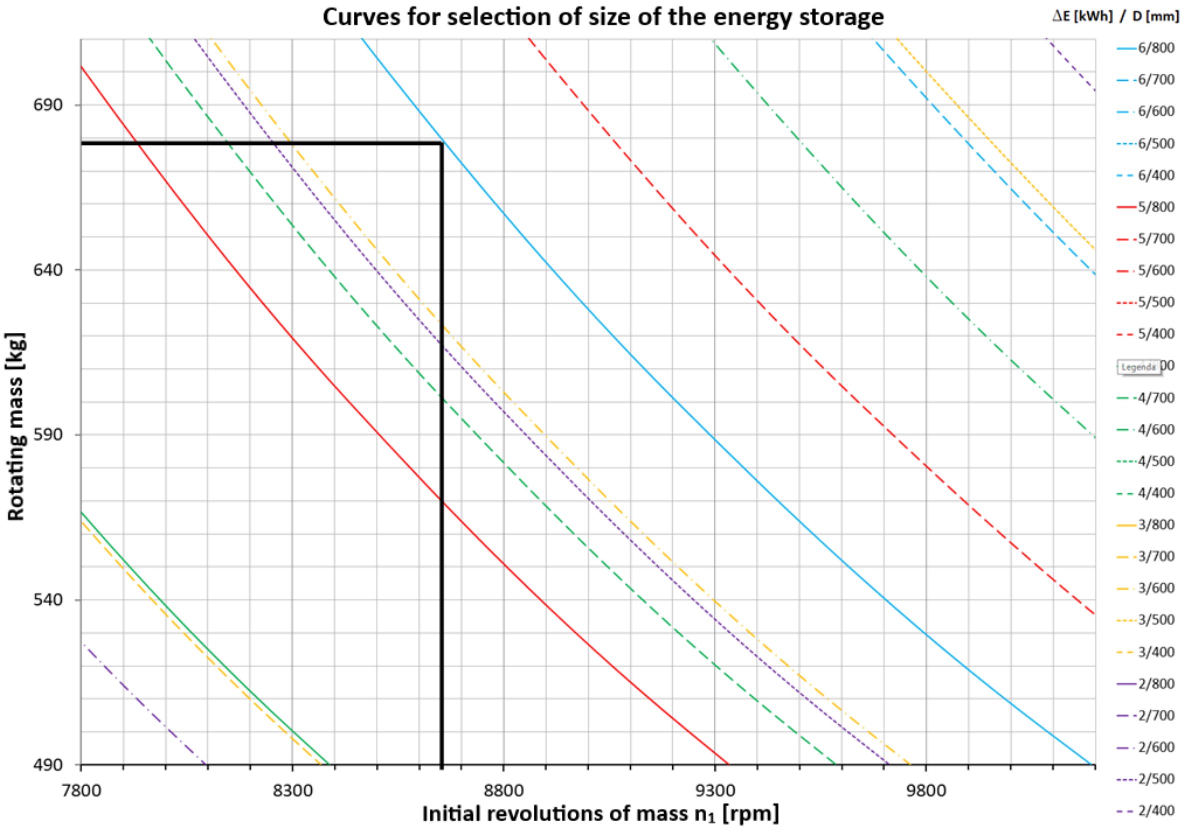


Fig. 3. Curves chosen for selection of basic parameters of kinetic energy storage in the range covering the adopted assumptions

3.2. Concept description

Proposed structure is fully assembled from parts and subassemblies. The largest and heaviest component of the device is the rotating mass, which was increased to 890 kg as a result of verification calculations.

The base of the device (Fig. 4) is made of a bolted frame consisting of three pillars (1), which connect the base (2) and the keystone (3). Body (4) of the lower aligning bearing (5) is screwed to the upper surface of the base (2). Body of the upper aligning bearing (6) is screwed to the bottom surface of the keystone (3).

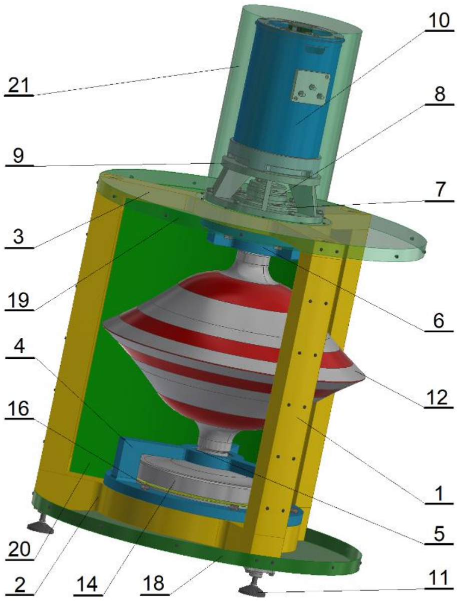


Fig. 4. 3D model of kinetic energy storage concept

The mounting flange (7) of the electromagnetic clutch (8) and the bracket (9) of the electric machine (10) are screwed to the upper plane of the keystone. Support feet (11) are installed in the bottom part of the base (2). In the alignment bearings (5 and 6) a rotating mass (12), connected to the electromagnetic clutch (8) by a sleeve, is installed. A disc (14) with a set of permanent magnets is screwed to the lower pivot of the rotating mass. A disc (16) with a second set of permanent magnets is attached to the base. Both of these components form a thrust bearing where there is no physical contact between the parts. Generated magnetic field forces keep the rotating mass on the air gap, which significantly increases the efficiency of such a system. The entire structure is shielded with sheet metal, divided into several parts. The lower shield (18) is screwed to the underside of the base (2). The upper shield (19) was screwed to the upper plane of the keystone (3). Chamber with the rotating mass was shielded with three metal sheets (20) around the circumference. The electric machine (10) was shielded with one cylinder-shaped cover (21).

After initial designing the shape of the rotating mass, the amount of energy released was calculated. Based on the moment of inertia I_y = 40.21 kg·m^2 of the modelled body read from the Inventor program, the maximum energy from which the energy storage will start to release it was determined. Due to the proposed shape of the rotating mass, its radius was averaged to 0.3 m. Thus, the initial rotational speed of the solid increased to the value n_1 = 10,081 rpm. After substituting these values into the formula (6):

$$E = \frac{I \cdot \omega^2}{2} \tag{6}$$

where:

I – moment of inertia of the modelled body as read out from Inventor, kgm^2,

ω – maximum angular velocity of the body 12 (Fig. 4), rad·s^{-1},

the result was $E = 22\,409\,168{,}5\,J = 6{,}22\,kWh$. Due to the large rotating mass and high rotational speed, the breaking strength of the body was also verified according to the following formula:

$$\sigma_m = \rho \cdot r^2 \cdot \omega^2 \tag{7}$$

where:

ρ – density of material used for rotating body, kg/m^3,

r – averaged radius of a body (due to its shape), m,

ω – angular velocity of the body, rad·s^{-1}.

The resulting stress $\sigma_m = 782{,}5\ MPa,$ excludes using the cast materials such as cast iron or cast steel due to too low tensile strength. Some structural alloy steels, whose tensile strength exceeds 1,000 MPa, are more suitable for use. However, it must be remembered that such steels will achieve their high strength parameters after heat treatment, and the correct heat treatment of such a large component will be a big technological challenge. Strength requirements are met by titanium alloys whose yield point exceeds 1,000 MPa. Using them, however, will cause a decrease in mass *(ρ = 4,600 kg/m^3)*, and thus the need to increase the rotational speed of the rotating mass to maintain the assumed amount of energy.

For the modelled body, the energy density stored in the energy storage was checked. For this purpose, the relationship (8), which takes into account the shape of a rotating body, was used. The shape coefficients are given in Table 2.

$$E_{sp} = K \cdot \frac{\sigma_m}{\rho} \tag{8}$$

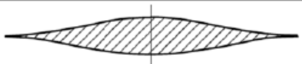
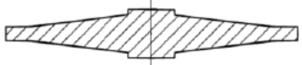
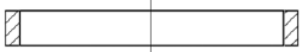
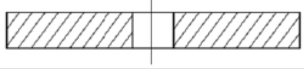
where:

K – shape coefficient of a rotating body,

σ_m – tensile stress, Pa,

ρ – density of material used for body, kg/m^3.

Table 2. K coefficient values for selected shapes of rotating bodies [6, 7]

Laval disk		1.00
Laval disk real		0.70–0.90
Laval-disk-with-rim		0.8–0.95
Conical disk		0.70–0.85
Solid disk		0.606
Thin ring		0.50
Disk with rim and centerhole		0.40–0.50
Thick rim		0.303

In order to calculate the energy density stored in the rotating mass of the shape specified in the model, the coefficient K = 0.75 was assumed on the basis of the first three lines in Table 2. After substituting the values into formula (8), the following expression was obtained:

$$E_{sp} = 20{,}9\ Wh/kg$$

The values calculated above were used as input parameters for the selection of the electric machine. For the calculations, it was assumed that the energy storage will be discharged in time t_1 = 60 min from the initial velocity ω_1 = 1055.75 rad·s^{-1} to the final velocity ω_2 = 189.6 rad·s^{-1}. Thus, the deceleration of the rotating mass was determined according to the following formula:

$$\varepsilon_h = \frac{\omega_1 - \omega_2}{t_1} \tag{9}$$

where:

ω_1 – angular velocity at which energy release begins, rad·s^{-1},

ω_2 – angular velocity at which energy release stops, rad·s^{-1},

t – time at which energy storage is to be discharged, s.

was the following:

$$\varepsilon_h = \frac{1055{,}75 - 189{,}6}{3600} = 0{,}24\ rad/s^2.$$

Time of speeding up the rotating mass to nominal angular velocity was assumed to be $t_2 = 150\ min$.

Speeding up of the body to ω_1 will take place with acceleration ε_r:

$$\varepsilon_r = \frac{\omega_1}{t_2} \tag{10}$$

where:

ω_1 – angular velocity at which energy release begins, rad·s^{-1},

t_2 – time taken for rotor to reach angular velocity ω_1, s.

Thus, after substituting to relationship (10), we obtain $\varepsilon_1 = \frac{1055{,}75}{9000} = 0{,}1173\ rad/s^2$.

To reach angular velocity ω_1 of the mass within expected charging time of 150 min, the electric machine should have a torque of at least 4.72 Nm.

Due to the fact that the analyzed energy storage is slow-speed, this will determine its increased dimensions and weight. In terms of strength, base of the frame on which the device will stand was analyzed. The frame is supported at three points. The Finite Element Method was used to analyze the frame in the FEM environment using the Inventor program. The assumed load is 15,000 N.

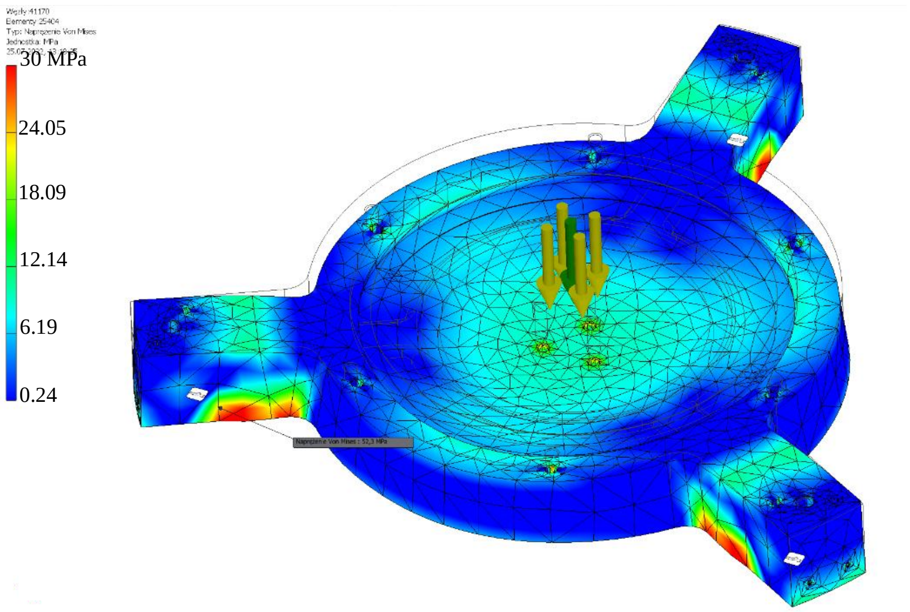


Fig. 5. Frame base stress map

The analysis (Fig. 5) shows that the highest stresses occur in the place where the curvature of the frame changes – the transition of the plane into the radius. The role of the radius is to eliminate concentrated stresses on the sharp edge, created by the intersection of the plane on which the feet (11, Fig. 4) are installed to the surface of the cone. The stress value read out in this area is 52.3 MPa. Safety factor for this area is 4, what means that the support should withstand the assumed load.

3.3. Calculations of the axial force in the designed magnetic bearing

In order to reduce the work resistance during spinning, a magnetic bearing made of permanent magnets was used. A cross-section through a magnetic bearing acting as a thrust bearing, in which the system of permanent magnets is shown in Fig. 6. The drawing of the bearing node was used to calculate the support force generated by the set of permanent magnets of the bearing.

