Modelling of automated steam coal transportation and enrichment systems for efficient operation and cost reduction of thermal power plants

Grishyn Maksym Volodymyrovych¹

¹ fourth-year PhD student; National University «Odesa Polytechnic»; Ukraine

Abstract.
This paper investigates the efficiency of fuel enrichment to reduce the costs of thermal power plants (TPPs). An objective function is formulated to define and measure the desired results. The annual costs of TPPs and additional costs associated with the use of highly abrasive coal are analyzed. The costs of enrichment, in particular, flotation enrichment, are considered. A cost analysis and a transportation problem are presented to demonstrate the results. In general, this paper provides insight into the financial implications of fuel enrichment strategies for thermal power plants.

Keywords:
fuel enrichment
thermal power plants
TPP
cost reduction
objective function
highly abrasive coal
transportation problem
**Problem statement.** The cost-effective and efficient operation of thermal power plants (TPPs) is essential to ensure sustainable electricity production. However, the presence of various cost factors creates challenges in optimizing the financial performance of TPPs. One significant cost factor is the use of highly abrasive coal, which leads to additional maintenance and repair costs. In addition, the lack of an integrated assessment system that takes into account annual costs, additional costs associated with the use of high-abrasive coal, beneficiation costs, and transportation issues hinders the ability to effectively assess the financial impact of fuel enrichment strategies. Therefore, there is a need to address these issues and develop a comprehensive approach to assessing the effectiveness of fuel enrichment to reduce TPP costs. In this way, decision-makers in the energy sector will be able to make informed choices to optimize operations, minimize financial risks, and improve the overall efficiency of TPPs.

**Analysis of recent research and publications.** This paper is based on a comprehensive assessment of the efficiency of thermal power plants (TPPs) using different types of coal [1]. This study provides valuable information on cost-reduction strategies and emphasizes the importance of fuel enrichment methods. The ISO 18283:2022 standard is used for accurate coal sampling [2]. The development of flotation technologies for coal sludge beneficiation, as studied in [3], contributes to the understanding of beneficiation processes and their impact on TPP efficiency. Paper [4] on abrasive wear of pipes in ash and slag waste separation and dust collection systems highlights the additional costs associated with the use of highly abrasive coal. Collecting information on modern environmental technologies in the energy sector expands the analysis of environmental aspects [5]. The study [6] on the eco-geochemistry of impurity elements in coal gives an idea of the composition of coal and its consequences. It recognizes the urgency of solving geo-environmental problems related to the energy sector in particular [7]. Finally, a study [8] on combined cycle plants adds to the technical understanding of thermal power plant performance. By combining these diverse sources, the paper
ENERGETICS

offers a comprehensive analysis of fuel enrichment strategies and their impact on reducing TPP costs.

Setting the objective function

The objective function of TPP costs is given:

\[ Z = 365 \text{ days} \cdot M \cdot (x + l \cdot S) \to \min, \tag{1} \]

where \( M \) — daily fuel consumption by the plant [tons/day];

\[ B = \frac{N}{\eta_{TPP} Q_h^0}, \tag{2} \]

where \( Q_h^0 \) — is the lowest calorific value per kg of the substance \([\text{MJ/kg or kcal/kg}]\); \( \eta_{TPP} \) — overall efficiency of TPP, \( N \) — plant capacity \([\text{MW} = \text{MJ/s}]\), \( x \) — a variable denoting the cost of fuel per ton \([\text{UAH/ton}]\), \( l \) — transportation tariff per ton of cargo and kilometre of distance \([\text{UAH/ton} \cdot \text{km} = \text{UAH} \cdot 1000 \text{kg} \cdot \text{km}]\); \( S \) — distance to the delivery point \([\text{km}]\). The efficiency is based on complete fuel combustion \([2]\).

