

## EROI OF THE UKRAINIAN COAL

### *Introduction*

Coal production in Ukraine is not only loss making and subsidized as a result but it is also a very power-consuming. This became clear as early as the 80<sup>th</sup> of the last century. At the time of a considerable reduction of coal production, consumption of rolled metal grew by 20%, consumption of electricity grew by 4% (specific consumption grew by 10%), steel intensity of mining equipment grew by more than 1 mln. tons, etc [1].

The problem of wide-scale liquidation of coal mines at Donbass became very acute [2]. But the demonstrative survey of coal mines of Sverdlovantstsite amalgamation [3] which was held in the post-soviet period was used as an argument in favour of further exploitation of these coal mines since direct and indirect electricity inputs for production of 1 ton of anthracite including those materialized in various stuff, equipment, buildings, structures, etc. amounted for one eighth/ ninth of a corresponding electricity costs at a thermal power station.

The situation in coal production and thermal power engineering sectors deteriorated considerably since then.

The problem of whether production of coal in Ukraine is reasonable or not is still quite topical. This thesis is substantiated by the article [4]. On the contrary, the situation in Donbass and requirement of increasing the anthracite imports from the USA make this problem even more acute. A methodology in use still does not give a clear understanding of factors influencing the energy efficiency of the Ukrainian coal production on a large scale.

Thus the main objective of this work is to review the current situation in the industry and to make out the methodology to be used in determining the basic factors which influence the fluctuations of energy efficiency indexes of the Ukrainian coal mines.

### *Methods of analysis*

One of the initial tasks to be fulfilled as a result of this research is to achieve the acceptance as a category of the proposed system of energy efficiency evaluation of all processes under study.

According to V. Pak, the Ukrainian scientist in mechanics and specialist on coal industry, the concept of exergy should be used in this regard [5]. His suggestion has possibly been influenced by a book of Polish scientists J. Szargut and R. Petela "Exergy" translated version of which was published in the USSR [6, original edition 7].

Being a category of thermodynamics, exergy as a derivative of a Greek word "work" having a prefix signifying the highest degree of something, means a maximum amount of work which can be accomplish by a system when it transforms from the existing state into a state of equilibrium with all components of the environment, i.e. with a source and the final receiver of any stream of energy such as water, vapour, raw materials, chemical products, various kinds of energy. It is well known, for example, that a burning fuel extracts more heat in the oxygen medium than in the open air. At the same time the summarized exergy of the system is less since some extra work should be performed for obtaining oxygen from the air.

The situation with coal production is similar. It requires more inputs of coal, materialized in electric and thermal energy, metal, etc.

The notion of exergy was modified by C.J. Cleveland, C.A. Hall, R. Costanza and R.K. Kaufmann into the notion of EROEI (energy returned on energy invested), or EROI (energy return on investment) almost 20 years ago [8]. This notion came into general use since then as a synonym of energy efficiency.

"One potentially useful alternative to conventional economic analysis is net energy analysis, which is the examination of how much energy is left over after correcting for how much of that energy (or its equivalent from some other source) is required to generate (extract, grow or whatever) a unit of the energy in question. Net energy analysis is sometimes called the assessment of energy surplus, energy balance, or, as we prefer, energy return on investment (EROI or sometimes EROEI)" [9, p. 25].

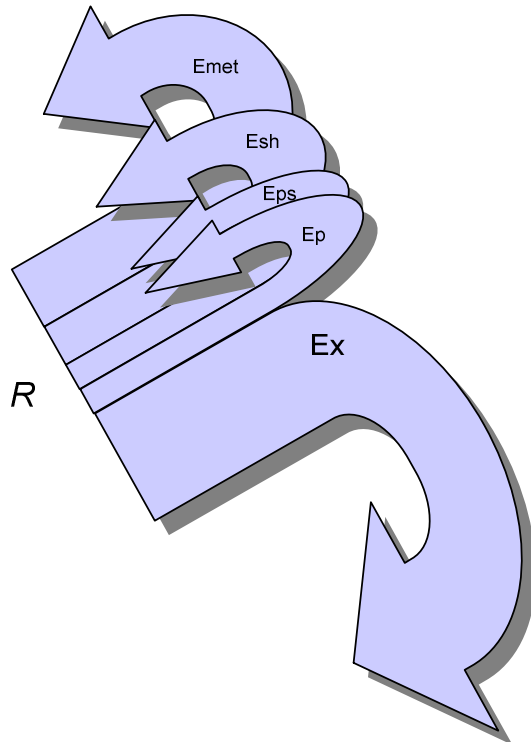
Keeping the above in view, EROI category is accepted in this work as the basis to evaluate coal mining efficiency.

To demonstrate the right approach in evaluation of EROI the diagram of Grassmann is suitable [6, c. 310]. Grassmann diagrams which are also known as Grassmann-Szargut diagrams usually show the system's streams of resources on a scale horizontally and in proportion to their numerical values. The diagrams graphically demonstrate the amounts of energy losses and their location as well as reallocations between the elements of the system (object) under study.

A coal mining enterprise can be shown in the form of distributed coal streams symbolizing energy resources (Fig. 1): one stream of coal consumed at a coal mine itself, the other one transported to the metallurgical

(by-product coking plant), to the power station, and the one domestically consumed by the personnel of all technologically combined enterprises, etc.

The elements of the Grassmann diagram are as follows:  $Ex$  – energy net-output of the system;  $E_{met}$  – energy inputs in metallurgical production,  $E_{sh}$  – energy inputs in coal mining and coal washery;  $E_{ps}$  – energy inputs for functioning of thermal power station and transformation of coal into electric energy;  $E_p$  – energy inputs to meet the requirements of personnel which is engaged in servicing of the system.



**Fig. 1. Grassman diagram**

The formula corresponding to Grassmann diagram looks as follows:

$$Ex = R - E_{pc} - E_{met} - E_p - E_{sh}. \quad (1)$$

EROI index of coal mining and processing system equals to:

$$EROI = Ex / (E_{pc} - E_{met} - E_p - E_{sh}). \quad (2)$$

Review of the system from the energy point of view gives a clear and stable (not depending on the state of the markets) presentation of the enterprise efficiency. This includes the understanding of whether a further existence of the enterprise is feasible from the resource point of view.

Thus a coal mine needs a certain electric power resources to produce a certain quantity of coal. In order to deliver a required quantity of electricity to the coal mine some volume of electricity should be ordered by a coal mine supplier of electricity from a thermal power station. This amount should exceed the amount required to the coal mine itself by the amount which will be lost

during its transportation in the electricity network. In order to meet the requirements of the electricity supplier, thermal power station should produce the amount of electricity ordered by the electricity supplier plus the amount required for its own needs.