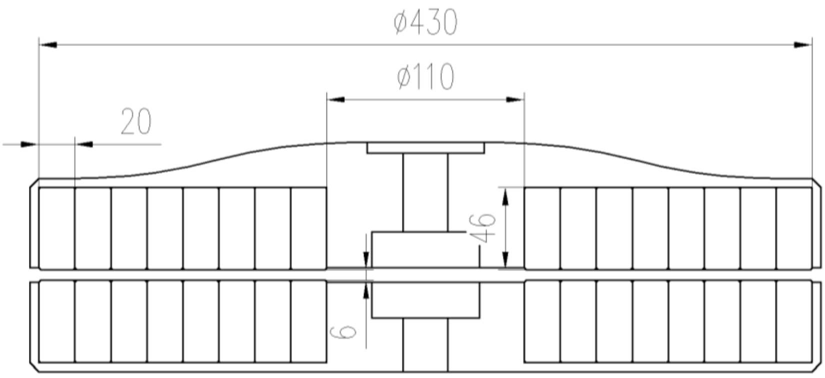


Fig. 6. Dimensions of the magnetic bearing cross-section

The cross-section in Fig. 6 was used to build the geometrical form of the numerical model of the magnetic bearing, created in the FEM 4.2 program. This program enables calculations of magnetic field strengths and interaction forces for 2D models of a given thickness.

Figure 7 shows a digital computational model with the directions of magnetic poles for each permanent magnet and the finite element meshing. The magnets in the disc are arranged alternately with magnetic pairs. The magnets are made of Neodymium N42. The alternating arrangement of the pairs will increase the force of interaction between the bearing disks several times.

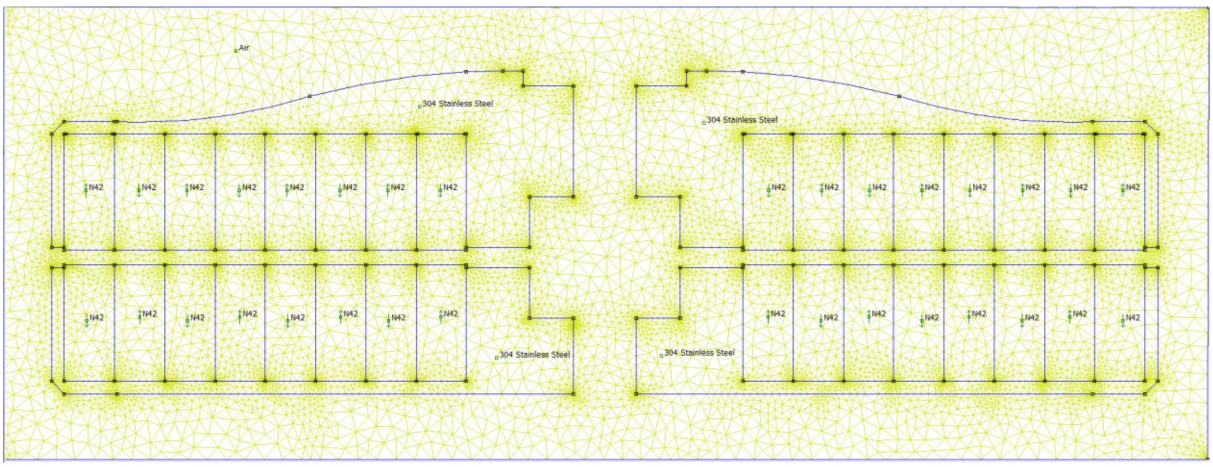


Fig. 7. Computational model with the direction of magnetic poles developed in FEM 4.2

The results of numerical calculations in a map form with the magnetic field strength and lines of force are shown in Figure 8.

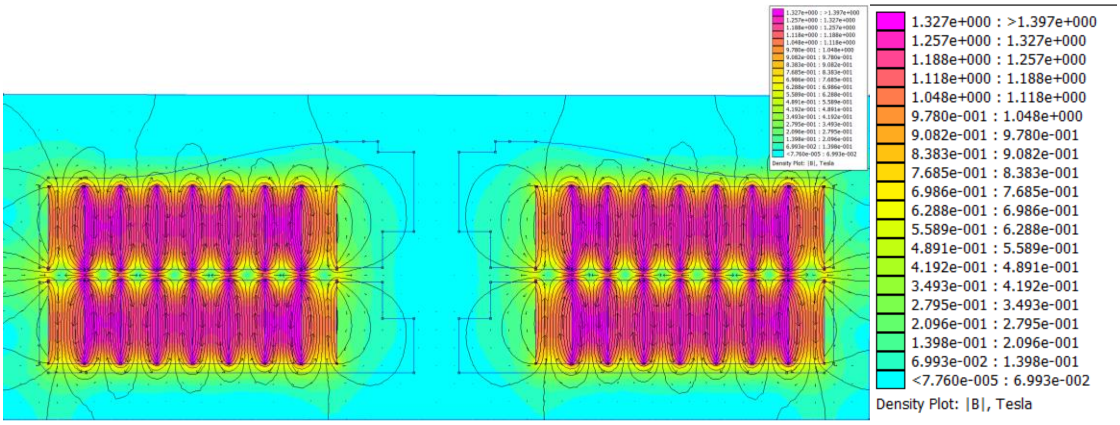


Fig. 8. Distribution of magnetic field lines against the background of the magnetic field strength map in a magnetic bearing

Figure 9 shows simulation of the force acting on the upper disc (marked in green). Calculated interaction force of 71.3 N corresponds to a 1 mm layer of magnets.

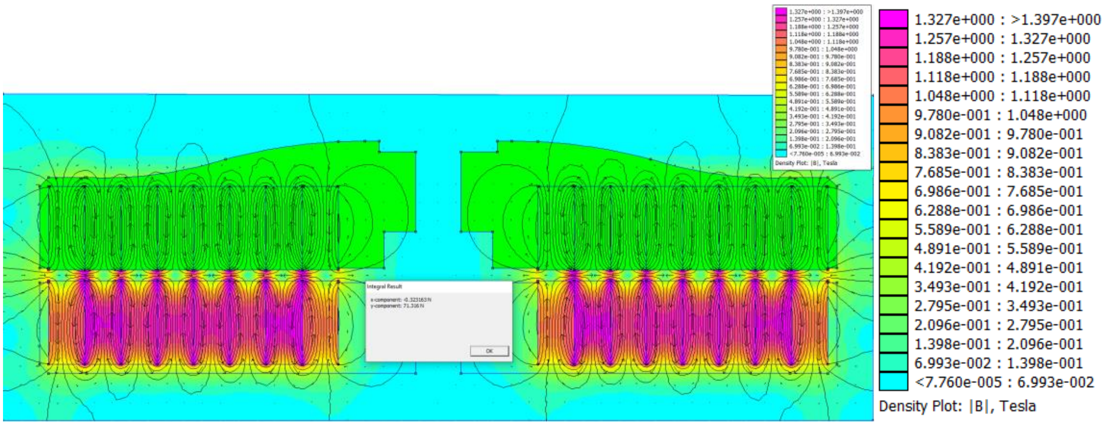


Fig. 9. Interaction force between the magnetic bearing discs for a 1 mm magnetic layer

Calculated force for a 1 mm layer was multiplied by the thickness of applied permanent magnets. The approximate force in the magnetic bearing will be 30.2 kN. This is the value of magnetic field strength for a 6 mm gap. This force is sufficient for the designed rotor-loaded bearing. For a 10 kN load, the gap between the discs will increase to approx. 10 mm.

4. Conclusions

The concept of low-speed kinetic energy storage - LSFESS fills a significant gap in the field of energy storage dedicated to individual households. In the case of prosumer applications, high-speed energy storages used in industrial conditions have significant disadvantages regarding very high operating costs and complicated maintenance [8, 9].

The overall dimensions of the LSFESS, developed in accordance with the presented concept, allow it to be moved through standard passages and crossings and placed in spaces that do not require special preparation. Problematic in this case is the total weight of the device, which exceeds 1,000 kg. In LSFESS there is also a much more easy-to-use and compact control and supervision system for the device operation. The device is assumed to be maintenance-free on the part of the potential user. However, it should be subject to an annual technical inspection by a specialized service.

The energy density accumulated in the proposed solution is nearly 21 Wh/kg.

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In the case of slow-speed energy storage, where the rotors are most often made of steel [4], for rotating steel masses, a maximum 40 Wh/kg can be achieved. It can therefore be concluded that more detailed research work on the shape and mass of the rotor is required to achieve a higher energy density. However, for the assumed parameters of the energy storage, this may be difficult to achieve.

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Technology for increasing the level of environmental safety of iron ore mines with use of emulsion explosives

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Abstract:

Laboratory and industrial studies have established the total impact of environmentally hazardous substances, taking into account the distance from the source of emissions and the specific consumption of explosives. With the help of physicochemical analysis and biological testing, the dependence of the change in the conditional indicator of damage to bioindicators with an increase in the distance from the source of emission and the specific annual consumption of explosives was revealed. A methodology for calculating the environmental assessment of the state of atmospheric air around the mine ventilation shaft has been developed. The exponential dependence of the influence of surface concentrations of environmentally hazardous substances on the damage of bioindicators at the cellular and organismic levels has been established, which makes it possible to assess the state of atmospheric air at industrial sites of iron ore mines. The proposed technology of sand drilling, which involves the use of emulsion explosives in mining ore deposits in chamber development systems will reduce emissions of environmentally hazardous substances into the atmosphere and increase the level of environmental safety of iron ore mines.

Keywords: source of emission, concentration, environmentally hazardous substances, physicochemical analysis, emulsion explosives, environmental hazard index

1. Introduction

Underground mining of iron ores is carried out with use of drilling and blasting method with explosives, in which the mine air, polluted by explosion products and iron ore dust, is released into the atmosphere without purification [1]. This generates an environmental hazard in the areas of operation of mining plants [2]. Long-term exploitation of deposits causes a negative impact on the environment, affecting almost all its elements, and leads to an increase in the levels of air pollution, contamination of water bodies, land, as well as to the accumulation of a significant amount of industrial waste in the mining regions of Ukraine. The range of anthropogenic impact on the biosphere depends on the volume of the main production, i.e. the volume of mined iron ore. This situation leads to a change in the natural conditions of living organisms, including humans, a decrease in biodiversity, an increase in morbidity, a decrease in quality and a reduction in the life expectancy of the population.

The level of environmental safety of underground iron ore mining operations remains quite low, due to insufficient knowledge of the mechanisms of mine and atmospheric air pollution by harmful emissions and the lack of effective means of controlling these emissions. As a result, pollution of environmental objects in the areas affected by iron ore mines increases. In this regard, scientific interest is oriented onto the establishment of patterns of air pollution from mine emission sources, which is the basis for the development of effective methods enabling to assess the level of environmental safety and to introduce highly effective environmental technologies. Therefore, an increase of the level of environmental safety in the extraction process of iron ores and an improvement of the condition of environmental objects in industrial regions is an urgent task.

2. Literature review

The mining industry is one of the most polluting industries in terms of production volume and the amount of pollutant emissions into the atmosphere. As a result of the activities of mining plants, organized and unorganized emissions of environmentally hazardous substances into the atmosphere have a technogenic impact on the air. This leads to pollution of the atmosphere in the surrounding areas, an increase in morbidity and a negative impact on living organisms [3]. At the same time, the nature and range of this impact in each case are different and are determined by the production rates, technical and zonal-climatic features of the deposits in operation.

The authors of the publication [4] presented the results of statistical data analysis of sanitary and hygienic indicators in the case of the environment in the Chervonograd mining region. Data concerning the number of samples of soil, water and atmospheric air, exceeding the standard values, were introduced into the single measurement system, namely to conditional pollution indicators of biological systems according to the methodology presented in the publication [5]. The performed studies of individual components of the environment according to sanitary and hygienic indicators, which considered their average value in the Chervonograd mining region (Lviv region, Ukraine), using an integral conditional indicator of pollution, showed that the level of environmental pollution in total should be defined as "above average", and the category of environmental hazard of the region's environment is "dangerous". Based on this, the authors concluded that significant environmental pollution in the region requires an implementation of measures aimed at improving the quality of the environment, and reducing the impact of the region's mining industry on biota and humans through an introduction of low-waste and waste-free technologies for the extraction and enrichment of minerals. In the conducted research work, there are no regularities of changes in biological indicators with an increase in the distance from emission sources, but only statistical data and a qualitative assessment of the state of the mining region are presented.

In the development process of ore deposits, the main method of extracting minerals is blasting. Almost a third of the explosives used in the mining industry are TNT-containing ones, which are a source of increased release of gaseous toxic emissions. A group of authors in the work [6] presents the results of experimental studies on the methods enabling to neutralize gaseous emissions during explosions in granite mining quarries. As a result of industrial research, it was found that the acceleration of chemical reactions during a transformation of explosives, caused by the presence of calcium hydroxide and sodium sulfate, reduces toxic emissions. The emissions reduction of carbon oxides and nitrogen is achieved by introducing neutralizers in special designs of clogging devices, by mixing with explosives, placing neutralizers at the junction of explosives and clogging, which does not affect the intensity of grinding rocks, and in some cases even improves it. After the secondary reactions take place, the toxic gases contained in the explosion products can be neutralized by alkali metal salts, oxides and alkaline earth metal hydroxides, since they easily bind the oxides of carbon and nitrogen to form the corresponding nitrates and nitrites.