Since coal was considered the main fuel, in addition to the main components, it was also necessary to take into account non-combustible ash-forming additives. Ash pollutes the environment and is sintered into slag, which makes it difficult to burn coal, and also has an abrasive destructive effect on the furnace tubes, superheater, economizer, etc. Depending on the type and conditions of coal mining, the amount of minerals in it varies. For example, the ash content of hard coal is 14-35%, and for anthracite, it is 5-20%.

At this stage, it is important to investigate to what extent an increase in ash content affects fuel consumption at power plants. When considering the hypothetical scenario represented by formula (1), it is necessary to provide a new formulation that will facilitate the determination of the daily demand of the power plant.

\[ M^* = \frac{M}{(1-Ad)}, \tag{3} \]
where $M^*$ is the volume of required daily supply, taking into account ash content, and the ash content index $A_d$. Thus, from (3) we obtain:

$$M^* = \frac{N}{\eta_{TPP}Q_n^{TPP}(1-A_d)}.$$  \hspace{1cm} (4)

The formula (1) for daily fuel consumption, taking into account ash content, is as follows:

**Additional costs are caused by the wear and tear of TPP equipment**

Abrasive wear is characterized by the continuous cutting action of large ash particles with a sufficient hardness on the surface of heat exchanger tubes. This erosion process leads to a gradual decrease in the wall thickness of the pipe in the affected area. In addition, particles of unburned fuel, especially in anthracite coal, cause wear and tear of dust collection systems, and the abrasiveness of ash leads to degradation of convective heating surfaces in the boiler, such as the water economizer (WEC) and superheater (SH). Therefore, the annual costs associated with the repair of the main and auxiliary equipment of the boiler, taking into account the abrasive properties of both coal and ash, include the cost of repairing dust collection systems and convective heating surfaces of the boiler.

It is important to note that these costs are part of the total annual costs of a thermal power plant (TPP) and depend on regular equipment replacement:

$$C_{TPP} = \frac{U_{eq \cdot rep + U_{ash \cdot collectors rep} + U_{ash \cdot removal} + U_{ash \cdot collector rep} + U_{storage}}}{365}. \hspace{1cm} (6)$$

These costs will remain unchanged, except for the cost of repairing steam preheater equipment, furnace screens, and festoon [1].

These costs were included in the objective function:

$$Z = \frac{N}{\eta_{TPP}Q_n^{TPP}(1-A_d)^r} \cdot (x + l \cdot S) + C_{TPP} \rightarrow \min.$$  \hspace{1cm} (7)

The following formula is used to calculate the operating
time in case of abrasive damage to equipment due to fuel combustion:

\[ T = \frac{(\delta_{ct} - \delta_{oct})}{(3.6 \cdot \delta_{spec} \cdot G_M)}, \]  \hspace{1cm} (8)

where \( \delta_{ct} \) - Pipeline wall thickness, \( \text{mm} \); \( \delta_{oct} \) - a standard minimum thickness of the pipeline wall, \( \text{mm} \); \( \delta_{spec} \) - specific linear abrasive wear of the pipeline, \( \text{mm/t} \) of abrasive in the flow of fuel and material to be burned; \( G_M \) - mass flow rate of the material, \( \text{kg/s} \). The calculation of the value of specific linear abrasive wear of pipelines of pneumatic conveying units of dust collection and ash and slag removal systems of TPPs \( \delta_{spec} \) is performed for horizontal and inclined sections according to the dependence:

\[ \delta_{spec} = \frac{5.55 \times 10^{-7} \cdot K_{II} \cdot U_m^2 \cdot k_{SiO_2}}{D^2 \cdot m^{0.4} \cdot k_{res}}, \]  \hspace{1cm} (9)

and for vertical sections:

\[ \delta_{spec} = \frac{1.39 \times 10^{-7} \cdot K_{II} \cdot U_m^2 \cdot k_{SiO_2}}{D^2 \cdot m^{0.4} \cdot k_{res}}, \]  \hspace{1cm} (10)

