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COMPARISON OF ENERGETIC EFFICIENCY OF STATIONARY AND MOBILE SYSTEMS ON THE EXAMPLE OF MINERAL AGGREGATES PRODUCTION IN KIELECKIE KOPALNIE SUROWCÓW MINERALNYCH S.A.***

1. Introduction

Kieleckie Kopalnie Surowców Mineralnych S.A. conduct exploitation in Tyree open pit mines: Jaźwica, Laskowa and Winna. The exploitation is performed by means of blasting method. The yearly exploitation is about 3 million Mg (mine Jaźwica — 1.8 million Mg, mine Laskowa — 0.5 million Mg and mine Winna — 0.7 million Mg). Limestones and Devonian dolomites are extracted in all three mines and are being used to production of:

- Aggregates for civil engineering and road industry (break stone and arch bloc),
- Calcium-magnesium fertilizer flours,
- Extenders for bitumic masses,
- Dolomite grits.

This paper analyses two processing installations working to produce mineral aggregates at the Jaźwica and Laskowa mines.

In the Jaźwica mine, the exploitation is conducted using four processing plants (two stationary and two mobile). In the Laskowa mine extraction is conducted using two stationary processing plants.

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*** The paper is the result of the realization of research work of MNiSW no. N N524 466139.

The best comparison of the two mineral aggregate producing systems can be achieved by means of evaluation of the final product, including particle size and shape and also various other factors (technological and economical etc.) characterizing the work of the various devices and how these can influence each other [1]. For example, energy consumption depends on device capacity, which in turn depends on the constructive and exploitative parameters of the machine, as well as the physical-mechanical properties of the raw material [1, 3, 4]. By comparing device capacity, with the comminution level obtained at certain levels of production, with total energy consumption — amount of energy used leading to a material granulation, it is possible to compare the two technological systems. One more very important factor should also be considered — namely, exploitation costs [1, 3, 4].

Measuring performance and making precise comparisons of both mobile and stationary systems is very difficult in practice, mainly due to the fact it requires an adequate collection of detailed data, covering certain periods of time as well as considering other technological systems associated with production. These factors include energy consumption as well as others connected with costs. When conducting such a study another essential factor is to compare systems processing the same mineral raw materials with known granulation of feed as well as other technological statistics [1].

In this paper, various devices were compared (crushers and screeners) working in mobile and stationary conditions in systems with and without a closed return, processing various kinds of limestone and dolomite aggregates. For a full evaluation certain factors were taken into consideration, such as fuel consumption costs for mobile systems and energy consumption costs for stationary systems, unit energy consumption, maximum comminution levels and factor W [MJ/Mg] being quotient between energy consumption and maximum comminution levels when lowering the feed of mass to 1 Mg. Furthermore, two mobile crushers were added into the analysis, both of which were powered by electricity and fuel [1, 2].

In practice [1] factor W_j was introduced, which correctly determined the energy consumption of a crusher, with a view to efficient operation and the quality of the comminuted product. For example, the energy consumption of two various crushers (jaw and cone crushers) can be very similar, but when energy consumption is compared to comminution level, it can be demonstrated that the efficiency of both of these types is not comparable. Factor W_j can be applied for the crusher itself, or crusher cooperating with a screener, especially in a system with a material return, and also for a whole multistage technological system consisting of several crushers and screeners [1, 2].

During the analysis of the two systems, it was accepted that the most appropriate method for comparing the energy consumption of processing installations powered in various different ways, was to measure the results of energy consumption in joules, using the established relations that 1 kWh of electric energy is equal to 3.6 MJ and caloric value of 1 liter of oil is equal to about 38 MJ [1, 2].

For calculating costs, the price of 1 liter of oil was accepted as 5.46 zł and the price of 1 kWh of electric energy was accepted as 0.37 zł (The costs of electric energy and oil are an average of gross prices which existed in 2012).

2. Analysis of technological installation in processing plant Jązwica II

The technological installation, at the Jązwica II processing plant is presented on Figure 1 in compounds of:

- Stationary jaw crusher MFL STE120-100 working in an open system (Tab. 1).
- Two stationary cone crushers 10.44 working in an open system (Tab. 2),
- Mobile jaw crusher STE 108/75 T-V working in an open system powered by electric energy and oil (Tab. 3),
- Stationary impact crusher MagImpact 2700 working in a closed system (Tab. 4),
- Four stationary vibratory two-deck screeners (Tab. 5).