The results of the study, presented in [7], consist in establishing the formulas of dispersion of the dust cloud after explosions in iron ore quarries of the Kryvyi Rih basin and the level of changes in the environmental hazard. On this basis, environmentally effective ways and means of reducing dust emissions into the environment have been developed. A methodology for calculating the height of dust cloud rise, taking into account the dispersion of dust particles and other influential factors, has been developed. Calculations of the dust cloud scattering showed that the emissions range of coarse iron ore dust is from 0.14 to 4.4 km, and finely dispersed – 40 – 70 km. At the same time, specific dust emissions with a total dispersion area of 28770 km^2 reach 1.302 kg/km^2. Dust cloud suppression is performed by water spraying [8]. An analytical formula for assessing the effectiveness of dust control in relation to the diameter of dust particles, water droplets, their speed of movement, the amount of water spray, the height of the cloud, as well as the total coefficient of capture of dust particles by water droplets has been established. A way to reduce the height of the dust cloud and gas emissions during explosions has been developed based on optimization of charges parameters. An improved design of borehole charges is proposed, which involves the use of a rubber plug with an anchor device as part of the hammering process. According to the results of the study, no regularities of changes in the stability of bioindicator plants, depending on the specific consumption of explosives during the explosions, were established.

3. Purpose

The analysis of the work performed in the direction of the technogenic impact of mining plants on the atmospheric air made it possible to establish that the research was carried out exclusively for quarries. An assessment of the impact of mining enterprises engaged in the development of ores using the underground method turned out to be needed. Lack of scientific substantiations of regularities of general toxico-mutagenic activity of atmospheric air and biological signs of agrophytocenosis in industrial sites and territories adjacent to the iron ore mine does not allow to assess the degree of impact on the flora, and, therefore, to take this into account in the technology of underground mining.

Therefore, the aim of the research work is to create a technology that increases the level of environmental safety of iron ore mines by reducing emissions of environmentally hazardous substances into the atmosphere.

To achieve this goal, the following tasks were solved:

- to assess the levels of pollution of environmental objects at different distances from the sources of emissions and to establish regularities of the impact of emissions of iron ore mines on the condition of atmospheric air;
- to assess the parameters of the environmental hazard of the iron ore mine regarding emissions into the atmosphere;
- to develop a technology for drilling and blasting, which increases the level of environmental safety of the underground mining of iron ores.

4. Methods

The tasks were solved by the following methods: laboratory tests with use of physicochemical method – to establish distribution formulas of ground concentrations of environmentally hazardous substances; biological testing – to assess the state of atmospheric air in the territory adjacent to the iron ore mine; methods of mathematical statistics – for processing test results, identifying relationships and assessing the reliability of the results of experiments; environmental analysis – to determine the level of

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reduction of environmental hazards using various technologies for drilling and blasting in the extraction process of iron ores.

5. Results

Ukraine has the 10th part of the world's iron ore reserves, a third of which accounts for the current production volume. The most significant deposits of iron ores are: Kryvyi Rih iron ore basin, Kremenchug iron ore district, Belozersk iron ore district, Konsky district of magnetic anomalies, Prydniprovsky iron ore region, Priazovsky iron ore district, Odessa-Bila Tserkva iron ore region and Kerch region. Of the listed iron ore deposits, the Kryvyi Rih-Kremenchug iron ore zone (basin) and the Belozersk iron ore region are currently being developed by open and underground methods [9]. The ores of the Kryvyi Rih basin are developed by 9 quarries and 8 underground mines, Kremenchug iron ore district – by 2 quarries, Belozersk iron ore district – by 2 underground mines. In order to reduce the negative impact on the environment during underground operations in 2011, all the quarries were transferred to using emulsion explosives (EVR). In underground mining operations, the introduction of EVR faced problems related to the development of drilling technology and charging machines for their use. Nowadays in the iron ore mines of Ukraine, TNT-containing explosives with the volume of 15-40% of the annual consumption of explosives are still used as the main explosives. After blasting operations, exhaust air from the mines is released without purification into the atmosphere through ventilation shafts. This is due to the fact that nowadays there is no effective equipment and treatment facilities for the capture and purification of gases that are emitted to the surface in significant volumes. Depending on the location of the mines and their ventilation shafts, the output stream of air affects negatively the condition of environmental objects and the health of the population living in the adjacent territory.

At present on the territory of the Krivoy Rog basin there are 8 mines. The structure of PJSC "Kryvyi Rih Iron Ore Plant" includes mines: "Batkivshchyna", "Pokrovska", "Kozatska" and "Ternivska", pjsc "Sukha Balka" – "Yuvileina" and "Im. Frunze", to PJSC "ArcelorMittal Kryvyi Rih" – "Them. Artema", to PJSC "Central Mining and Processing Plant" – "Them. Ordzhonikidze". The structure of PJSC "Zaporozhye Iron ore Plant" (PJSC "ZZRK"), which develops rich iron ores of the Yuzhno-Belozersk deposit (Bilozerka iron ore district, Zaporizhia region), includes the mines "Operational" and "Tunneling". According to the Target Regional Programme of transition of mining and processing plants to TNT-free, environmentally friendly EVR, in 2009 an iron ore plant with the most modern equipment and ore mining technology, which is PJSC "ZZRK" (Dniprorudne), was chosen as the basic enterprise. Therefore, the industrial site of PJSC "ZZRK" and the adjacent territory is a present testing area for research to improve the level of environmental safety.

During 2006 – 2010, measurements of the concentration of harmful gases in air samples were carried out with use of the Palladium-3M gas analyzer and the GX-M gas detector. With the help of these devices, the concentration of carbon monoxide and nitrogen oxides was measured for three ventilation shafts of mines. Sampling of the analyzed air was carried out during the inter-shift break after blasting in the mine. Next, the ground concentration of environmentally hazardous substances was determined, which is necessary to obtain a qualitative and quantitative assessment of their total impact on atmospheric air. Analysis of the values of ground concentrations of the total impact of environmentally hazardous substances has shown that with an increase in the distance to 1500 – 2000 m from the source of emission, the concentration value decreases by 3–5 times. Thus, the performed studies enabled to get empirical formulas that determine the ground concentration of environmentally hazardous substances in unit fraction of limiting of concentration (u.f. of LOC), taking into account the specific consumption of explosives and the distance from the source of emissions:

– for the "North-Ventilation" tube:

$$C_{sum.v} = 1.39 \cdot q^{1.65} \cdot e^{-0.001 \cdot L} \text{ u.f. of LOC} \quad (1)$$

where:

q – average annual unit consumption of explosives, kg/t;
L – distance to the source of release, m.

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– for the "South Ventilation" tube:

$$C_{sum.v} = 1.07 \cdot q^{1.24} \cdot e^{-0.0009 \cdot L} \text{ u.f. of LOC} \tag{2}$$

– for the "Drainage-Ventilation" tube:

$$C_{sum.v} = 0.72 \cdot q^{2.34} \cdot e^{-0.0008 \cdot L} \text{ u.f. of LOC} \tag{3}$$

The results of the study on the state of mine air in the conditions of PJSC "ZZRK" are fully presented in [10].

To assess the toxico-mutagenic activity of atmospheric air, test sites were identified, which were located in four directions of the world at the distance of 50, 100, 300, 500, 1000 and 2000 m from three ventilation tubes. Sampling of plant pollen at all the points of test sites was carried out during the spring-summer season in 2009-2011. The assessment of the toxicity or potential mutagenicity of atmospheric air was carried out according to the test "Sterility of plant pollen, Methodical recommendations 2.2.12-141-2007" [11] using the iodine method of staining. The essence of the method consists in staining of pollen cells of higher plants, depending on the starch content in them. Under the microscope, using a meter, sterile (non-viable) and fertile (viable) pollen grains were counted.

According to the results of the research, it was found that in 2009 the highest values of conditional damage indicators (UPU) of bioindicators in the range of 0.400 – 0.550 conventional units (USD) were observed at the distance of up to 500 m from emission sources. With the distance from emission sources (from 500 to 2000 m), there is a decrease in the UPU of bioindicators from 0.400 to 0.250 USD, and at the distance of more than 2000 m, the UPU decreases to 0.200 USD. In 2010, it was found that at the distance of 600 – 700 m from emission sources, the UPU decreased from 0.600 to 0.400 USD. Sources of UPU emissions are approaching 0.200 USD. According to the results of studies conducted in 2011, it was found that near emission sources at the distance of up to 500 – 600 m, UPU decreased from 0.600 to 0.400 USD. With an increase in distance from 500 to 2000 m, there is a further decrease in UPU from 0.400 to 0.250 USD. Over 2000 m UPU decreases to 0.200 USD, which is associated with a decrease in the negative impact of pollution.

According to the results of the study, an empirical formula was obtained that determines the UPU, taking into account the specific annual consumption of explosives and the distance from the source of emission:

$$UPU = 0.41 \cdot q^{-0.53} \cdot e^{-0.0003 \cdot L} \text{ u.f.} \tag{4}$$

Further studies of the toxico-mutagenic activity of atmospheric air have given a correlation between the UPU change and the value of the ground concentration:

$$UPU = 0.53 \cdot C_{sum.v} + 0.25 \text{ u.f.} \tag{5}$$

The main results of the study of toxic-mutagenic activity of atmospheric air around mine emission sources are presented in [12].

To determine the anthropogenic impact on the processes of ontogenesis of winter wheat in July 2011, wheat sheaves were selected from test sites at the area of 1 m^2, located along the predominant wind direction at distances of 50, 100, 300, 500, 1000 and 10000 m from the source of the emission. To establish the nature of the change in the biological characteristics of winter wheat, studies of ontogenesis indicators of trial sheaves were carried out. Analysis of the values of linear dimensions of wheat has been carried out. It was stated that environmentally hazardous substances coming from ventilation tubes significantly affect the linear dimensions of winter wheat ontogenesis, and contribute to their increase when approaching the source of exhaust. Due to a further analysis of the values of the weight indicators of wheat, it was found that harmful gases that came from the ventilation tubes also significantly affected the weight indicators of ontogenesis of winter wheat, and contributed to their increase when removed from the source of exhaust.

Further research enabled to obtain an empirical formula of biological yield from the value of the ground concentration of the total impact:

$$B_{biol} = 82.21 \cdot e^{-0.986 \cdot C_{sum.v}} \text{ c/ha} \quad (6)$$

In the absence of emissions, the biological yield reaches the maximum value of 82 c/ha. In the case of an increase in the ground concentration of the total impact to 0.5 hours from the LOC, which corresponds to the distance of up to 150 m from the source of emissions, the biological yield is expected to decrease to 50 c / ha, which corresponds to 40% of losses. When the ground concentration is reached, the total impact of the LOC value leads to a drop in yield of up to 60% or 1.4 times, which is about 30 centners per hectare. The obtained formula will provide a forecast of the biological yield of winter wheat with a change in the value of the total ground concentration impact of environmentally hazardous substances.

The experiment to determine the effect of technogenesis consisted in the germination of winter wheat grains. To do this, 100 prepared grains were placed on filter paper laid out in laboratory dishes. The germination of winter wheat grains was carried out for 72 hours while maintaining a constant ambient temperature of 25°C, while every 12 hours the number of germinated seeds was determined in order to assess their germination. After 3 days, the average length, cottage cheese and dry mass of the roots of grain seedlings selected at test sites at the distance of 50, 100, 300, 500 and 1000 m were determined, which were then compared with the grain indicators of the control site (10000 m) to obtain reliable results.

The analysis of the values of biological characteristics of sprouted wheat grains enabled to find out that environmentally hazardous substances coming from ventilation shafts significantly affect the crops of agrophytocenosis in the first generation, and contribute to an increase in technogenesis when approaching the source of exhaust. Studies on the influence of technogenesis on agrophytocenosis crops in the first generation of winter wheat enabled to establish correlation of changes in the phytotoxic effect and the amount of the ground concentration:

– by the length of the seedlings

$$FE_v = 0.008 \cdot e^{17.53 \cdot C_{sum.v}} \ \% \quad (7)$$

– by the length of the root system

$$FE_k = 0.046 \cdot e^{13.96 \cdot C_{sum.v}} \ \% \quad (8)$$

– by raw weight

$$FE_{syr.v} = 12.16 \cdot e^{2.95 \cdot C_{sum.v}} \ \% \quad (9)$$

– by dry weight

$$FE_{sukh.v} = 7.64 \cdot e^{2.94 \cdot C_{sum.v}} \ \% \quad (10)$$

The main results of the analysis of changes in the biological characteristics of winter wheat and the effect of technogenesis on winter wheat in the first generation are presented in [13].

To save time and increase speed of environmental assessment, the conducted research work necessitates a development of an algorithm for calculating the level of environmental hazard. Based on the results of the study of the ecological condition of atmospheric air, a methodology for calculating its

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parameters within the industrial site and in the territories adjacent to the mine in the following sequence was proposed.

1. Total ground concentration impact of environmentally hazardous substances

$$C_{sum.v} = 1.06 \cdot q^{1.74} \cdot e^{-0.0009 \cdot L} \text{ u.f. of LOC} \quad (11)$$

2. The UPU of indicators is determined by the formula (5);
3. The yield of winter wheat is determined by the formula (6);
4. The phytotoxic effect is determined by the formulas (7) – (10).

The results of many years of research on the ecological state of the atmospheric air of the industrial site and the territories adjacent to the mine, using physicochemical analysis and biological assessment, made it possible to make an environmental assessment of the condition of atmospheric air around emission sources. The necessary data on determining the environmental assessment of the condition of atmospheric air around the ventilation shaft of the mine are presented in Table. 1.