Fuel consumption at a thermal power station depends on its technological efficiency and quality of a fuel. For the Ukrainian thermal power stations it is three times higher than the output of a secondary energy resources when calculated in coal equivalent units (tce).

A coal mine consumes not only an electricity but a thermal energy on a large scale. That is why some quantity of coal produced by a coal mine should be used as a boiler fuel at a coal mine itself in order to ensure its operation.

To cover its requirements in metal products a coal mine transports another portion of produced coal to a by-product coking plant to use it as a coal blend for coking. Besides some coal will be transported to electric power station and will be used to generate electric energy to cover the requirements of by-product coking plant, metallurgical plants, energy transportation losses in electricity networks plus the requirements in electric energy of thermal power station itself.

Besides some quantity of coal goes to the power station for generation of energy used in the process of coal beneficiation and transportation, as well as in production of some auxiliary materials used in various technological processes at a coal mine, etc.

Some coal is needed to meet the requirements in electric and thermal energy of metacorporation personnel.

If coal mine ensures a sizable net-output of useful resource, then some unprofitability of it can be considered acceptable. At the same time a combination of low economical and energy efficiency and moreover an energy cannibalism are absolutely impermissible.

Direct inputs of electric energy at the enterprise are considered a basic index for calculation of coal EROI.

Despite well-known declarations on the unique nature of each of Donbass coal mines, it was proved in the article [10] that the level of electricity consumption at the underground coal mining enterprises follows certain rules.

Statistical analysis of data from 93 separate coal mines [11] made it possible to find a correlation between energy, geological and mine technical factors. This analysis was accomplished at the period when the mine list of the Ukrainian coal industry was quite representative in quantity.

$$W = 0.260 \cdot P + 0.224 \cdot H + 0.679 \cdot N, \quad (3)$$

where  $W$  – a total electricity consumption at a coal mine;

$P$  – production capacity of a coal mine;

$H$  – a maximum mining depth;

$N$  – a number of simultaneously developed coal seams.

Indexes which are present in the formula are given in a standardized form (from minus one to plus one, irrespective of the factors' nature). Standard errors of variables were used in the process of standardization as variability interval. At the same time mathematical expectations of values are used as the natural value of the factor. A mean level was equal to zero.

The values of regression indexes show that the number of developed coal seams (variable  $N$ ) has the highest effect on coal mines' energy consumption. This has a direct connection with the attitude of bed: the value of this factor is much higher for steep gradient seams than in the case of flat-lying seams.

A depth of mining and a production capacity of a coal mine affect the energy characteristics of mining enterprise practically in the same way. At the same time they do not play the primary role in this process. Evaluations of  $W$  by  $N$  value explain such a high energy intensity observed at coal mines developing steep-pitch seams.

Five coal mine clusters were formed as a result of cluster analysis of three determining variables ( $P$ ,  $H$  and  $N$ ) (Table 1).

Table 1

**Mean values of variables by mine clusters**

(in standardized estimation)

| Cluster No. | Number of coal mines | $W$    | $P$    | $H$    | $N$    |
|-------------|----------------------|--------|--------|--------|--------|
| 1           | 14                   | 0,021  | 0,530  | 1,614  | -0,455 |
| 2           | 36                   | -0,199 | -0,301 | -0,394 | 0,101  |
| 3           | 10                   | 0,285  | 2,098  | -0,534 | -0,261 |
| 4           | 23                   | -0,842 | -0,838 | -0,754 | -0,750 |
| 5           | 10                   | 2,339  | 0,171  | 0,945  | 2,261  |

It is clear that energy consumption in the first cluster is almost on a mean level according to our data base (45,5±13,4 GWh or 5,6±1,6 thousand tons of coal equivalent per year). This cluster included the following industrial objects - 14 coal mines which existed at the moment. All of them had relatively high production capacity (740±155 thousand tons) and developed limited number (2,7±1,9) of deep-lying (1088±165 m) coal seams.

Energy consumption in the second cluster is below average (33,8±12,9 GWh or 4,2±1,6 thousand tons of coal equivalent per year). A production capacity here is also below average (522±145 thousand tons), depth occurrence is less than an average one as per our data base (587±120 m). At the same time a number of seams which are developed is sizable (4,4±1,9).

The second cluster has the second by rank gradation average mine wise number of coal seams. By this index the second cluster is next to the fifth cluster only. Actually it is explained by the fact that the second cluster

also includes some coal mines which develop steep-pitch seams like "Bulavinskaya", "Enakievskaya" and other mines of "Ordzhonikidzeugol" amalgamation. A number of objects in the cluster is 36.

The third cluster combines 10 objects having the highest production capacity (1153±146 thousand tons) and developing a limited number of seams (3,3±1,2), which are lying at the average depths (672±164 m). Thus by an electric energy consumption the third cluster coal mines occupy the position which can be characterized as exceeding by approximately one third the average level by a number of objects (51,1±15,0 GWh or 6,3±1,8 thousand tons of coal equivalent per year).

The fourth cluster combines objects with characteristics in the bottom of the range: these are shallow coal mines (498±147 m) with a minimum number of coal seams (1,8±0,8) and a low production capacity (380±113 thousand tons). Energy consumption at such coal mines constitutes (16,4±7,9 GWh or 2,0±1,0 thousand tons of coal equivalent per year).

The fifth cluster is featured by an impressive depth of mining (921±132m) and a great number of simultaneously developed seams (10,9±1,4). The depth of mining here is approaching the top of the range and the production capacities are high enough - 646±138 thousand tons (at least they are above the average). This substantiates such a high energy inputs in coal production. They greatly exceed the overall level of energy consumption in a coal industry (112,5±18,9 GWh or 13,8±2,3 thousand tons of coal equivalent per year). This cluster combines 10 coal mines.

Conversion of electricity units into equivalent fuel indexes was made taking into account the ratio 1 kWh = 123 grams of coal equivalent, which comes from the conversion of SI units (1 kwh = 3,6 MJ; 1 kg of coal equivalent = 7000 kcal or 29,3 MJ).

$$E = 0.123 \cdot W \quad (4)$$

where  $E$  – electric energy consumption, expressed in the units of equivalent fuel, thousand tons of equivalent fuel.

There is a statistical difference (with a probability of 95%) between all the clusters in the level of energy consumption and a striking difference of the fifth cluster from all the other ones.

Beside the general energy consumption clusters differ from each other by energy consumption in various technological processes.

About 29% of energy goes on mine ventilation and only 9% goes on operation of compressors in the first cluster. At the same time 56% of energy goes on operation of pneumatic equipment, and 12% of energy is consumed by the ventilators of main ventilation system in the fifth cluster.

Cluster wise energy intensity characteristics in kind for the main coal mining processes (Table 2).