Fig. 1. Technological scheme of processing plant Jązwica II:

- 1 — drawer feed unit, 2 — jaw crusher STE120-100, 3 — two-deck screener WK2,
 4 — cone crusher 10.44, 5 — impact crusher MagImpact 2700,
 6 — three-deck screener WK3, 7 — two-deck screener WPB821,
 8 — two-deck screener SG2P, 9 — mobile crusher STE 108/75 T-V)

TABLE 1

Factors of work for stationary jaw crusher MFL STE120-100 working in open system (Jaźwica II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
104	0.37	120	0.87	0.32	3.13	900	150	6.0

TABLE 2

Factors of work for two stationary cone crushers 10.44 working in open system (Jaźwica II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
120	0.37	284	0.42	0.16	1.52	200	125	1.6

TABLE 3A

Factors of work for mobile jaw crusher STE 108/75 T-V working in open system powered by electric energy (Jaźwica II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
104	0.37	100	1.04	0.38	3.74	750	150	5.0

TABLE 3B

Factors of work of mobile jaw crusher STE 108/75 working in open system powered by oil (Jazwica II)

Amount of consumed fuel per hour, [l/h]	Cost of 1 liter of oil, [zł/l]	Production, [Mg]	Fuel consumption per Mg, [l/Mg]	Cost of oil consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level, S_{max}
16	5.46	100	0.16	0.87	6.08	750	150	5.0

TABLE 4

Factors of work for stationary impact crusher MagImpact 2700 working in closed system (Jazwica II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level, S_{max}
400	0.37	330	1.20	0.35	4.32	125	31.5	4.0

TABLE 5

Factors of work for stationary screeners (Jazwica II)

Screener	Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]
WK-2	12.0	0.37	120	0.10	0.04	0.36
SG2P	19.5	0.37	100	0.20	0.07	0.72
WK-3	24.0	0.37	330	0.07	0.03	0.25
WPB 821	17.6	0.37	171	0.10	0.04	0.36

In Tables 1–5 device operational factors were demonstrated. The lowest energy consumption level being equal 0.42 kWh/Mg was indicated for the Makrum 10.44 cone crusher working in an open system (Tab. 2) with the lowest maximum comminution level being equal to 1.6, while the highest energy consumption — 1.2 kWh/Mg was indicated for the MagImpact 2700 (VSI) impact crusher with a vertical rampart, working in a closed system, which had a comminution level of 4.0 (Tab. 4). The lowest energy consumption, 0.16 zl/Mg was demonstrated by a cone crusher. AVSI working on the last stage of comminution in a closed system is proved very efficient (0.35 zl/Mg). The lowest efficiency was indicated for mobile the STE 108/75 T-V jaw crusher working in open system powered by oil (Tab. 3b) and then the same crusher powered by electric energy (Fig. 3a).

The factor W_j of unit energy consumption (MJ) required for the comminution of 1 Mg of raw material causing a once off lowering of feed for a system powered by electricity, was equal to 3.31 MJ/Mg (0.92 kWh/Mg). If a technological system with screeners is taken into consideration, then factor W_j grows to 3.65 MJ/Mg (1.01 kWh/Mg) (An electric powered screener was also taken into account).

3. Analysis of technological installation in processing plant Jązwica III

The technological installation in processing plant Jązwica III, presented on Figure 2, consists of:

- MFL, type RCI 130-130/T-V mobile impact crusher working in closed system, powered by electric energy and oil (Tab. 6),
- Three-deck screener PEWERSCREEN CHIEFTAIN 2400 (Tab. 7).