Table 1. Environmental assessment of the state of atmospheric air around the mine emission source

Ground concentration of total exposure, $C_{sum.\ v}$, u. f. of LOC	**Conditional indicator of damage *UPU*, u. f.**	**Biological yield, In_{biol}, c / ha**	**Level of damage indicators**	**Condition of atmospheric air**
≤ 0. 095	0 – 0. 150	≥ 74. 9	low	Favorable
	0. 151 – 0. 300		below average	Alarming
0. 096 – 0. 378	0. 301 – 0. 450	74. 8 – 56. 7	medium	Conflict
0. 379 – 0. 661	0. 451 – 0. 600	56. 6 – 42. 9	above average	Threatening
0. 662 – 0. 944	0. 601 – 0. 750	42. 8 – 32. 4	high	Critical
0. 945 – 1. 415	0. 751 – 1. 000	≤ 32. 3	maximum	Dangerous

From Table 1 it can be seen that the magnitude of the total ground concentration impact, UPU and biological yield of winter wheat, determines the level of damage to the indicators and the condition of atmospheric air within the industrial site and the territory adjacent to the source of emissions of the mine.

Analysis of the test results of atmospheric air near the ventilation shafts of PJSC "ZZRK" with the use of physicochemical analysis and biological assessment showed that the mine air coming from the tubes was saturated with environmentally hazardous substances that were generated as the result of underground mining, in particular blasting operations, having a negative impact on the surrounding flora. Therefore, the conducted studies need the use of modern environmentally friendly EVR and a development of new technologies for drilling and blasting, both during mine operations [14] and when performing cleaning activities [15].

The extraction of iron ores using the underground method is associated with drilling and blasting [16], which largely determine the efficiency of the field development [17]. Taking into consideration high costs of industrial TNT-containing explosives, danger during their transportation and the prospects for a development of mining plants, it would be advisable to use explosives manufactured directly at the blasting sites [18]. This is due not only to the safety of transportation [19] and mining [20], but also due to smaller volumes of exhaust explosion products [21]. The authors proposed the use of liquid EVR Ukrainite-PP-2 [22]. Thus, when 1 kg of such EVR is used, 0.056 mol or 1.25 liters of carbon monoxide is generated in the cloud. In addition, the presence of calcium oxide (CaO) in the exhaust products of the explosion ensures the absorption of nitrogen oxides, which can be generated in violation of the stoichiometric ratio of components or incomplete response of components during the explosive transformation of charges [23].

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The analysis of the technology of cleaning activities in mining blocks showed that the technology of ore extraction in chamber development systems involves the use of sucking fans [24], in which for the use of liquid EUR Ukrainite-PP-2 it is necessary to apply special means to keep EUR charges. Therefore, for the extraction of ore, it is proposed to improve the BPD technology, namely, to apply new technological schemes for conducting cleaning activities using EVR, when working out deposits with a capacity of more than 5 m (Figs. 1 and 2).

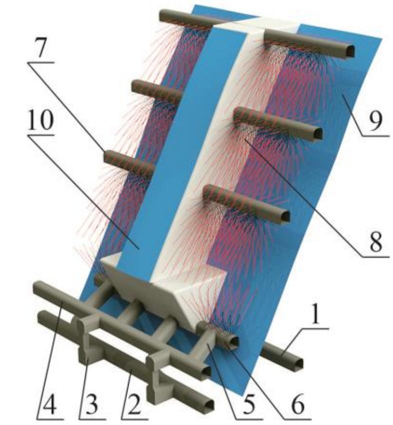

Fig. 1. Technological scheme of cleaning activities in blocks with the use of EVR for the fire bridge of ore with the capacity of 5 – 25 m: 1 – field view of the drift lying side; 2 – ore sliding drift; 3 – niche for a vibrating feeder; 4 – drift of the delivery horizon; 5 – loading device for self-propelled truck; 6 – trench drift; 7 – subsurface drilling drift; 8 – downward wells; 9 – lying side of the deposit; 10 – hanging side of the deposit

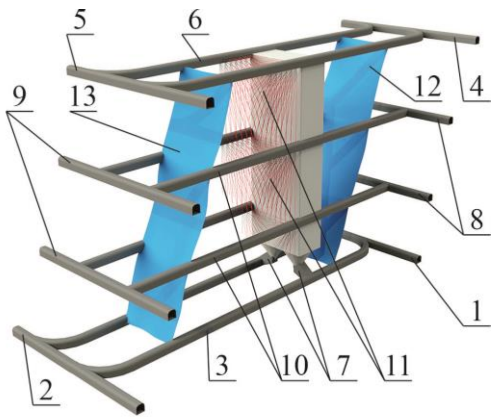

Fig. 2. Technological scheme of cleaning activities in blocks with the use of EUR for ore deposits with the capacity of more than 25 m: 1 – recoil drift of the lying side; 2 – recoil drift of the hanging side; 3 – recoil item; 4 – ventilation shaft of the lying side; 5 – ventilation shaft of the hanging side; 6 – ventilation and drilling item; 7 – niche for vibrating feeder; 8 – subsurface drift of the lying side; 9 – subsurface drift of the hanging side; 10 – drilling item; 11 – downward wells; 12 – lying side of the deposit; 13 – hanging side of the deposit

The essence of the proposed technology of ore extraction is that the drilling is carried out in the direction of the lower subsurface or floor [25]. After that, the downward wells are charged with the EVR [26]. Technological schemes for extracting downward wells during cleaning operations in chambers, using EVR, have been developed, to reduce the complexity of charging and reduce the cost of blasting operations due to eliminating special means for keeping EVR charges in wells.

6. Conclusions

1. By determining the ground concentration in the result of total exposure to hazardous substances, it was established that their ground concentration is influenced by the distance from the emission source and the specific annual costs of explosives, which made it possible to identify formulas of changes in the total ground concentration impact of environmentally hazardous substances with an increase in the distance from each ventilation shaft of the mine. An assessment of the total toxico-mutagenic activity of atmospheric air enabled to find a correlation between the UPU change and the magnitude of the total ground concentration impact.

2. Studies of changes in the biological characteristics of winter wheat, which grows at different distances from the mine emission source, enabled to find that its linear dimensions near the emission source increase, and with distance from it decrease, and weight indicators, on the contrary, nearby – they decrease, and with increasing distance – they increase. According to the results of the study, a correlation of changes in the biological yield of winter wheat and the value of the total ground concentration impact and the distance to the source of emission was established.

3. By determining the consequences of technogenesis in the first generation, it was found that toxic gases coming from the ventilation shafts of the mine significantly affect cultures in the first generation, and contribute to an increase in technogenesis. The results of the study showed a correlation between the change in the phytotoxic effect and the value of the total ground concentration effect.

4. Based on the results of the study, an algorithm for calculating the environmental assessment of the atmospheric air condition at the mine industrial site and the territory adjacent to it was developed and an assessment scale was drawn up, which enabled to determine the parameters of environmental hazard of iron ore mine emissions.

5. To reduce the complexity of charging and reduce the costs of blasting operations by eliminating special means of keeping EVR charges in wells, technological schemes for extracting ore using downward wells have been developed when conducting cleaning operations in blocks using EVR for ore deposits with the capacity of more than 5 m. Developed technology of ore extraction during the treatment activities provides for the use of liquid EVR Ukrainite-PP-2. This solution will increase the level of environmental safety of iron ore mines by reducing emissions of environmentally hazardous substances into the atmosphere.

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Justification of rational parameters of the support mounting device of the roadheader

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Abstract:

An expert assessment of the existing means of keeping roof rocks in the area of work of people and machines was carried out. On the basis of computer modeling of the processes of interaction of rocks of mine workings with arched design options, variants of the design of the roof and their elements for temporary fastenings support are proposed. The parameters of the four sectional support are presented. Temporary arched support was used in the area of operation of the roadheader, which helps to reduce a number of technological operations and the use of manual labor and to increase the safety of service personnel. The results of research aimed at the design improvement of the machine are described. The obtained parameters are checked by calculations and design solutions. The results can be applied in the passage of subway tunnels and other similar workings, in the construction of tunnels of roads and railways. The design of the device has the ability to adjust in height depending on the condition of the roof of the workings.

Keywords: temporary arched support, sectional hydraulic support, roadheader, state of breeds of roof and soil

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1. Introduction

Depending on the mining and geological conditions and the type of support of the development or exploitational workings of underground structures, the cost of support is from 30 to 45% of the total cost and the time spent on supporting reaches 20-25% of the time of the entire mining cycle. The workings that are carried out are supported with wooden, metal, bolting, precast concrete or monolithic concrete supports. The process of erecting supports, especially artificial ones made of wooden or reinforced concrete racks and arched metal, is still difficult to mechanize. To a greater extent, the process of bolting installations made of reinforced concrete tubing and monolithic concrete is convenient for mechanization. Mechanization of the construction of supports is complicated by the fact that it must be interconnected with other processes and machines in the workings, and especially with roadheader, drilling rigs, trucks, as well as with other means of transport. In addition, the variety of sections of mine workings and the occurrence of a continually changing rock pressure make it difficult to create a small number of uniformly shaped sizes of supports. These circumstances also complicate the task of mechanizing the construction of supports.

For temporary and permanent supporting of mine workings, mechanized supports are used, designed to support the roof above the machine in order to reduce the exposure of area near the face and transfer the machine, to a less compressed space, to install permanent support. The use of mechanized supports is very efficient, as it makes it possible to combine tunneling operations in the face and the construction of permanent supports and, in addition, ensures, due to the presence of overlap, the safety of machine operators. Mechanized supports are usually used in the roof, which is difficult to collapse, since otherwise there are phenomena of the so-called "trampling" of the roof and its collapse.

Work on the installation of a metal arched supports, using monoEIC supports [1-3] includes the delivery of a set of fasteners to the face, the installation of the frame and the movement of the monorail. Delivery of a package with elements of arched supports to the tail section of the machine is carried out in transport cars [4] on a special cargo monorail located in the drift. Arched supporting elements are stored on the platform.

In the work on the delivery of supports from the place of storage to the face, two operators are involved, one of which is the driver of the controlling device. Elements of the arched support from the drive are delivered to the mounting table, where the fastener is installed. The element is captured by the mounting boom, unfolded into a transport position and transported to the face for installation. This is a rather laborious and multi-way operation using manual labor. In addition, it is dangerous. Last few years presented works about temporary roof support in roadway development and tunneling [5-7].

Analysis of the state of the issue shows that the development and justification of the parameters of a fully mechanized, controlled and purposeful spacer-supporting device of a roadheader is an urgent task.

Conducting research on the work of a temporary mechanized support is an integral part of a roadheader. Depending on the condition of the roof, options for two- and four-units are considered. As a result of the analysis of two options, the results of software calculations for different roof loads were obtained. Comparing two designs, a two- or four-section design can be chosen. Given their weight and better adjustment to the unevenness of the workings, the weight reduction is possible due to the safety margin of the unit. Research results on the proposed options of the roof supports enable to protect the roof from collapse, protecting personnel and machines. To study this objective, an expert assessment of the existing means of supporting roof rocks in the area of work of people and machines was carried out.

2. Materials and Methods

In general, the supporting device is a hydraulic manipulator (Fig. 1) with a hydraulic cylinder 1 and an overlapping component 2. There may be several devices (Fig. 2), which are installed according to different schemes on the base of the machine. The top part is in contact with the roof and (or) with the side wall of the workings [8]. Depending on the working conditions, the design solutions of the devices may be different [9]. Local support of the workings according to the results of the predicted data of the stress state in front of the lying mountain range at a distance of up to one meter deep into the rock [9] is even assumed.

To calculate the loads [10], as the initial data, geometric parameters of the main or development mine workings can be taken, as well as mining and geological conditions, for example, in the following form: S_{cs} – cross-sectional area of the workings in the penetration, m^2 ; S_{ml} – the area of the workings in light, taking into account the profile of fastening and tightening, m^2 ; B – the width of the workings in the light, taking into account the profile of fastening and tightening, m; B_m – additional width of the workings in the light, taking into account the profile of fastening and tightening, m; γ_r – volumetric weight of rocks, kN/m³; H_m – height of workings in the penetration, m; H – depth of development, m.

Calculation of the coefficients required to determine the load from the rocks acting on the device

The coefficient of influence of the workings in the penetration

$$B_p = 1.1B + B_m, \text{ m} \tag{1}$$

The coefficient of influence of the geometric dimensions of the workings

$$K_s = 0.2(B_p - 1) \tag{2}$$

Coefficient of α type of support for the workings in the case of its implementation or operation.