Table 2

**Energy consumption characteristics by technological processes, GWh**

| Номер кластера<br>Cluster No. | $W$        | $W_3$    | $W_4$   | $W_5$     | $W_{10}$ | $W_{11}$ |
|-------------------------------|------------|----------|---------|-----------|----------|----------|
| 1                             | 45,5±13,4  | 12,9±7,1 | 5,6±3,7 | 4,3±4,1   | 11,0±5,1 | 3,6±2,3  |
| 2                             | 33,8±12,9  | 7,2±4,4  | 4,9±3,8 | 6,7±10,4  | 7,5±4,5  | 1,9±1,1  |
| 3                             | 51,1±15,0  | 16,1±7,0 | 3,9±3,6 | 2,7±4,0   | 10,1±4,2 | 5,4±3,2  |
| 4                             | 16,4±7,9   | 3,8±2,7  | 2,2±1,4 | 0,3±0,9   | 4,5±4,6  | 2,0±1,6  |
| 5                             | 112,5±18,9 | 13,7±3,8 | 8,1±4,4 | 62,2±15,4 | 11,1±5,4 | 1,4±1,0  |

The designations are following:

- $W_3$  – Annual energy consumption for Ventilation process, GWh;
- $W_4$  – Annual energy consumption for “Mine hoist” process, GWh;
- $W_5$  – Annual energy consumption for “Compressed air supply”, GWh;
- $W_{10}$  – Annual energy consumption for “De-watering” process, GWh;
- $W_{11}$  – Annual energy consumption in underground transportation processes, GWh.

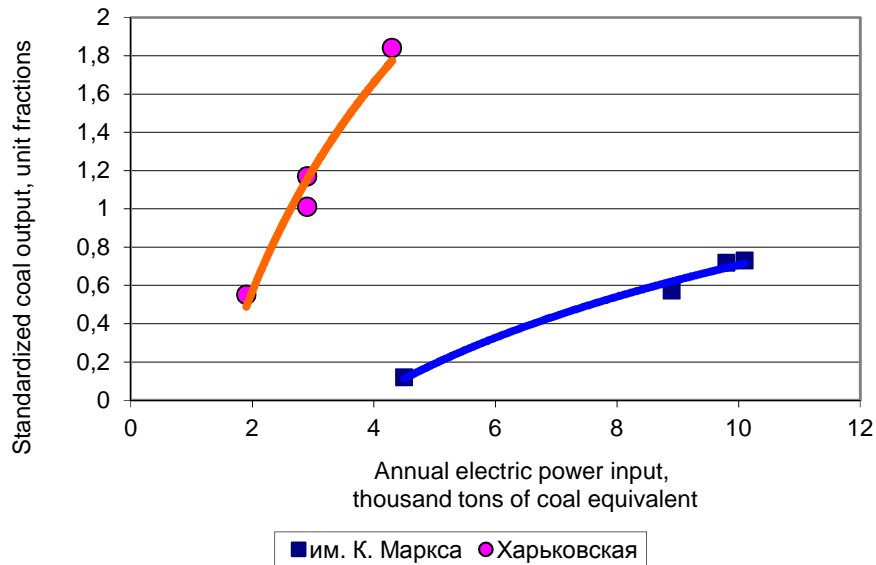
The above mentioned patterns are typical for those cases when mine production funds are used to a great extent and implementation rate is close to one. Productive capacity implementation rate equal to zero ( $D = 0$ ) represents the “idle running” operation of the enterprise

using the mechanics terminology. With some exaggeration we can assume that when a coal mine is in “full idle run” operation the only really operating equipment are the ventilation and pumping installations.

If we know the electricity consumption for these processes, we can determine the requirements of a coal mine when production capacity implementation rate equals zero.

A power production function of a coal mine – is a correlation between the production output and energy consumption.

Fig. 2 gives graphs of actual electric power consumption for production of coal at two coal mines belonging to marginal fourth and fifth clusters. Standardized coal production at mine S forms the ratio of the annual coal output to production capacity of the mine.



**Fig. 2. Correlation between a production development and electric power consumption at coal mines belonging to various clusters**

Coal mine “Kharkovskaya” situated at Sverdlovsk of Lugansk region has a capacity of 320 thousand tons/year and belongs to the fourth cluster. Coal mine named after Karl Marx situated at Enakievo has a capacity of 900 thousand tons and belongs to the fifth cluster.

The production function of a coal mine shown in its totality forms a logarithmic function graph beginning in the point having coordinates ( $E_{(D=0)}$ ;  $D=0$ ) and going through the point having coordinates ( $E_{(D=P)}$ ;  $D=P$ ),

where  $E_s$  – summarizes the basic inputs of coal used for functioning of an enterprise.

$$D = K_e \ln(E_s) + C, \quad (5)$$

where  $D$  – Annual coal output, thousand tons;

$K_e$  and  $C$  – Logarithmic function coefficients;

$E_s$  – total standardized coal consumption for production needs which is in correspondence with a total coal mine output.



$$E_s = E_3 + F_{MET} + f_p N_p + F_{Sh}, \quad (6)$$

where  $E_3$  – Total electric power consumption in the system which includes energy resource production at a thermal power station and energy losses in the electric networks;

$F_{MET}$  – Consumption of coal in metallurgical production;

$f_p N_p$  – Consumption of coal by personnel for domestic needs;

$F_{Sh}$  – Coal consumption for coal mine needs.

Table 3 shows the electric energy consumption at a coal mine in two cases: when a coal mine production reaches its maximum which corresponds to its production capacity and in the “idle-run” operation. Based on this data one can make a coal mine production function typical for the particular cluster.

Table 3

**Mean cluster wise electric power consumption, thousand tons of coal equivalent**

| Cluster No. | Electricity consumption when $D=P$ | Electricity consumption when $D=0$ |
|-------------|------------------------------------|------------------------------------|
| 1           | 5.6                                | 2.0                                |
| 2           | 4.2                                | 1.8                                |
| 3           | 6.3                                | 2.5                                |
| 4           | 2.0                                | 0.8                                |
| 5           | 13.8                               | 5.5                                |

Based on the review of observation data published in [3, p. 16-17], a conclusion can be made with regards to electric power consumption in coal dressing processes, its transportation by rail road, as well as a volume of electric power materialized in consumed materials, buildings and structures and equipment which was put into action during the period of the year. Percentage-wise, these figures constitute, respectively: 11,1±3,0; 5,1±0,9; 65,3±8,6; 6,6±1,2; and 10,6±1,8% of direct electric power consumption at a coal mine.

Still these indexes are typical for coal mines with flat pitch coal seams.