Fig. 2. Scheme of processing plant Jązwica III:
 1 — mobile impact crusher MFL, type RCI 130-130/T-V,
 2 — three-deck screener PEWERSCREEN CHIEFTAIN 2400

TABLE 6A

Factors of work for mobile impact crusher MFL, type RCI 130-130/T-V working in closed system powered actually by electric energy (Jaźwica III)

Amount of consumed energy, [kWh]	Cost of energy, [zt/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zt/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
162.5	0.37	130	1.25	0.46	4.5	125	22.4	5.6

TABLE 6B

Factors of work for mobile impact crusher MFL, type RCI 130-130/T-V working in closed system powered by oil (Jaźwica III)

Amount of consumed fuel per hour, [l/h]	Cost of 1 liter of oil, [zt/l]	Production, [Mg]	Fuel consumption per Mg, [l/Mg]	Cost of oil consumption, [zt/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
25	5.46	130	0.19	1.05	7.3	125	22.4	5.6

TABLE 7

Factors of work for mobile screener (Jaźwica III)

Screener	Amount of consumed energy, [kWh]	Cost of energy, [zt/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zt/Mg]	Energy consumption E per Mg, [MJ/Mg]
PEWER-SCREEN CHIEFTAIN 2400	17	5.46	130	0.13	0.71	5.0

Tables 6 and 7 compare factors associated with where working devices are positioned. Here it can be observed that a mobile impact crusher powered by oil generates above 2 times higher costs than one powered by electric energy. Furthermore, the costs of oil consumption by screener being equal to 0.71 zł/Mg are very high, about 14 times higher than in case of screener powered by electric energy (Tab. 5 and 7).

The factor W_j of the unit energy consumption (MJ) required for the comminution of 1 Mg of raw material, causing a once off lowering of feed for a system powered by electricity would be equal to 0.80 MJ/Mg and for system powered by oil — 1.30 MJ/Mg. Taking this into consideration, factors for a crusher with a screener powered by electric energy show a figure equal to 1.70 MJ/Mg whereas in the case of one powered by fuel, the figure would be — 2.20 MJ/Mg.

4. Analysis of technological installation in processing plant Jaźwica IV

The technological installation in the Jaźwica IV processing plant is presented in Figure 3 consisting of:

- Mobile jaw crusher Premiertrack 1100 × 800 working in open system (Tab. 8),
- Two-deck screener PEWERSCREEN WARRIOR 1400 (Tab. 9).

Fig. 3. Scheme of processing plant Jaźwica IV:
1 — mobile jaw crusher Premiertrack 1100 × 800,
2 — two-deck screener PEWERSCREEN WARRIOR 1400

In Tables 8 and 9 various factors affecting the operation of a device were presented. Here we can see that the fuel consumption for a Premiertrack 1100 × 800 jaw crusher operating in an open system being equal to 0.2 l/Mg is not much higher than an MFL, type RCI 130-130/T-V impact crusher working in a closed system (Tab. 9 and 6b).

The factor W_j of unit energy consumption (MJ) required for comminution of 1 Mg of raw material by one time lowering of the feed for the crusher was equal to 1.52 MJ/Mg, while for the system with screener — 2.28 MJ/Mg.

TABLE 8

Factors of work for mobile jaw crusher Premiertrack 1100 × 800 working in open system powered by oil (Jaźwica IV)

Amount of consumed fuel per hour, [l/h]	Cost of 1 liter of oil, [zt/l]	Production, [Mg]	Fuel consumption per Mg, [l/Mg]	Cost of oil consumption, [zt/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. S_{max}
22	5.46	110	0.2	1.09	7.6	750	150	5.0

TABLE 9

Factors of work for mobile screener (Jaźwica IV)

Screener	Amount of consumed energy, [kWh]	Cost of energy, [zt/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zt/Mg]	Energy consumption E per Mg, [MJ/Mg]
PEWER-SCREEN WARRIOR 1400	11	5.46	110	0.1	0.55	3.8

5. Analysis of technological installation in processing plant Laskowa II

The technological installation in the Laskowa II processing plant, presented in Figure 4 is compounded of:

- Stationary jaw crusher Makrum 40.17, working in an open system (Tab. 10),
- Stationary cone crusher DKT 1200, working in an open system (Tab. 11),
- Stationary impact crusher MagImpact 2100, working in a closed system (Tab. 12),
- Three stationary two-deck vibratory screeners (Tab. 13).

Fig. 4. Scheme of processing plant Laskowa II:
1 — drawer feed unit, 2 — jaw crusher 40.17, 3 — cone crusher DKT 1200,
4 — two-deck screener WK-2, 5 — impact crusher MagImpact 2100

In Tables 10–13 various factors affecting the operation of devices were observed. Cone and jaw crushers in open systems indicate low energy consumption in comparison to that of an impact crusher (VSI) working on the final crushing stage at the highest level of comminution.