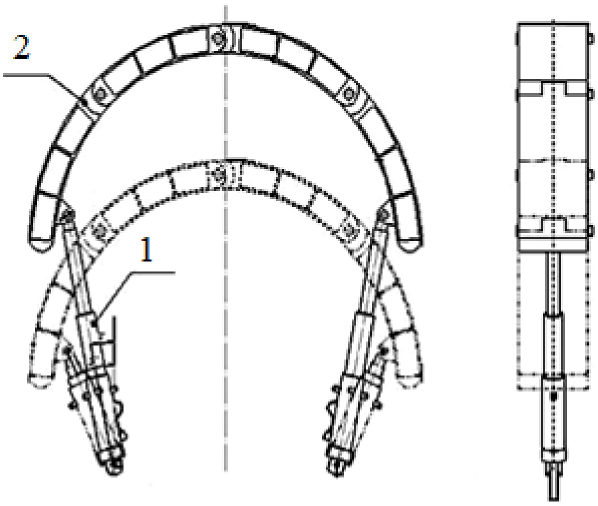

Fig. 1. Hydraulic manipulator of the supporting device:
1 - hydraulic cylinder; 2 - overlapping (component)

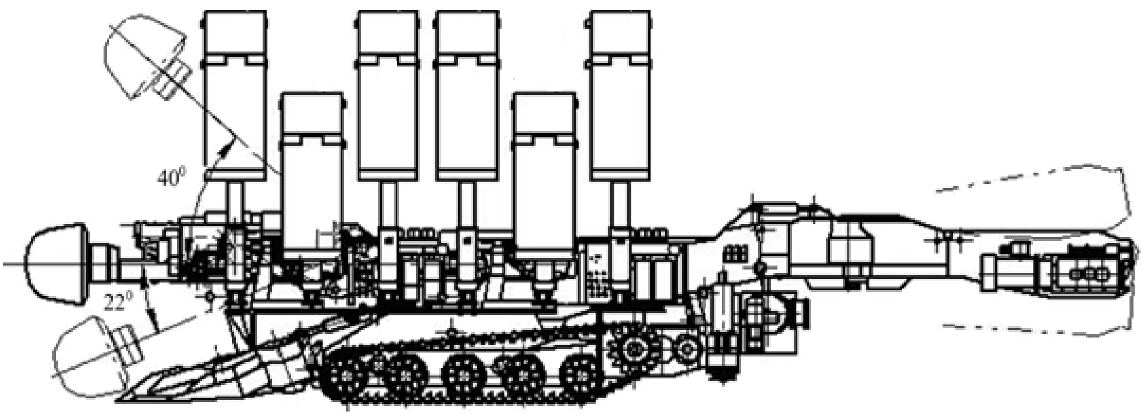

Fig. 2. Tunneling machine with support-mounting device

Calculation of strength from individual layers of the roof

The strength of rocks according to the design scheme of its definition [11] is determined. The effect of flattening [12] must be taken into account at least 20 m from the centre of the workings in the roof and floor. In this layer, rocks of considerable thickness should be divided into layers with a thickness of slightly more than 5 m [8, 13]. If the workings are watered, the resistance of the rocks is reduced by: 20% – for sandstones, 30% – for limestone, 40% – for aleurolites, 50% – for argillites.

$$R_j = R_r \cdot K_c, \text{ MPa} \tag{3}$$

where:

R_r – rock resistance to uniaxial compression, MPa,

K_c – coefficient that takes into account the violation of the breed array; $K_c = 1$ for an unbroken array; $K_c = 0.7$ – for a significantly disturbed array; $K_c = 0.4$ – in the zones of crushing, folds,

R_j – strength of individual layers of rocks, MPa.

Determination of the distance from the center of the workings to the center of the reservoir

According to the formula (4), the coefficient of influence of rock layers on the strength, K_i is calculated.

$$K_i = exp(-\alpha(l_i - (h/2)) \tag{4}$$

where:

l_i – distance from the center of the workings to the center of the reservoir, m.

h – the width of the coal seam, m

Calculation of the average strength of rocks

Strength of roof and floor rocks (5)

$$R_r = (R_1 m_1 K_1 + R_2 m_2 K_2 + R_3 m_3 K_3 + \dots + R_i m_i K_i)/(m_1 K_1 + m_2 K_2 + m_3 K_3 + \dots + m_i K_i), \text{ MPa} \tag{5}$$

According to the formula (6), the average strength of rocks is determined

$$R_m = (R_r + R_p)/2, \text{ MPa} \tag{6}$$

where:

R_p – strength of rock layers in a coal seam, MPa

Calculation of the displacement of rocks in the workings

Expected displacement of rocks in the workings

$$U_r = U \cdot K_r, \text{ m} \tag{7}$$

where:

U – displacement of the roof and rock mass, m,

K_r – coefficient that characterizes part of the shifts.

$$K_r = R_p \cdot K_n \cdot /(R_r + R_p) \tag{8}$$

where:

$K_n = 1.2$ – coefficient of proportionality of the roof displacement relative to the soil depends on the condition of the roof and soil components.

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The magnitude of the displacements of lateral rocks in mm is calculated by the following formula U_6:

$$U_l = U \cdot K_l, \text{ mm} \quad (9)$$

where:

K_l – coefficient characterizing the production layers changes in relation U_l to the total displacement of roof rocks from the total displacements of the roof and rock mass U.

The total displacement of rocks in the workings in a previously disturbed form is calculated according to the formula U_b:

$$U_b = 1.5 \cdot H \cdot K_s \cdot K_y, \text{ m} \quad (10)$$

where:

N – depth of embedding, m,

K_s – coefficient of influence of rock stability,

K_y – coefficient of stability of rocks.

$$h_v = U_r / \alpha, \text{ m} \quad (11)$$

The weight of rocks in kN is calculated from the formula:

$$P = 2/3 \cdot B_p \cdot \gamma_r \cdot h_v, \text{kN} \quad (12)$$

Calculation of the required force in the cylinder

The scheme (Fig. 3) [11], necessary to determine the force in the hydraulic props is taken into consideration.

From the equilibrium condition of loads P and the reactions in the hinges that reinforce the arch, the equation (13) is formulated

$$\sum F_{ix} = 0 \quad (13)$$

Given that, the effort in hydro-resistance can be defined as $d_s = rd_\varphi$.

$$N = \int_0^\pi \sin\varphi \cdot q \cdot r \cdot d\varphi = q \cdot r, \text{ N}$$

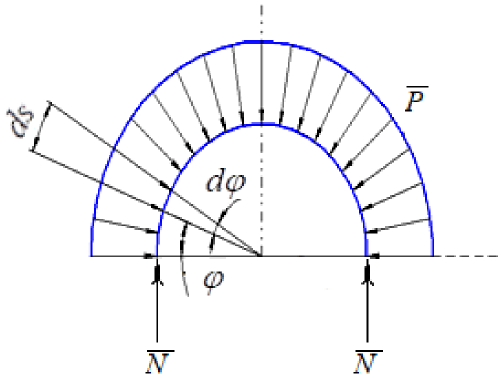

Fig. 3. Calculation scheme for determining the hydraulic resistance:
d_φ – elementary angle used during integration; φ – current angle, measured from 0 to π;
ds – the length of the elementary arc on the vault α

The design scheme (Fig. 4) of the determination of the working resistance in the hydraulic props depending on the angle of their installation is considered.

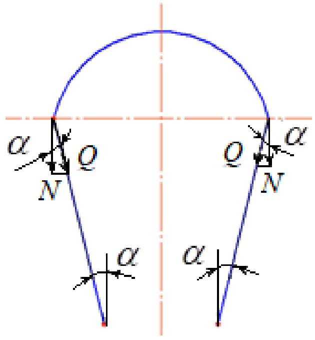

Fig. 4. Calculation scheme for determining the resistance in hydraulic props, depending on the angle of their installation: where α is the angle of installation of hydraulic props; Q – resistance of hydraulic prop, N

Resistance depending on the angle of support installation

$$Q = N/\cos\cdot(\alpha),\ \text{N} \tag{14}$$

According to the magnitude of the resistance from the typical series, a mine hydraulic with 1 or 2 displacements are taken into account.

Overlapping options for support-mounting devices of the tunneling machine

It is necessary that the overlap (Fig. 5) [11] has the possibility to adapt to the irregularities of the roof. Existing overlapping structures are metal-intensive and have a large weight. It is necessary to create an overlap that will withstand the weight of the rocks, and at the same time the increasing stresses in the roof should not exceed the permissible values.

Justification of the parameters of the four sectional overlapping device.

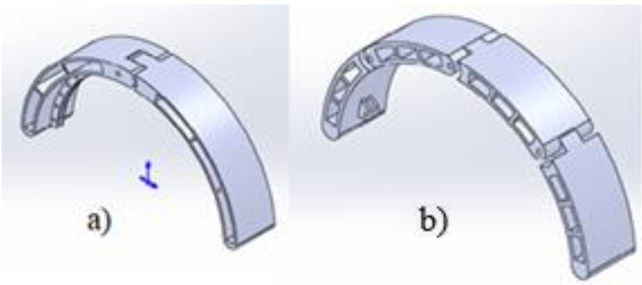

Fig. 5. Examples of overlapping devices: a) two-sectional, b) four sectional

These two constructions (Fig. 6) using the SolidWorks Simulation program are compared.

Set the load on the weight of the roof rocks P = 288.9 kN.

Set the alloy steel as material.

1) The weight of this structure is 2.5 tons.

The safety factor is approximately 10.

2) The weight of the 2-sectional overlap is 2.8 tons.

The safety factor is approximately equal to 17.

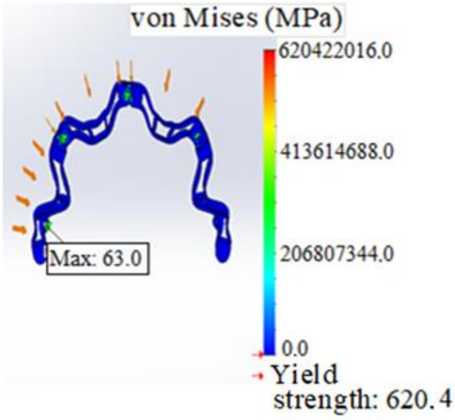

Fig. 6. The results of calculations of 2-sectional overlap

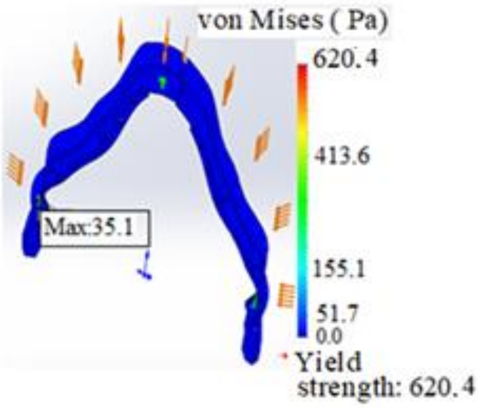

Fig. 7. The results of calculations of 4-sectional overlap

Comparing the two structures, based on the results (Fig. 6 and Fig. 7), a 4-sectional overlap is chosen, since it has a smaller weight and displacement, adapts better to the irregularities of the production, and has a lower strength coefficient.

Reducing the weight of 4-sectional overlapping element

Weight reduction is possible due to the large margin of safety factor of units [13].

With use of the Solid Works Simulation program, the overlapping units are analyzed.

Loading scheme of the 4-sectional overlapping unit (Fig. 8)

Estimated load *P*, kN;

material – alloy steel;

fasteners – fixed hinge.

The thickness of the overlap and of under-rib reinforcement is changed from 50 mm to 15 mm.

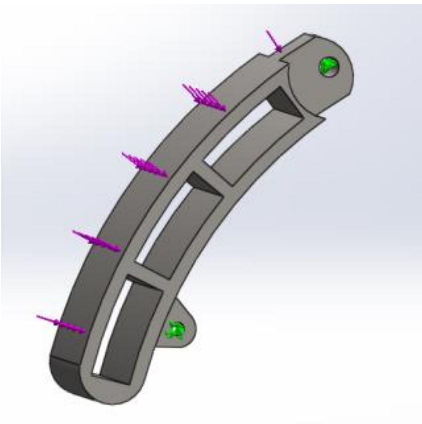

Fig. 8. Loading scheme of the 4-sectional overlapping unit

3. Results

The results of the study are listed in Table 1.

Table 1. Overlapping results

Item	Indicators	Numerical values							
1	Thickness of overlap, mm	50	45	40	35	30	25	20	15
2	Stress, MPa	39	42	53	56	60	62	85	140
3	Displacement, mm	0.02	0.1	0.13	0.19	0.28	0.43	0.89	2.1
4	Mass. kg	670	655	628	596	565	539	522	501

According to the obtained data. the graphs are built:

a) graph of the dependence of stresses on the thickness of the overlap and the under-rib reinforcement of Fig. 9;

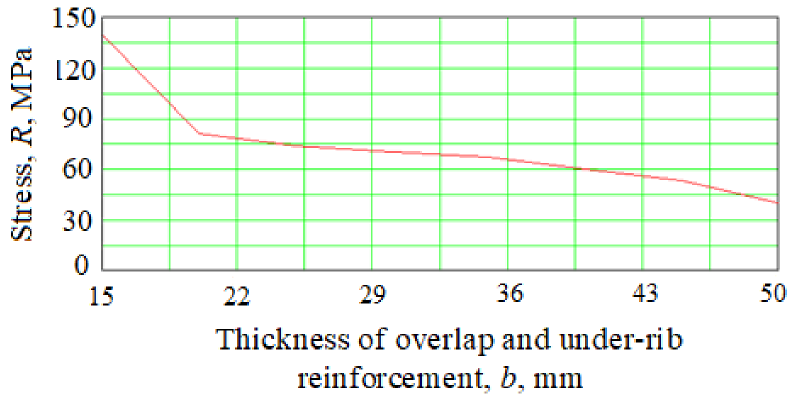

Fig. 9. Graph of stress dependence on overlap thickness and under-rib reinforcement

b) graph of the dependence of displacement on the thickness of the overlap and under-rib reinforcement (Fig. 10);

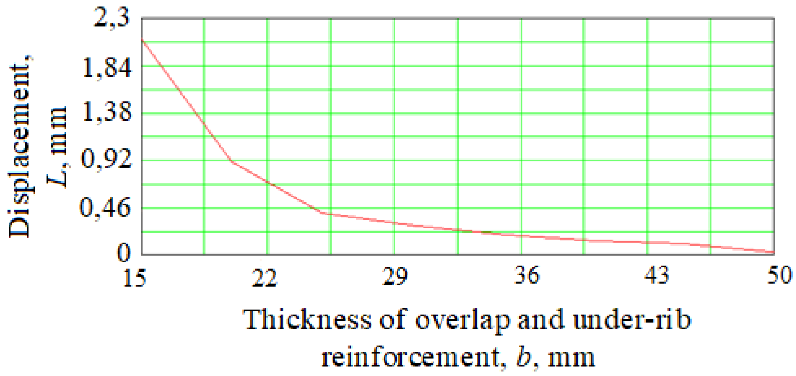

Fig. 10. Graph of displacement dependence on overlap thickness and under-rib reinforcement

c) graph of the mass dependence on the thickness of the overlap and the under-rib reinforcement (Fig. 11).