According to the research made by DonUGI specialized laboratory of wood and material stores [12, p. 8] there exist considerable differences in consumption of materials depending on bed attitudes. On the basis of long term observations, functioning of coal mines developing flat pitch seams goes under the following pattern as far as a daily material consumption is concerned:

$$Q_{MAT}^I = 25.5 + 25.3 \cdot D_1 + 2.5 \cdot L_{np} + 1.3 \cdot L_p, \text{ t}, \quad (7)$$

where  $Q_{MAT}^I$  – A daily consumption of materials at a coal mine, tons/day;

$D_1$  – A daily extraction of coal at a coal mine, thousand tons/day;

$L_{np}$  – An average daily penetrating face advance, m/day;

$L_p$  – An average daily overhauled advance in mine workings, m/day.

For coal mines developing steep pitch seams

$$Q_{MAT}^K = 51.4 + 150 \cdot D_1 + 2.0 \cdot L_{np} + 1.2 \cdot L_p, \text{ t}. \quad (8)$$

All elements of the above formulas may be divided into 2 groups: the one in which consumption is calculated in tons of materials and a group of elements referring to a running meter of mine workings which are being advanced or overhauled. As a rule a nomenclature of the latter combines the metallurgical products such as arch support, rails, pipes.

According to standard requirements of a relatively small coal mine having a daily output of 1 thousand tons (or around 250 thousand tons of coal per year) a daily supply of about 51 tons of mixed cargo and 20 tons of metal products is needed i.e. a total requirement is 71 tons if coal mine develops flat pitch coal seams and 169 tons of loads if a coal mine develops steep pitch seams.

Because of geological conditions the difference in material consumption of an average mine having an annual capacity of 700 thousand tons is about 3,4 times. At the same time coal mines developing steep pitch seams consume 2,5 times more electricity.

That’s why in case of coal mine with steep pitch seams the ratio between the electricity consumption materialized in goods and consumed directly requires correction: this ratio should be increased 1,4 times compared to coal mines developing flat pitch seams. At the same time, keeping in view the abovementioned increased electricity consumption for own needs of coal mines with steep pitch seams, specific costs for the other categories at these mines should be reduced.

Data on coal mines of both types is given in Table 4.

Table 4

**Electricity consumption rate, unit fractions, from direct electricity consumption at a coal mine**

|                          | Coal mine with flat pitch seams | Coal mine with steep pitch seams |
|--------------------------|---------------------------------|----------------------------------|
| Coal dressing            | 0,11                            | 0,04                             |
| Railroad transportation  | 0,05                            | 0,02                             |
| Materials                | 0,65                            | 0,92                             |
| Equipment                | 0,11                            | 0,04                             |
| Buildings and structures | 0,07                            | 0,03                             |

Costs of electric power supply to a coal mine are as follows:

$$E_3 = \frac{E \cdot (1 + \rho) \cdot (1 + \lambda) \cdot (1 + \phi)}{\eta_{PS}} \quad (9)$$

where  $\rho$  – electricity inputs for processes of coal dressing and transportation, inputs of electricity materialized in goods, metal products, buildings and structures, equipment;

$\lambda$  – electricity losses in its transportation;

$\varphi$  – electricity inputs for own needs of a thermal power station;

$\eta_{PS}$  – energy efficiency of thermal power station with regards to fuel consumption.

Coal mines are heavy users of not only an electric power energy but of thermal energy and motor oil as well.

Based on the regression analysis it is determined that summary inputs of fuel (boiler coal, petrol and diesel fuel) are comparable with electricity consumption [13, 14]. With a high degree of accuracy this dependence can be presented in the following way:

$$F_{Sh} = 1.133 \cdot E. \quad (10)$$

$$F_{MET} = f_{MET} \cdot Q_{MET}, \quad (11)$$

where  $f_{MET}$  – specific consumption of energy resources in metallurgical production, thousand tons of equivalent fuel;

$Q_{MET}$  – annual consumption of metal rolled stock at a coal mine, thousand tons.

The data provided in the work [15, p. 113] shows that on the whole 1,3 tons of coal equivalent is consumed in production of 1 ton of rolled stock. At the same time this data involves net-inputs of electricity. It does not take into account fuel inputs at generating plants.

Taking into account the data given in the work [16, p. 52] a summarized specific consumption of materialized coal if recalculated considering all cycles of metallurgical treatment can be considered equal to 2,1 tons of equivalent fuel for 1 ton of rolled stock consumed by a coal mine. However, there is a reason to divide costs and under  $f_{MET}$  understand only the consumption of coal for the production of coke – 640 kg per ton of coal/ton of rolled metal [16, p. 157], and the remaining part of the costs included in the electricity consumption.

The following dependences defining the respective requirements in metal-roll by coal mines developing flat-pitch and steep-pitch seams respectively are based on generalized statistical data.

$$Q_{MET}^n = 10^{-3} \cdot l_1 \cdot P \cdot s \cdot (2.5 + 1.3 \cdot k_p), \quad (12)$$

thousand tons,

$$Q_{MET}^k = 10^{-3} \cdot l_1 \cdot P \cdot s \cdot (2.0 + 1.2 \cdot k_p), \quad (13)$$

thousand tons,

where  $l_1$  – specific ratio of a coal output and preparatory works made during the year (6,5 m/thousand tons);

$k_p$  – Ratio coefficient between face advance activities and underground overhauling activities (according to previous experience this ratio can be admitted as 0,5 on the average).

Evaluation of energy inputs for participation of personnel in production processes is a matter of special attention. Instead of evaluating a direct labour it is suggested in the work to calculate energy inputs in domestic needs of company personnel. Coal consumption clearly prevails in total energy consumption for domestic heating but at the same time one needs to consider inputs of electric and thermal energy as well.

According to the terms of the Mining Code of Ukraine [17, art. 43], all personnel of coal mining (coal processing) and mine building companies are enabled to acquire a free coal for domestic needs in quantity of 5,9 tons of coal for 1 person which can be equated with 4,2 tons of coal equivalent.

$$F_p = 10^{-3} \cdot N_p \cdot f_p, \quad (14)$$

where  $F_p$  – An annual consumption of furnace and chimney fuel for personnel needs, thousand tons of coal equivalent;

$N_p$  – Number of free coal receivers, men;

$f_p$  – Specific consumption of furnace/chimney fuel, tons of coal equivalent/men.

During the period of intensive exploitation of mine fund objects, cluster wise direct labour inputs by coal mines are equal (with a probability of 0,95) to  $2,7 \pm 0,3$ ;  $3,8 \pm 0,4$ ;  $2,3 \pm 0,8$ ;  $4,4 \pm 0,9$ ;  $3,3 \pm 0,2$  persons / 1000 tons of produced coal. Any changes in the production output do not lead to linear changes in personnel number.