The factor W of unit energy consumption (MJ) required for a comminution level of 1 Mg of raw material, causing a once off lowering of feed for a system without screeners is equal to 2.8 MJ/Mg (0.78 kWh/Mg) and with screeners — 3.57 MJ/Mg (0.99 kWh/Mg).

TABLE 10

Factors of work for stationary jaw crusher Makrum 40.17 working in open system (Laskowa II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. $S_{\max}$
48.8	0.37	100	0.49	0.18	1.76	750	150	5

TABLE 11

Factors of work for stationary cone crusher DKT 1200 working in open system (Laskowa II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. $S_{\max}$
48.8	0.37	100	0.49	0.18	1.76	150	125	1.2

TABLE 12

Factors of work for stationary impact crusher MagImpact 2100 working in closed system (Laskowa II)

Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Max. feed particle size, [mm]	Max. product particle size, [mm]	Comminution level. $S_{\max}$
91	0.37	60	1.52	0.56	5.46	125	22.4	5.6

TABLE 13

Factors of work for stationary screeners (Laskowa II)

Screeners	Amount of consumed energy, [kWh]	Cost of energy, [zł/kWh]	Production, [Mg]	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]
WK-2	14.3	0.37	100	0.14	0.05	0.51
WK-2	12.0	0.37	60	0.20	0.07	0.72
WK-2	12.0	0.37	34	0.35	0.13	1.27

6. Analysis of open and closed technological systems

For the evaluation, all types of crushers and systems working in open and closed systems were taken into consideration, both powered by electric energy or oil. The results were presented in Tables 14–16.

The lowest energy consumption costs in stationary systems were found to be for jaw crushers working in open systems. These crushers work in the initial comminution stages and take full advantage of their possibilities for obtaining the highest comminution level — till 6.0. The factors W_j for crushers are equal to 0.35–0.52 MJ/Mg (what means 0.10–0.15 kWh/Mg) (Tab. 14).

The impact crushers MagImpact as VSI working with a material return on the final stage of comminution also work efficiently. Their energy consumption is however twice as high, being equal to 0.98–1.08 MJ/Mg (0.27–0.30 kWh/Mg) in comparison to jaw crushers caused by the necessity of using more energy for the comminution of finer fractions, this done in order to produce a more specific product, according to Rittinger and Bond theorems [1, 4].

The cone crushers in open systems work inefficiently. Their values of the factor W_j are very high (especially for crusher DKT 1200) and are equal to 0.95–1.47 MJ/Mg (0.26–0.41 kWh/Mg). in comparison to the other devices. Considering the technological systems in Jaźwica II and Laskowa II and the working cone crushers from which products are directed towards VSI without sieving, it seems to be useful to conduct the analysis of their optimization with the purpose of increasing their efficiency by obtaining finer products (growth of comminution level). This seems to be the correct way especially because, i. a., in cone crushers 10.44 there are not considered to be final products.

The STE 108/75 T-V mobile jaw crusher, powered by electric energy (Tab. 15) works by the factor of energy consumption W_j being equal to 0.75 MJ/Mg (0.21 kWh/Mg) and is less efficient than stationary a jaw crusher MFL STE 120–100 (Tab. 14). The same jaw crusher working within the same parameters is least efficient when powered by oil, due to the fact its factor is equal to 1.22 MJ/Mg and oil is double the cost. (Tab. 16). The type RCI 130-130/T-V impact crusher MFL, working in a closed system and powered by oil (Tab. 16) also consumes more energy than when powered by electricity (Tab. 15).

7. Conclusions

On the basis of the analyses conducted, it seems to be justified to state that mobile crushers powered by oil cost twice as much to operate than in case of being powered by electricity. The cost of fuel consumption for such crushers exceeds 1 zł/Mg of processed aggregate. At the same time the cost of energy for a stationary system is as low as one third of this cost.

Impact crushers working in closed systems on the final stages of comminution, despite being heavily loaded during the comminution of finer material, and working at high comminution levels, even exceeding the value 5.0, are more efficient than cone crushers working in open systems on secondary crushing stages.