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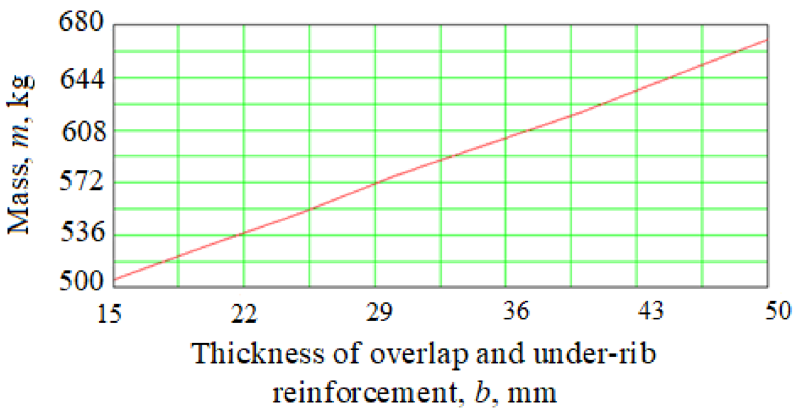

Fig. 11. Graph of mass dependence on overlap thickness and under-rib reinforcement

Depending on the condition of the roof and soil, the optimal structural parameters of the mechanized hydraulic fastening are chosen. Graphical dependences allow you to choose the working parameters of the roadheader with a spacer-fastening device. It is possible to remotely control the mining pressure control in the working area of the tunneling machine. According to the results of computer modeling, it was determined that the optimal design of the sections of the overlaps of the spacer-fastening device of the road combiner according to the criterion of the minimum mass with the specified strength and rigidity of the structure is a four-section overlap with the parameters: r = 2000 mm is upper radius; r = 1750 mm is lower radius; B = 20 mm is overlap thickness; k = 2 is the number of reinforcement edges.

4. Conclusions

Based on the operational analysis of a roadheader with a lightly collapsed roof some conclusions can be drawn. The results of research, aimed at the constructive improvement of the machine, are presented. The components may vary depending on the mining and geological conditions. The obtained parameters are checked by calculations and design solutions. The minimum mass of supporting device is significantly reduced, having a simultaneous impact on the rigidity and strength of the structure. The results can be applied to driving of subway tunnels and other similar workings, in the construction operations of roads and railways. The design of the device has the ability to adjust in height depending on the condition of the working roof.

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The diversity and plant species composition of the spontaneous vegetation on coal mine spoil heaps in relation to the area size

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Abstract:

Any newly created area includes human-created habitats such as the mineral material of post-coal mining spoil heaps undergoing natural colonization and ecosystem development during the succession processes of vegetation colonization. The study of the factors that influence the succession dynamics, and the mechanisms behind this, have a long history (including the species-area relationship or Arrhenius equation). Nevertheless, the list of scientific questions is increasing. One of the significant issues in the study of these processes is the relationship between factors influencing the Biodiversity–Ecosystem Functioning (BEF) relationships. The main prerequisite is the relationships between the plant species' assemblage mechanisms including diversity and the variety of assembly rules concerning the environmental abiotic habitat processes and these properties are not straightforward. At the large scale, parameters such as age and area of the colonized sites are considered to be important. These relationships are more complicated in newly established post-mineral excavation habitats where novel ecosystems are developing. Regardless of the degree of disturbances, vegetation re-establishes in such environments, as a result of spontaneous succession, by the colonization and establishment of the best-adapted organisms. In the habitats of post-coal mining spoil heaps with pure oligotrophic mineral conditions, the non-analogous, newly formed composition of flora, fauna, and saprophytes has been stated in many previous field studies. This study aimed to explore the biodiversity *versus* area size relationships, in particular, it investigated the species composition and diversity found in the development of the spontaneous vegetation formed during primary succession on mineral substrate habitats of post-coal mining spoil heaps of different area sizes. We tested the hypothesis: species diversity of the vegetation patches on coal mine spoil heaps becomes more diverse on larger sites over time. These results indicate that the area size of the spoil heap significantly affects the diversity of the vegetation. Regardless of which of the characteristics of the vegetation type (dominant species) is compared, the vegetation on the heaps differs depending on its area size.

Keywords: species-area relationship, Arrhenius equation, spontaneous succession, biodiversity–ecosystem functioning, non-analogous species composition, novel ecosystems.

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1. Introduction

In the urban-industrial landscape, it is possible to observe diverse natural, semi-natural and anthropogenic habitats that are undergoing natural ecosystem successional processes (Fig. 1). The change in plant species composition of spontaneous vegetation is a process which depends on many factors. The successional development is indicated by the sequential appearance and replacement of plant species assemblages that follow a disturbance event or the establishment of new land. The new habitat, and new area, can be the consequence of natural, or human, activity [1-4]. The biomass established as a result of primary production is the prerequisite of a heterotroph's (all grazing animals) survival. While the biochemistry of the organic matter of autotrophs and heterotrophs is the factor that shapes the saprophytic species composition and the process associated with the decomposition of organic matter e.g., bacteria, fungi, and mesiofauna assemblage that are consequently causing environmental changes in the substrate [5]. The feedback changes in biotic and abiotic environmental parameters induce the change in matter and energy flow during an ecosystem's successful development. These dynamic processes have led to intense discussion and to further studies on biodiversity–ecosystem functioning (BEF) relationships [6], which have now focused on a wide range of ecosystem functions (e.g. biomass production, carbon sequestration, litter decomposition, water retention, nutrient cycling, global change resistance) [7,8]. Clarifying the causality that is underlying the relationships between the plant species assemblage's mechanisms including diversity and the variety of possible assembly rules and environmental abiotic habitat processes and properties is not straightforward [9]. This is because synergetic influences and inherent feedback mechanisms between species assemblages, the structure of communities and the environment's biotic and abiotic parameters are all involved [10].

Human activity, mostly urbanization and industrialization, affects a vast area of the Earth's surface [11-13]. Many of Earth's landscapes, existing vegetation and the abiotic and biotic soil components have been disturbed or destroyed [14]. Frequently the resulting anthropogenic habitats provide unique conditions such as no soil profile, inadequate water conditions in the soil substrate, high salinity, lack of nutrients and diasporas, and a unique microclimate [15-20].

The plant species compositions and spatial distribution of the vegetation of novel ecosystems of post-industrial areas (e.g. coal mine spoil heaps) are usually different from that of plant communities known from natural and semi-natural habitats which makes it difficult to classify them using the accepted phytosociological (socio-ecological) which describe naturally occurring plant communities. Regardless of the degree of the disturbance, plants return to such habitats as a result of spontaneous succession that enhances the colonization and establishment of the best-adapted organisms. In these unusual habitats of pure oligotrophic mineral conditions, the non-analogous newly formed flora, fauna, and saprophytes has been described from many previous empirical studies [1,21-24]. The novel ecosystems which establish on these *de novo* sites differ significantly from the original and surrounding habitats [25-27]. These novel ecosystems become established as a consequence of differences in the physical and chemical properties of the primary substrate and thus the new soil substrate parameters [20,28,29].

This fact makes it difficult to assign them to commonly known phytosociological units of Braun-Blanquet system. A characteristic feature of the vegetation growing on coal mine spoil heaps is the mosaic of different vegetation patches which are dominated by various species confined to a variety of microhabitats [30-32]. The abundance of the dominant plant species causes the distinctiveness of each particular vegetation patch. The dominant species originate from a wide range of habitats, including aquatic, swamp, mire and marsh, as well as those from dry meadows and other grassland communities, stony gravel communities, and ruderal habitats. For the vegetation growing on the studied areas of post-coal mine spoil heaps, the most precise diagnosis is the identification of the dominant plant species, which determines the physiognomy of each distinctive vegetation patch. The dominant plant species (in terms of their percentage cover abundance) can be accompanied by numerous other species with varied abundances [32,33].

Fig. 1. The mineral materials of coal mine spoil heaps provide an environmental island within the urban-industrial landscape. The human-created habitats undergoing natural ecosystem succession and developing into novel ecosystems (Photo: G. Woźniak)

Natural succession is the process of gradual change within plant species assemblages and the associated organisms that are best adapted to the current biotic and abiotic habitat conditions. In natural and semi-natural conditions, the mechanisms of primary and secondary succession are relatively well understood [4]. At the large scale, time and area significantly influence the vegetation and species composition during the development of succession. There have been many studies focused on time as an important factor. There are fewer studies which consider the size of the area of a site that is undergoing colonization and succession as a significant factor influencing the colonization, establishment and persistence of species. In natural and semi-natural habitats, the dependence of the number of species on the size of the study area has long been known as the species – area relationship (SAR) [34]. Succession processes take place on all types of habitats and in all types of ecosystems, from water and wetland habitats, oceans, deserts, salt marshes to tundra, and rainforests. During succession, a pattern of changes is expected and appropriate for a particular habitat and ecosystem type whenever a new habitat becomes available or whenever an environment is disturbed.

For habitats developing on the sites of post-mineral excavation and other man-made sites, less research has been done to specify the Species – Area Relationship (SAR) and more studies are needed to address such relationships.

The aim of this study was to explore the composition of the vegetation and species composition diversity of the spontaneously developing *de novo* habitats on post coal mine spoil heaps of different heap areas and to investigate some aspects of their functional diversity during the primary succession process.

We tested the hypothesis on coal mining heap sites in Upper Silesia that species diversity of the vegetation patches will become more diverse on larger sites as the SAR Arrhenius concept suggested.

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2. Methods

2.1. Study area

The study was conducted on one type of post-industrial mineral excavation site: coal mine spoil heaps, located in the Upper Silesia coal mining district (Poland) (Fig. 2). The study area lies in the transitional climate zone between a temperate oceanic climate in the west and a temperate continental climate in the east. The mean annual temperature fluctuates between 7 and 9°C and precipitation varies between 700 and 900 mm. The vegetation season (days with average temperature > 5°C) is between 210 and 220 days [33].

A total of 112 post-coal mining sites were studied in the area. The studied heaps were of carboniferous rock and were composed mainly of claystone, siltstone, sandstone, conglomerate, coal shale, and small quantities of coal [33,35]. The surface of most of the heaps was characterized by longitudinal elevations and depressions established by the heaping process. The resulting vegetation had developed spontaneously since heaping and there were no subsequent manipulations of the heap substrates at the studied.