Empirical dependence for coal mines developing flat pitch seams looks as follows:

$$N_{Sh}^{bl} = B_{Sh}^{aK} \cdot P \cdot s^{(1-0.398)}, \quad (15)$$

where  $N_{Sh}^b$  – A current number of mine personnel, men;

$B_{Sh}^a$  – Labour coefficient in production of coal at a coal mine having a high degree of production capacity utilization, men/thousand tons.

The dependence for coal mines developing steep pitch seams (the fifth cluster) looks as follows:

$$N_{Sh}^{bk} = B_{Sh}^{aK} \cdot P \cdot s^{(1-0.516)}. \quad (16)$$

Workers of metallurgical, by-product coking plants and thermal power stations involved in processes associated with coal production can be considered a personnel participating in coal production on the basis of outsourcing agreements. To estimate the number of this personnel it is acceptable to use data on labour-intensiveness of various operations/processes at the corresponding enterprises.

As far as metallurgical companies are concerned, the labour-intensiveness of metallurgical production is equal to 7,4 persons per 1 thousand tons of steel (the data was provided by Monitor Company Group, analytical firm which made a development strategy of Donetsk Region).

According to the data published in article [18], a labour content in operation of power generating enterprises in its dependence from the annual quantity of processed fuel is as follows:

$$N_{PS} = 0.539 \cdot d - 7 \cdot 10^{-5} \cdot d^2 - 94, \quad (17)$$

where  $N_{PS}$  – Number of personnel involved in servicing of energy generating company, men;

$d$  – Annual consumption of fuel (coal) at the thermal power station, thousand tons of equivalent fuel.

Though the personnel involved in metallurgical production and energy generation is not on the coal mine staff, their involvement in coal production provides the ground for considering this personnel as consumers of domestic coal.

The total number of personnel in production system is as follows:

$$N_p = N_{sh} + N_{PS}(d) + N_{MET^*}(Q_{MET}), \quad (18)$$

where  $N_{PS}(d)$  – Labour-intensiveness in servicing of power station in respect of a coal mine requirements, persons;

$N_{MET}(Q_{MET})$  – Labour-intensiveness in servicing of metallurgical production in respect of a coal mine requirements, persons/

Graph-analytic method is most suitable for defining a production function and determining the coefficient  $K_e$ . This means the requirement to calculate the value  $E_s$  which forms the combined energy inputs of a coal mine in  $D = 0$  and  $D = P$  modes. After this the logarithmic dependence graph should be made with the help of Excel MS software.

The following formula describes a quantity of useful coal mine production:

$$Ex = R - E_s. \quad (19)$$

It is acceptable to use a simplified dependence [19] in order to recalculate a quantity of produced coal given in physical terms into coal equivalent terms

$$\beta = \frac{Q^r = (31505.7 - 332.8 \cdot A^d)}{1000 \cdot 29.3}. \quad (20)$$

where  $\beta$  – Transfer coefficient from physical units into units of coal equivalent;

$Q^r$  – The lowest heating power of coal at a particular mine, determined on the basis of coal ash content, kJ/kg;

$A^d$  – Coal ash content, percent.

$$R = Q^r = D \cdot \beta. \quad (21)$$

The consumption of energy resources at a coal mine depends on a number of variables. It is essential to determine to which extend each of the variables affects it. To achieve this it is suggested in the work to use the above model for making a multi-factor experiment by Box-Wilson method of experiment planning theory [20, p. 80].

A coal mine when described by its production function is a device at the outlet of which a response function (or criterion function when one says about optimization) is formed under the influence of inlet signals (factors).

Numerical factors can be denoted by any of a great number of acceptable values. Box-Wilson method permits deviation of factors on two levels only: the lower one which is designated by minus 1 and the upper one – by plus 1.

To reduce the labour inputs for analysis, it would be appropriate in the first place to conduct a screening experiment making use of software Statistica® [21]. The

program enables the maximum of 11 factors to be used for analysis. On the assumption of this it is reasonable to form the composition of variables used in the variation in the following way:

- $F_1$  – power energy inputs in coal beneficiation processes;
- $F_2$  – power energy inputs in coal transportation by railroads;
- $F_3$  – power energy materialized in goods;
- $F_4$  – power energy materialized in buildings and structures;
- $F_5$  – power energy materialized in equipment;
- $F_6$  – coal consumption for thermal energy generation;
- $F_7$  – labour inputs in coal mining at a specific mine;
- $F_8$  – electric power energy losses in electric networks;
- $F_9$  – consumption of coal used for personnel domestic needs;
- $F_{10}$  – specific fuel consumption at thermal power station;
- $F_{11}$  – coal inputs in coke production.

Factor variation levels correspond to those indicated in Table 5. As an object of analysis on the stage of a screening experiment the following coal mine was chosen: the one belonging to the third cluster with a production capacity of 1150 thousand tons per year and a respective electric power consumption of 2,5 and 6,3 thousand tons of coal equivalent per year which correspond to a coal mine operation in the idle run mode and with a full load of production funds.

Table 5

Values of factor setting levels

| Nomenclature of a factor | The upper level (+1) | The basic level | The lower level (-1) | Variation interval |
|--------------------------|----------------------|-----------------|----------------------|--------------------|
| $F_1$ , unit fractions.  | 0,08                 | 0,11            | 0,14                 | 0,03               |
| $F_2$ , unit fractions.  | 0,04                 | 0,05            | 0,06                 | 0,01               |
| $F_3$ , unit fractions.  | 0,57                 | 0,65            | 0,73                 | 0,08               |
| $F_4$ , unit fractions.  | 0,05                 | 0,065           | 0,08                 | 0,015              |
| $F_5$ , unit fractions.  | 0,09                 | 0,105           | 0,12                 | 0,015              |
| $F_6$ , unit fractions.  | 1,03                 | 1,135           | 1,24                 | 0,105              |
| $F_7$ , men./th.tons     | 1,5                  | 2,3             | 3,1                  | 0,8                |
| $F_8$ , unit fractions.  | 0,05                 | 0,085           | 0,12                 | 0,035              |
| $F_9$ , t.e.f./man.      | 0                    | 2,1             | 4,2                  | 2,1                |
| $F_{10}$ , gr.c.e./kWh   | 200                  | 300             | 400                  | 100                |
| $F_{11}$ , t/t           | 0,40                 | 0,525           | 0,65                 | 0,125              |

Appropriateness of applying a fractional factorial experiment matrix for factor variation is substantiated by the necessity to reduce research labour inputs since a comprehensive plan involving 11 factors varied on two levels would have constituted 2048 tests.

A matrix containing 16 tests (fractional factor experiment having a view of  $2^{(11-7)}$ ) and generated by software Statistica® is designated for systematic variation of variables.