TABLE 14

Factors of work for stationary systems powered by electric energy

Type of crusher	Type of system	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Comminution level, $S_{\max}$	Factor ^{*)} $W_f = E/S_{\max}$ [MJ/Mg]
Jaw MFL STE120-100 (Jaźwica II)	open	0.87	0.32	3.13	6.0	0.52
Jaw Makrum 40.17 (Laskowa II)	open	0.49	0.18	1.76	5.0	0.35
Cone 10.44 (Jaźwica II)	open	0.42	0.16	1.52	1.6	0.95
Cone DKT 1200 (Laskowa II)	open	0.49	0.18	1.76	1.2	1.47
Impact magimpact 2700 (Jaźwica II)	closed	1.20	0.35	4.32	4.0	1.08
Impact magimpact 2100 (Laskowa II)	closed	1.52	0.56	5.46	5.6	0.98

*) — Factor of unit energy consumption (MJ) required for comminution of 1 Mg of raw material by one time lowering of the feed, [MJ/Mg].

TABLE 15

Factors of work for mobile systems powered by electric energy

Type of crusher	Type of system	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Comminution level, $S_{\max}$	Factor ^{*)} $W_j = E/S_{\max}$ [MJ/Mg]
Jaw STE 108/75 T-V (Jaźwica II)	open	1.04	0.38	3.74	5.0	0.75
Impact MFL type RCI 130-130/T-V (Jaźwica III)	closed	1.25	0.46	4.5	5.6	0.80

*) — Factor of unit energy consumption (MJ) required for comminution of 1 Mg of raw material by one time lowering of the feed, [MJ/Mg].

TABLE 16

Factors of work for mobile systems powered by oil

Type of crusher	Type of system	Energy consumption, [kWh/Mg]	Cost of energy consumption, [zł/Mg]	Energy consumption E per Mg, [MJ/Mg]	Comminution level, $S_{\max}$	Factor ^{*)} $W_j = E/S_{\max}$ [MJ/Mg]
Jaw STE 108/75 T-V (Jaźwica II)	open	0.16	0.87	6.08	5.0	1.22
Jaw Premiertrack 1100 × 800 (Jaźwica II)	open	0.2	1.09	7.6	5.0	1.52
Impact MFL type RCI 130-130/T-V (Jaźwica III)	closed	0.19	1.05	7.3	5.6	1.30

*) — Factor of unit energy consumption (MJ) required for comminution of 1 Mg of raw material by one time lowering of the feed, [MJ/Mg].

TABLE 17

Juxtaposition of results for installations Jazwica II and Laskowa II

Factors	Jazwica II Devonian limestone	Laskowa II Devonian dolomite
$W = E/S_{\max}$ without screeners, MJ/Mg	3.31	2.80
$W = E/S_{\max}$ with screeners, MJ/Mg	3.65	3.57
Mean compressive strength, MPa	88	110
Mean contents of SiO_2 , %	2.47	6.23
Mean general susceptibility for comminution LA, %	28.9	21.5
Mean general susceptibility for comminution LA after cone crusher, %	24.5	24.0
Mean general susceptibility for comminution LA after impact crusher, %	19.5	17.0
Irregular particles contents FI after cone crusher, %	—	—
— in fraction 2–8 mm	17–21	17–22
— in fraction 8–16 mm	18–19	17–19
Irregular particles contents FI after impact crusher, %	—	—
— in fraction 2–8 mm	5–10	6–11
— in fraction 8–16 mm	12–13	8–11

In Table 17, the installations of Jażwica II and Laskowa II processing plants, powered by electricity were compared. Both installations consist of three stages in similar configurations of open and closed comminution systems, with screeners, while the installation at Jażwica II is equipped with an additional mobile comminution and classification system. This additional installation causes the value of the factor W_j representing the energy required for comminution of 1 Mg of raw material causing a one off lowering of the feed is higher by 0.51 MJ/Mg than in case of the installation in Laskowa II.

It is worth pointing out that an increase in the efficiency of cone crushers working in both plants would lower the value of the energy consumption factor W_j , especially in case of the Jażwica II installation. This is due to the fact that the comminuted Devonian limestone is characterized by lower compressive strength, lower silica contents, and a higher susceptibility to comminution LA in ratio to comminuted Devonian dolomite in installation Laskowa II.

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