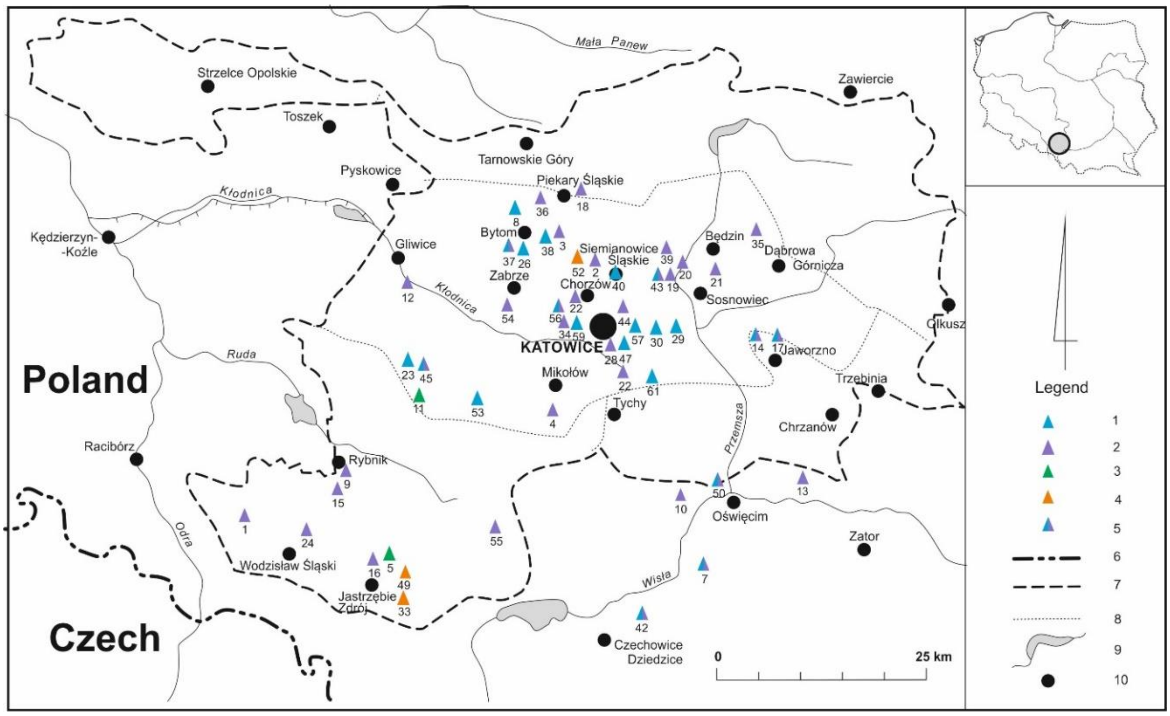

Fig. 2. The distribution of the coal mines of the Silesia Upland and heaps belonging to them: 1–5 – area size categories of heaps: blue triangle – up to 10 ha; purple triangle – up to 50 ha; green triangle – up to 100 ha; orange triangle – more than 100 ha; purple-blue triangle – area size of heap up to 10 ha and 50 ha; 6 – state border; 7 – borders of the Silesia Upland; 8 – minor geographical borders; 9 – rivers and lakes; 10 – towns and cities [33 – changed]

Coal mine spoil heaps are habitats that are difficult for plant colonization, establishment, and development. They are characterized by extreme abiotic conditions, e.g., large variations in humidity and daily temperatures (often reaching 50°C), high salinity, lack of soil, susceptibility to wind and water erosion, substrate instability, dusting, chemical, and thermal activity, and also biotic parameters such as lack of a seed bank and a deficiency of nutrients in the substrate. All of these determine the specificity of the flora and vegetation types which can tolerate the conditions found on these post-industrial areas [1,16,29,36-40]. These abiotic conditions are variable both in time and space, as well as are changing with the depth of the substrate. All these factors combine to present the environment of unmanaged coal mine spoil heaps and these are model examples of a novel ecosystem. Despite the harsh environmental conditions, including long periods of drought, and the high levels of compaction of spoil material [33], these heaps can be spontaneously colonized by herbaceous vegetation.

2.2. Vegetation sampling

Before starting field studies, the selected heaps have been divided into four area size categories (A – up to 10 ha; B – up to 50 ha; C – up to 100 ha; D – more than 100 ha). The vegetation sampling was conducted in randomly chosen patches on coal mine spoil heaps of different area sizes. The vegetation samples were collected in different environmental conditions in order to cover all the available habitat conditions occurring on unmanaged coal mine spoil heaps which were independent of the studied heap size. For each studied vegetation patch, a homogenous study plot was selected. The species composition and abundance (expressed as percentage coverage) of all species present were visually estimated. The cover abundance of species was estimated on a 12-point scale according to the rules (<1%, 1-5%, 5-10%, 10-20%, and then every 10%). The distribution of the studied heaps on the local map is shown in Fig. 2.

2.3. Measure of vegetation diversity

On the basis of species composition and abundance for each recorded vegetation patch, the following metrics were determined: the species richness, affinity of species to socio-ecological groups. The study covered vegetation patches consisting of species identified as typical of e.g. meadow, grassland rush and species without preferences to certain ecosystems and vegetation types.

Some of the analyses focused on dominant plant species according to the mass ratio hypothesis [41]. The identified dominant plant species were characterized by their socio-ecological origin, according to Oberdorfer et al. [42]. The analyzed species represented the following habitats: forest species: (Cl. *Vaccinio-Piceetea*) and (Cl. *Ouerco-Fagetea*, *Alnetea glutinosae*) and other species associated with forest habitats; meadow species (Cl. *Molinio-Arrhenatheretea*); broadly defined grassland species: (Cl. *Festuco-Brometea*) and (Cl. *Sedo-Scleranthetea*, *Nardo-Callunetea*); species of rock habitats, rock rubble – karst species (Cl. *Asplenietea rupestria*, *Violetea calaminariae*, *Thlaspietea rotundifolii*), species of clearings and fringes (Cl. *Epilobietea angustifolii*, *Trifolio-Geranietea*); ruderal species (Cl. *Artemisietea vulgaris*, *Agropyretea intermedio-repentis*, *Plantaginetea majoris*, *Agrostietea stoloniferae-Potentilla anserina*); salt marsh species (Cl. *Zosteretea marinae*, *Ruppietea maritimae*, *Asteretea tripolium*, *Honckenyo-Agropyretum juncei*, *Cakiletea maritimae*, *Ammophiletea*); segetal species (Cl. *Chenopodietea*, *Secalietea*); peatbog species (Cl. *Montio-Cardaminetea*, *Scheuchzerio-Caricetea*, *Oxycocco-Sphagnetea*); rush and aquatic species: (Cl. *Phragmitetea*, *Isoëto-Nanojuncetea*, *Bidentetea tripartiti*) and (Cl. *Lemnetea*, *Utricularietea*, *Potametea*).

The identified dominant species have also been analyzed in terms of geographical-historical groups, the alien and native plant species represent [43]: K – kenophytes (neophytes), A – apophytes.

2.4. Data analysis

The recorded vegetation patches were divided into four groups in terms of the coal mine spoil heap size area. Each group of records gathered data about vegetation patches growing on heaps with the same area. The vegetation taxonomic diversity (TD) was measured using several approaches and indices. For each vegetation patch, the dominant plant species were identified, the number of species were recorded, and the diversity metric such as Shannon-Wiener diversity index was calculated.

Based on the calculated species richness and the diversity index for each spoil heap area size group, the mean value, standard deviation, minimum and maximum were calculated. The list and frequency of vegetation patches dominated by particular species was prepared for each of the four spoil heap area sizes. The dominant plant species were categorized into socio-ecological and geographical-historical groups.

3. Results

3.1. Species richness, and diversity of vegetation patches on heaps of various area sizes

The lowest number (124) of patches was recorded on spoil heaps (of up to 100 ha), followed by 236 patches on the largest heaps (>100 ha), 475 patches were found on the smallest heaps up to 10 ha, and the highest number (1732) were found in those patches from heaps (up to 50 ha).

Species richness was highest on spoil heaps of up to 100 ha (4.17), and smallest (3.43) on heaps of up to 50 ha. However, differences found in species richness did not reach statistically significant level (H (3.2567) = 2.34, p = 0.5043) (Table 1).

Table 1. Species richness in patches in relation to the heap size area

Species richness	Heap size area			
	10 ha n =475	**50 ha** n =1732	**100 ha** n =124	**>100 ha** n =236
Mean	3.62	3.43	4.17	3.48
SD	2.31	2.23	3.44	2.03
Min.	1.12	1.00	1.25	1.15
Max.	12.88	17.11	16.62	1.15

n – the number of vegetation patches on each of the heap size area of the studied heaps

The highest number of different dominant plant species was recorded in vegetation patches growing spontaneously on heaps, with an area size up to 50 ha. In the vegetation patches present on the heaps of up to 100 ha, 29 different dominant plant species were identified, followed by 40 dominants in patches of more than 100 ha and 49 dominant species in patches up to 10 hectares of area. Eight of all dominant species were the most common (Table 2).

Table 2. Number of patches dominated by the most common dominant species in relation to area of the heap

The most common dominant plant species	The area of the heaps				
	10 ha	**50 ha**	**100 ha**	**>100 ha**	**TOTAL**
Betula pendula a	41	98	15	15	169
Betula pendula b	24	46		9	79
Betula pendula c	4	8			12
Calamagrostis epigejos (Fig. 3)	59	170	13	15	257
Chamaenerion palustre	13	64		17	94
Daucus carota	31	74	3	6	114
Melilotus alba	9	98	6	10	123
Phragmites australis (Fig. 4)	8	86	4	3	101
Poa compressa	46	82	5	6	139
Tussilago farfara (Fig. 5)	54	142	5	21	222

Betula pendula (as a tree) (present in 41 patches), *Calamagrostis epigejos* (59) (Fig. 3), *Poa compressa* (46) and *Tussilago farfara* (54) (Fig. 5) were the dominant species in more than 40 patches

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on the smallest spoil heaps (area up to 10 ha). On heaps with an area of 50 ha, 101 dominant plant species were observed. There were, on average, 17 patches per dominant species. In this area group, two dominant plant species such as *Calamagrostis epigejos* and *Tussilago farfara* were present in over 100, 170 and 142 vegetation patches respectively. On heaps with an area of up to 100 ha, 29 dominant species were found, with, on average, only 4 patches per dominant plant. On heaps with an area of more than 100 ha, 40 dominant species were found, with almost 6 vegetation patches per dominant plant species.

Fig. 3. Spontaneous vegetation type with dominance of *Calamagrostis epigejos* (Mysłowice site, Upper Silesia, Poland) (Photo: G. Woźniak)

Fig. 4. Patches with *Phragmites australis* in Sosnowiec (Upper Silesia, Poland) (Photo: G. Woźniak)

Fig. 5. Spontaneously occurring common patches of *Tussilago farfara* on coal mine heaps (Mysłowice site, Upper Silesia, Poland) (Photo: G. Woźniak)

3.2. The socio-ecological groups of dominant species on heaps of various sizes

The number of recorded patches of spontaneously developed vegetation dominated by species representing different socio-ecological groups is unequal on heaps of different area size. The largest number of vegetation patches dominated by ruderal, forests as well as segetal species was recorded on heaps with an area of up to 50 ha. In this group of heaps worth underlying are also patches dominated by aquatic or rush species. In contrast, the least number of vegetation patches was recorded on heaps with an area up to 100 ha. They were dominated mainly by ruderal species (Fig. 6).

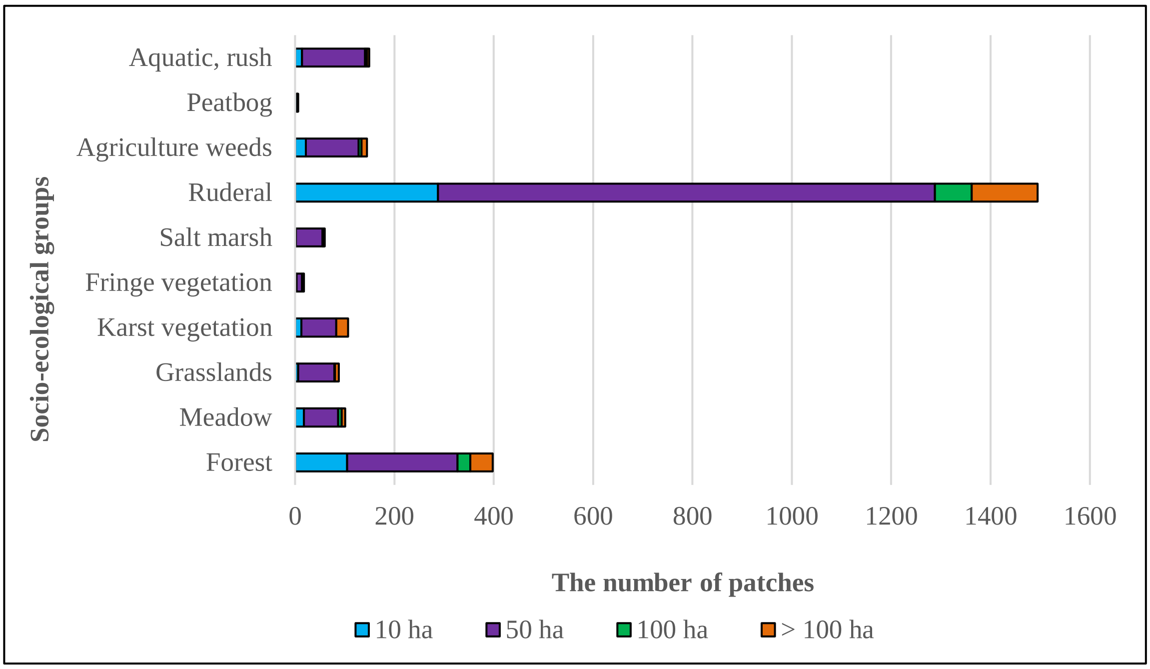

Fig. 6. Distribution of the number of patches in relation to heap area and the socio-ecological group of the dominant species in the patch

The distribution (percentage participation) of the number of patches dominated by particular socio-ecological groups, depending on the heap area size, is presented in Table 3.

Table. 3. Percentage participation of vegetation patches dominated by plant species representing particular socio-ecological groups in relation to spoil heap area and socio-ecological groups of the dominant species in the patch

Socio-ecological groups	The area of the heaps			
	10 ha	50 ha	100 ha	> 100 ha
Rushes and aquatic species	9	85	3	3
Peatbog species	71	15	0	14
Segetal species	15	73	4	8
Ruderal species	19	67	5	9
Salt marsh species	3	88	6	3
Species of clearings and fringes	17	61	16	6
Species of rock habitats, rock rubble – karst species	12	66	0	22
Broadly defined grassland species	7	83	1	9
Meadow species	18	68	7	7
Forest species (deciduous and coniferous)	26	56	7	11

The observed distribution of the number of vegetation patches on heaps of varied area sizes reveals significant differences and relationships (G=118.60; p <0.001) between the frequency of patches dominated by species representing particular socio-ecological groups and the area size of the spoil heaps.