When the factors affecting the third factor in a big way are selected in the course of the screening experiment it is required to start the experiments at the coal mines representing the marginal clusters, the fourth and the fifth ones. To achieve this the selected factors should be supplemented by another factor, a qualitative one, the lower level of which embodies a coal mine of the fourth factor, and the upper level – a coal mine of the fifth cluster.

The results of experiment at coal mines representing the marginal clusters are aimed at presenting a full spectrum of the Ukrainian coal mines characteristics.

### Results

The results of screening experiment, fulfilled with the use of a software pack Statistica 6.0<sup>®</sup>, show that one factor only, the tenth one, which is a specific fuel inputs at the thermal power station, has a statistically significant effect on function  $E(s)$  in the idle run mode.

The following dependence reflects the values of the variable

$$E_{(D=0)} = 20.408 + 4.614 \cdot F_{10}. \quad (22)$$

Two factors, the tenth and the ninth, the same specific fuel consumption at thermal power station and rates of coal allocated for domestic needs of the personnel, have statistically sizable effect on accumulated energy consumption at coal mine operating at full swing.

Energy loads at the coal mine operating at full swing are formed according to the following dependence

$$E_{(D=P)} = 63.639 + 8.341 \cdot F_9 + 11.934 \cdot F_{10}. \quad (23)$$

Thus a production function of coal mines belonging to the third cluster can be formed by two sets of data, estimated in thousands of tons of coal equivalent: when setting factor values at the upper level  $E_{(D=0)} = 25.0$ ;  $E_{(D=P)} = 83.9$ ; and setting factor values at the lower level  $E_{(D=0)} = 15.8$ ;  $E_{(D=P)} = 43.4$ . Corresponding production functions are given on the Fig. 3.

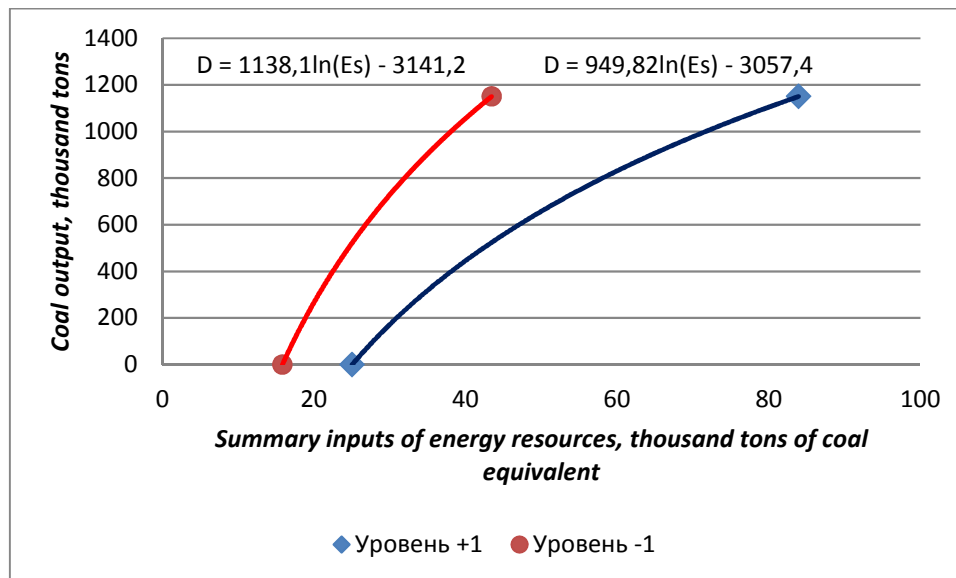


Fig. 3. Production functions of coal mine belonging to the third cluster (Level +1 and Level -1)

Coefficient  $K_e$  for the first production function is equal to 1138, for the second one – 950; coefficients  $C$  are 3141 and 3057 respectively. It is clear that the elasticity of production functions in standardized imaging becomes less with the increase of effecting factor values.

Such effect can actually be achieved if one applies the system which includes the elimination of benefit for the mine personnel which is a free provision of coal (zero rate) plus improving the effectiveness of thermal power stations by reducing fuel consumption rates.

According to the estimates a maximum energy efficiency of a coal mine is achieved when it operates at a maximum capacity. Depending on the attendant factors EROI of a coal varies from 17,5:1 to 8,6:1.

Keeping in view the obtained data on effect of various factors it makes sense to carry out the next experiment. This time it is a three-phase hypothetical (computer) experiment with one qualitative factor by matrix of a comprehensive factor experiment  $2^3$  consisting of 8 tests. The first factor  $F_1$  is a cluster type (+1 corresponds to a coal mine of the fifth cluster, and -1 corresponds to a coal mine of the fourth cluster). The second factor  $F_2$  – is a distribution rate of a free coal provided to the personnel of a coal mine. The third factor  $F_3$  – is a fuel consumption efficiency at a thermal power station.

According to the experimental conditions it is admitted that a coal mine of the fourth cluster has a production capacity of 380 thousand tons of coal per year, direct inputs of electric power energy at a coal mine



operating in the idle run mode is 0,8 thousand tons of coal equivalent and 2 thousand ton of equivalent fuel when the coal mine operates at a full swing.

The capacity of the fifth cluster coal mine is 650 thousand tons, corresponding direct electricity inputs are 5,5 and 13,8 thousand tons of equivalent fuel. The values of those factors which are statistically of no importance for the response function i.e. electricity inputs for coal beneficiation, coal railway transportation and those materialized in products, etc. are fixed at the average level.

The experiment results bring one to the conclusion that only two factors, the first and the third ones, as well as their interaction, have statistically sizable effect on energy consumption of coal mining process. The difference between coal mines representing clusters which are marginal in terms of energy inputs is so sizable that they overlap the effect of the second factor.

The effect of the first and third clusters correlation  $F_1F_3$  is also of essence: it is positive which means that the response function value increases when factors are set on one and the same level.

The dependence of response functions from the factors are as follows:

$$E_{(D=0)} = 23.726 + 16.931 \cdot F_1 + 6.151 \cdot F_3 + 4.629 \cdot F_1F_3; \quad (24)$$

$$E_{(D=P)} = 65.582 + 42.630 \cdot F_1 + 15.685 \cdot F_3 + 11.363 \cdot F_1F_3. \quad (25)$$

The marginal sets of indexes for coal mines of the fourth and the fifth clusters, calculated in thousands tons of coal equivalent, amount: when the factor values are set on the upper level  $E_{(D=0)} = 51.4$ ;  $E_{(D=P)} = 135.3$ ; when factor values are set on the lower level –  $E_{(D=0)} = 5.3$ ;  $E_{(D=P)} = 18.6$ .