3.3. The origin of dominant species in patches on heaps that differ in terms of size

Among the varied plant species characteristics that could be applied, the division between the alien (kenophytes =neophytes – neophytes recently introduced alien plants; archaeophytes – older alien plant species), and native plant (apophytes) species is very important, as alien plants threaten some ecosystems.

The distribution of the number of patches depending on the area of the spoil heap and the geographical-historical group represented by the dominant species in a given patch is shown in Fig. 7.

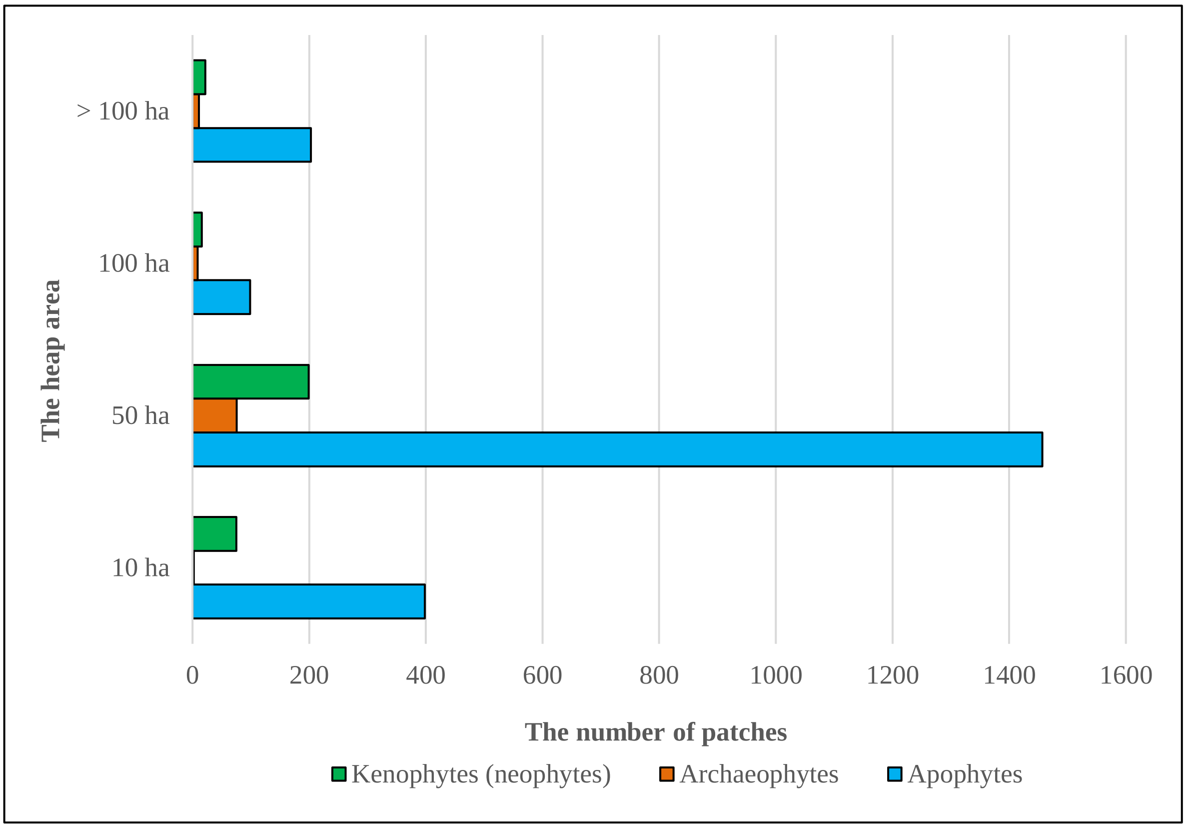

Fig. 7. The number of patches in relation to heap area and geographical-historical group of the dominant in the patch

It is worth underlying that apophytes predominate in patches developing on coal mine spoil heaps regardless their size area.

Kenophytes and apophytes occur more often than archaeophytes (older alien plant species), on heaps with an area of up to 10 ha. The highest number of patches with archaeophytes as well as apophytes as dominance were found on heaps up to 50 ha (Fig. 7).

As many as 199 patches dominated by kenophytes were recorded on heaps up to 50 ha. Among them are such species as *Conyza canadensis*, *Datura stramonium*, *Helianthus tuberosus* or *Robinia pseudoacacia*. Archeophytes such as *Lactuca serriola*, *Matricaria maritimia* subsp. *inodora* or *Lepidium ruderale* were found on coal mine spoil heaps. The observed regularities in patch proportions

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reflect the covariation ($G = 35.785$; $p < 0.001$) of the heap area and the geographical-historical groups of the dominant species.

4. Discussion

The relations between size of the spoil heap area and the diversity of the spontaneous vegetation

The species richness and species diversity of the vegetation patches recorded on the post-coal mine heaps of various sizes differed insignificantly. However, a comparison of the number of dominant species representing particular socio-ecological groups showed a dependence in terms of the area size of the post-coal mining heaps, however, not all the differences were significant. The species-area relationship [34] provided the theoretical background to formulate predictions regarding the results of this relationship between the size of the heap and the plant species diversity of the vegetation. The species-area relationship, or species-area curve expresses the relationship between the area of a habitat, or part of a habitat, and the number of species recorded within the studied area. Larger areas can contain more species, and empirically, the relative numbers seem to follow systematic mathematical relationships [44].

Connor and McCoy [45] discussed two main hypotheses to explain the increase of the number of species along with increasing area size. One is the habitat diversity hypothesis, and the other is a hypothesis based on demographic processes. The first assumes that the regularities resulting from the SAR are the result of the fact that there is a larger mosaic of habitats over a larger area and the increase in habitat diversity generates a SAR dependency. The demographic explanation, on the other hand, takes into account the dynamics of the spread and colonization process. Larger areas will be more intensively colonized, and in addition, larger heaps similar to large islands, reduce the probability that a given species will disappear [46,47]. The theory of island biogeography by MacArthur and Wilson in 1967 [46] predicted that, small populations in habitat patches are more likely to disappear than populations in large patches of habitat and that patches of habitat more isolated from the source of diaspores are less likely to be recolonized than patches closer together. Considering the diversity of dominant species on coal mine spoil heaps in terms of their life forms, it was found to be size dependent. The vegetation (dominant structure) of heaps with an area of up to 100 ha differs the most from that in the other three area size classes, due to the participation of patches dominated by species representing particular life forms. Among patches of vegetation occurring on heaps of this size class, no dominant plant species were found that represented the chamaephyte and nanophanerophyte life forms.

The species-area relationship is usually completed for one type of organism, e.g., in this study for the plant species composition of the vegetation. In a different approach, all species of a specific trophic level can be analyzed within a particular site. Rosenzweig [48] found that, a wide range of factors specifying the slope and elevation of the species-area relationship. The discussed factors enclose the proximate equilibrium between colonization, immigration and extinction, the number, rate and extent of disturbance in small vs. large areas, and the grouping of individuals of the same species as an effect of habitat heterogeneity or dispersal limitation [46,49]. However, the SAR was formulated as the consequence and to follow the second law of thermodynamics in ecology, the environmental scientific requirements have to be fulfilled [50]. The attractive-"mechanistic" explanation of the SAR observation in some studies needs to be tested as to whether the outcome is only the result of an accident, or whether it follows the rules of the environmental pattern and requirements.

To prove that the SAR observed in the field is genuine the results should be tested against the same data set randomized by permutation tests [45]. The rules concluded from the SAR are often considered in conservation science to forecast extinction rates in the case of habitat loss or habitat fragmentation [51]. Scientists have classified the SAR according to the type of habitats and ecosystems being tested and the census (period) procedure used. Preston [44], who investigated the theory of the SAR, divided the studied issue into two types: samples (contiguous habitat types that grow in the extended area), called "mainland" species-area relationships the isolates (discontiguous habitats, such as islands), also called "island" species-area relationships. Rosenzweig [48] emphasized those SARs for large areas, (those containing various biogeographic provinces or continents), present different patterns from those SAR from islands or smaller neighboring areas. The differences mentioned by Rosenzweig [48] are reflected by the presumed "island"-like SARs, which have steeper slopes in the log-transformed relationship than the "mainland" SARs [48,52]. Regardless of the time scale and habitat type, SARs are often suited to a simple function. Preston [44] supported the function based on his investigation of the relative species abundance distribution (RAD) or species abundance distribution. The -RAD defines the relationship between the number of species recorded in a field investigation as a function of their observed quantity or amount. The result of which performs as an index of biodiversity in the ecosystem that is studied [53].

Conversely, SARs for contiguous habitats will invariably rise as areas increase, provided that the sample plots are nested within one another [34]. The SAR for mainland areas (contiguous habitats) will differ according to the sampling design used [54]. A common method is to use quadrats of successively larger size so that the area enclosed by each one includes the area enclosed by the smaller one (i.e. sampling areas are nested). At the beginning of the 20th century, the species-area curve was used to estimate the minimum size of a quadrat necessary to sufficiently characterize a community. This is done by plotting the curve (usually on arithmetic axes) and assessing the area under it after which the use of the larger quadrats results in finding only a few additional species. This is the way to assess the minimal sampling area to be used. A quadrat that encloses the minimal area is called a vegetation record, and the use of species-area curves in this way is called the relevé method and was largely developed by Braun-Blanquet [55]. To avoid subjectiveness, some ecologists like to define the minimal sampling area as the area has at least 95 per cent (or some other large proportion) of the total species recorded. The species-area curve does not usually reach an asymptote, so it is not apparent what number of species is the total. The number of species grows with the size of the area. It is not feasible during fieldwork to achieve the point where the area accumulating all the species will be covered by the study [56].

The tests performed (G test to check the frequency differences between the groups for qualitative data) revealed that for the spontaneous vegetation developed on spoil heaps of different area sizes the number and diversity of identified vegetation types (dominant plant species) differs significantly. However, when considering the dependence of diversity on the size of the heap, it is necessary to refer to the concept of SAR (dependence of the number of species on the size of the area studied). This concept assumes that the number of species increases as the area increases. The concept of SAR was created as a result of searching for regularity in patterns of diversity. The assumption that the number of species increases with an increase in the area has been recognized as a regularity since Arrhenius [34] described this relationship. However, some researchers believe that the Arrhenius equation is not universally applicable [46,48]. A slightly different mathematical description of the relationship between the number of species and the size of the area was proposed by Gleason [57]. His studies have shown that the equation does not apply to large and small areas [47,48]. Pueyo [58] believes that there is a fundamental relationship between the SAR (increase in the number of species with an increase in the size of the study area) and the patterns of SAD (species abundance distribution) with a small group of dominant species and a large group of low-abundance species.

The number of vegetation patches diversity estimated by the different dominant plant species representing particular geographical-historical groups reflects a dependence on the area size of the heap. The participation of vegetation patches dominated by kenophyte (neophytes) plant species decreases with increasing area. On the largest heaps, the participation of kenophytes (newcomers) is the smallest and the participation of native plant species (vegetation patches dominated by apophytes) is the largest.

The results obtained from research on the factors determining the vegetation diversity on spoil heaps differ from those results obtained from previous research e.g., in forest size as the analyzed factor is taken into account. A study conducted in secondary forests revealed that the only variable affecting the total number of species was the area [59]. Recent studies indicate that in many types of communities, species richness, apart from the size of the study area, is strongly influenced by other factors. Differences in the species richness is strongly influenced by other factors apart from the size of the study area. Differences in the species richness of a site during the initial stages of succession are associated less with competition, animal interactions and population dynamics, but the importance of differences in the number of species on a larger regional spatial scale is increasingly being [52,60].

Researchers testing the metacommunity theory [61-63] and the experiments of Cadotte & Fukami [64] have also shown that the patterns of species coexistence should be seen in a spatial and area size context. They emphasize the importance of connections and exchanges between local habitats and the wider environment for maintaining regional species richness.

5. Conclusion

The natural processes observed, and recorded, in the novel ecosystems that are established based on the analogous plant species composition of the primary producers need to be tested against the theories and concepts formulated for undisturbed natural and semi-natural ecosystems. The novel ecosystems, such as those developing on the mineral oligotrophic habitats of post-coal mining spoil heaps, can present different organismal adaptations and solutions in the living organisms and the colonized habitats relations due to the ecological threshold crossed.

The species-area relationship (SAR) is among the most fundamental of described relationships. The results presented in the article indicate that the differences in the size of the area of the spoil heap affects (significantly for some aspects) the diversity of plant species composition of the colonizing vegetation. Regardless of which of the characteristics of the dominant species is compared, the vegetation on the spoil heaps differs depending on their area size.

Despite differences in the proportions of the recorded number of vegetation patches, it is difficult to indicate a pattern that would reflect the SAR of the colonizing vegetation. The results of this preliminary study which explored the vegetation and species composition diversity of the spontaneous vegetation development during the primary succession processes on mineral substrate habitats on post coal mining spoil heaps of different area sizes, revealed that diversity is not greater on the larger heaps.

It is concluded that the species diversity of the vegetation patches is not more diverse on larger sites. The development of the spontaneous vegetation in the novel ecosystems of the mineral oligotrophic habitats of post-coal mining spoil heaps does not follow the species area relationship (SAR) of Arrhenius.

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