The higher capacity and more energy consuming coal mines of the fifth cluster have more elastic production function. That is why smaller coal mines developing flat pitch seams require a greater increase of energy inputs (in relative terms) in order to achieve a sizable increase of coal output. For the coal mines which develop steep pitch seams an increase of coal output does not require such a high increase of energy inputs.

The effect of the second significant factor  $F_2$  is of no less importance: coal mines are not self-sufficient: a low effectiveness of thermal power stations' operation reduces greatly the effectiveness of the entire coal mining industry. And actually the more energy consuming a coal mine production is, the more the fuel inputs at the thermal power stations effect a coal mine operation. This is reflected by plus or minus symbol showing the factors' mutual effect.

Table 6 shows at which conditions the optimum operation of coal mines belonging to different clusters at various effectiveness of thermal power station operation can be achieved. Optimality conditions are calculated with the help of "Search for a solution" module of Excel MS software.

Table 6

Optimal coal mine operation modes

| Optimization conditions   | Optimal standardized output, fractions of one | Optimal energy input, thousand tons of coal equivalent | EROI of a system |
|---|---|--|------------------|
| Coal mine of the 4 <sup>th</sup> cluster, high effectiveness of TPS | 0,709   | 201  | 9,60             |
| Coal mine of the 5 <sup>th</sup> cluster, high effectiveness of TPS | 0,948   | 412  | 4,79             |
| Coal mine of the 4 <sup>th</sup> cluster, low effectiveness of TPS  | 0,756   | 208  | 8,00             |
| Coal mine of the 5 <sup>th</sup> cluster, low effectiveness of TPS  | 0,989   | 377  | 3,08             |

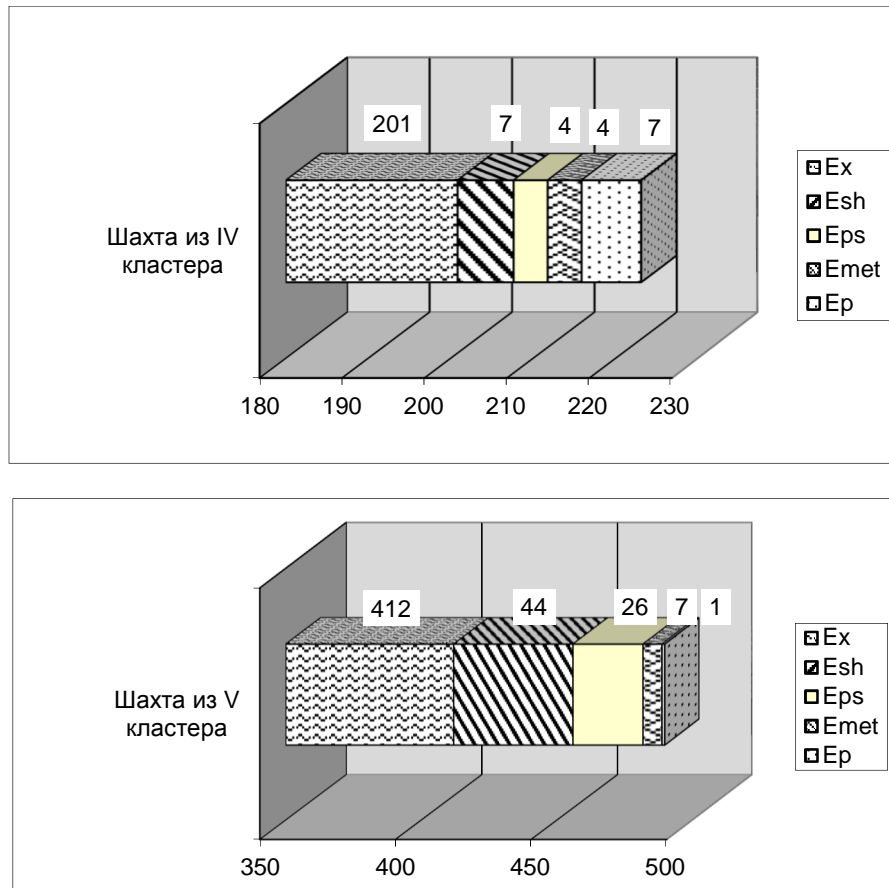
To achieve the highest possible energy efficiency it is required to control and adjust the operation modes at the fourth cluster coal mines which have a more rigid production function as far as a resource aspect is concerned. The optimal values of standardized coal production at such mines varies between 0,71 and 0,76. As to the fifth cluster coal mines the basic condition for achieving an effective operation mode is the increase of an annual coal output to reach a rated level of production capacity.

This goal is hard or more likely impossible to achieve since it requires to attract very sizable investments and involve a lot of additional manpower. Since these enterprises are loss-making they do not have any resources of their own to achieve the above. Budget resources are limited and are not sufficient to support even more efficient coal mines. This is the reason why the

majority of state-owned coal mines have low production loads and their energy efficiency is at a very low level.

The following Grassmann diagrams (Fig. 4) are indicative of the operating efficiency of the fourth and fifth clusters' coal mines when they operate in the optimal operation modes at a high efficiency of thermal power station operation.

Actually these are the descriptions of how the produced coal is distributed. The fourth cluster coal mine consumes 7 thousand tons of equivalent fuel (in coal) for its own technological needs. Besides it sends: 4 thousand tons of equivalent fuel to electric power station, 4 thousand tons of equivalent fuel to the by-product coking plant and 7 thousand ton – for the domestic needs of personnel. EROI of coal mine having a useful coal output at the level of 201 thousand tons of equivalent fuel equals 9,60.



**Fig. 4 Comparative Grassmann diagrams for coal mines of the fourth and the fifth clusters when thermal power stations operate with a high efficiency**

Out of 650 thousand tons of equivalent fuel produced by the hypothetical fifth cluster coal mine, 44 thousand tons of equivalent fuel (in coal) is consumed by the coal mine directly (in a boiler house) or indirectly for its own technological needs. Besides, 26 thousand tons of equivalent fuel goes to electric power station, 7 thousand tons goes for production of coke and another 9 thousand tons goes for domestic needs of personnel. The actual useful output of coal amounts for 412 thousand tons of equivalent fuel. And EROI of this coal mine constitutes 4,79.

When electric power stations operate inefficiently, the inputs  $E_{ps}$ , i.e. the amount of fuel to be used at the energy generating enterprise increases to 13 and upto 80 thousand tons of equivalent fuel depending on whether a coal mine belongs to the fourth or to the fifth cluster. In this case a net energy production of the system constitutes 208 and 376 thousand tons of equivalent fuel respectively. And EROI is 8,0 and 3,08 respectively.

#### **Discussions**

According to the available information EROI of the American coal is 80:1, and the average EROI worldwide is 46:1, a Chinese coal has the ratio of 27:1 (according to the data of 2007) [22]. Research in the sphere of various processes in the energy sector of the national coal mining sector can be concluded in the following way: EROI index of the best national enterprises operating

in the most favourable geological conditions and with the most efficient thermal power station is about 18:1. The actual profitability in the Ukrainian fuel and energy complex is much worse.

In the pre-depression and prewar 2006, a cumulative curve of EROI distribution by groups of coal mines excavating Steam Coal and Anthracite had the form, given in Fig. 5.

A general situation with anthracite coal has been improved by few high-performance coal mines forming an integral part of Sverdlovanthracite and Rovenkianthracite amalgamations. One of them has an EROI index which corresponds to an average global level of energy efficiency by coal, two other mines have EROI index on the level of Chinese coal mining industry. The rest of coal mines do not show any improvement as far as the energy characteristics of coal are concerned. There is a great number of coal mines in both groups having a low coal output which leads to a sort of energy cannibalism in coal mining industry.

For the first group a total reported coal production amounted 18,5 million tons, and EROI turned to be 9,3:1, as for the second group a reported coal production is 15,5 million tons and EROI is 10,1:1. A general EROI index of the Ukrainian steam coals is equal to 9,6:1 (according to the data of 2006).

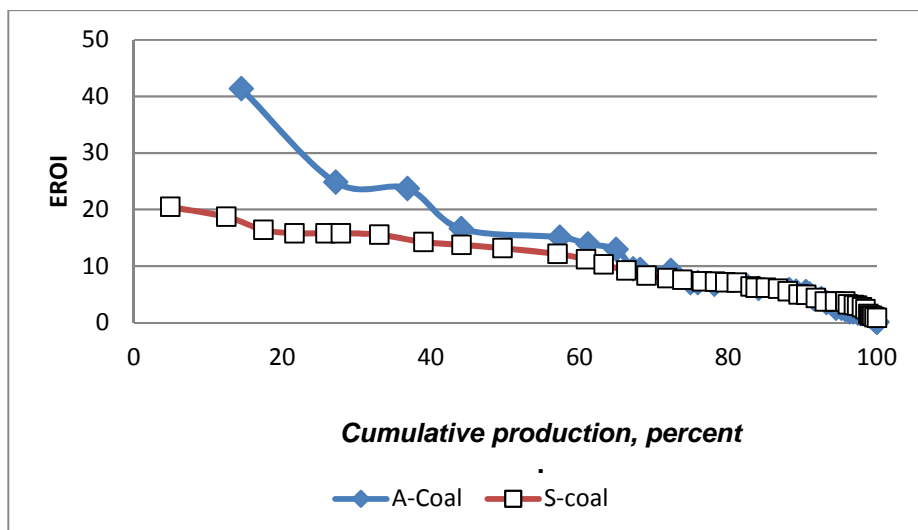


Fig. 5. Cumulative curves, characterizing energy cost-effectiveness of various coal grades mines

Such a low efficiency of the national coal mining industry is substantiated by unfavourable geological conditions (great depths and high gassiness of coal seams), neglect of technical facilities especially of state-owned coal as well as by the backwardness of thermal power engineering.

It should not be overlooked that Donbass basin is one of the oldest in the world, its history goes back to 200 years ago. The deepest coal mine in the world, “Shakhterskaya glubokaya”, is situated here. Mining activities are conducted at this mine at the depths exceeding the minus 1546 meters mark. No other country “takes risk” of developing such deposits. And until recently Ukraine was one a dozen of the biggest coal producing countries in the world. In view of the abovesaid, coal mining enterprises of Donbass are more likely the productions of hard, liquid and gaseous coal wastes (more than 5 т on 1 ton of excavated fossil) than on the contrary [23].

As shown in the article, a high fuel capacity of electric power energy production at the thermal power stations is one of the most powerful factors affecting the energy profitability of the Ukrainian coal.

Sigmund Freud believed that the technical expansion of Civilization is akin to a culturally acceptable form of sadism. But est modus in rebus: the desire for sustainable development requires the legislative restriction of enterprises with a low EROI [24].

It makes sense to update the obtained results to the recent situation in the coal mining industry of Ukraine, but even the given data is suitable for taking decisions on restructuring of capital assets in coal mining industry as well as developing policies on fuel provision of the national energy sector.

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#### **Череватський Д. Ю., Атабсков О. І. EROI українського вугілля**

Поняття EROI (energy return on investment) стало загальноживаним синонімом енергетичної рентабельності, певною альтернативою традиційної економічної оцінки.

Дослідження виконано з метою складання методичних положень щодо встановлення значимості основних чинників, що впливають на динаміку показників енергетичної ефективності вугілля українських шахт, і оцінки реальної ситуації в галузі.

Вугледобувне підприємство представлено як розподілені потоки вугілля, які символізують енергетичні ресурси: що витрачаються по шахті; відправляються на металургійний (коксохімічний) завод; на електростанцію; споживаються в побуті персоналом всіх технологічно пов'язаних підприємств тощо.

*Ключові слова:* EROI, вугільна шахта, коксохімічний завод, електростанція, персонал, витрата енергетичних ресурсів.

#### **Череватский Д. Ю., Атабеков О. И. EROI украинского угля**

Понятие EROI (energy return on investment) стало общеупотребительным синонимом энергетической рентабельности, определенной альтернативой традиционной экономической оценки.

Работа выполнена с целью составления методических положений по установлению значимости основных факторов, влияющих на динамику изменения показателей энергетической эффективности угля украинских шахт, и оценки реальной ситуации в отрасли.

Угледобывающее предприятие представлено в виде распределенных потоков угля, символизирующих энергетические ресурсы: собственно расходимые на шахте; отправляемые на металлургический (коксохимический) завод; на электростанцию; расходимые в быту персоналом всех технологически связанных предприятий и т.п.

*Ключевые слова:* EROI, угольная шахта, коксохимический завод, электростанция, персонал, расход энергетических ресурсов.

#### **Cherevatskyi D., Atabyekov O. EROI of the Ukrainian coal**

The concept of EROI (energy return on investment) has become a commonly used synonym for energy efficiency, an alternative to traditional economic evaluation.

This work was carried out with the goal of drawing up methodology for determining the significance of the main factors affecting the dynamics of the energy efficiency of Ukrainian coal and assessing the real situation in the coal branch.

The coal mining enterprise is represented in the form of distributed flows of coal, symbolizing the energy resources: actually spent at the mine; sent to the metallurgical (by-product) plant; to the power station; spent in the everyday life of all technologically related enterprises personnel, etc.

*Keywords:* EROI, coal mine, by-product coke plant, power station, personnel, energy consumption.

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