where \( k_{SiO_2} \) - coefficient of relative \( \text{SiO}_2 \) content in the transported material; \( K_{II} = \frac{\rho_S \cdot d_0}{6} \) - criterion of aerodynamic lightness of particles during pneumatic transportation of fine bulk materials, \( \text{kg/m}^2 \); \( \rho_S \) - density of the transported material, \( \text{kg/m}^3 \); \( d_0 \) - weighted average equivalent diameter of the material particles; \( U_m \) - average cross-sectional flow rate of material particles; \( D \) - internal diameter of the pipeline, \( \text{mm} \); \( m \) - mass flow rate concentration of the mixture of material and air, \( \text{kg of material/kg of air} \); \( k_{res} \) - is the coefficient of relative wear resistance of the pipeline material. \( k_{res} \) is determined by the HV dependence (Vickers hardness of the pipeline wall material):

\[ k_{res} = 6.42 \times 10^{-5} \cdot HV^2 - 0.0157 \cdot HV + 1.97. \]  \hspace{1cm} (11)
ENERGETICS

The coefficient of the relative content of SiO₂ in the transported material is determined as follows:

\[ k_{SiO_2} = \frac{n_{SiO_2}}{\text{percentage of SiO}_2} = \frac{n_{SiO_2}}{94\%} \]  

(12)

where \( n_{SiO_2} \) - the percentage of quartz content in the material:

\[ n_{SiO_2} = A_d - n_{\text{other minerals}} \]  

(13)

where \( n_{\text{other minerals}} \) - percentage content of other ash minerals in the transported material.

Therefore, the costs of TPPs will also be a function of this indicator.

\[ C_{TPP} = C_{TPP}(T(n_{SiO_2})) \]  

(14)

\[ Z = N_{\text{enrich}}(A_d) + \log(V_{\text{purch}}) + C(T_{\text{equip}}); \]  

(15)

The efficiency of ash collectors is characterized by the following indicators:

\[ h = (G_{in} - G_{out}) / G_{in} = (c_{in} - c_{out}) / c_{in}, \]

where \( h \) - level of ash captured in ash traps; \( G_{in}, G_{out} \) - amount of ash at the inlet and outlet of the ash collector per unit of time; \( c_{in}, c_{out} \) - ash concentration at the inlet and outlet of the ash collector [5].

To calculate the volumetric flow rate of gas resulting from the reaction, the chemical formula of coal and air in the form of an air-coal mixture is given.

\[ z_1C + z_2SiO_2 + z_3(Fe_2O_3 + CaSiO_3) \] - coal fuel, where \( z_2 + 2 \cdot z_3 = A_d \), and \( z_2 = n_{SiO_2} \), while carbon and oxygen are involved in the reaction (for a simplified air formula, we use the ratio 20%/80% oxygen/nitrogen

**Fuel enrichment**

It is necessary to check the feasibility of using
flotation fuel enrichment directly at TPPs. The mechanical flotation machine MFU-25 was used as a prototype [3].

According to the equipment specifications, the concentrate extraction is $I_{\text{conc}} = 87.6\%$ (hence the tailings extraction is $12.4\%$). The recovery of valuable components into the concentrate during mineral processing ranges from 60 to 95% and above. For example, we took the recovery of $\varepsilon_{\text{coal}} = 95\%$ and calculated the mass of concentrate, tailings mass, and variable ash content per 100 tons of coal at the initial $Ad = 30\%$.

$$\varepsilon_{\text{coal}} = \frac{M_{\text{conc}} \cdot I_{\text{enrich}}}{M_{\text{carbone}}};$$

$$M_{\text{conc}} = I_{\text{conc}} \cdot M$$ - concentrate extraction, $\varepsilon_{\text{coal}}$ - extraction of valuable components, $M_{\text{byrra}} = M \cdot (1 - Ad)$ - mineral content in the original volume, $I_{\text{enrich}}$ - mineral content in the concentrate.

$$Ad_r = \begin{cases} Ad_r > Ad_{\text{perm}}; r = r + 1 \\ 1 - \left(1 - \frac{(1 - Ad_r) \cdot \varepsilon_{\text{coal}}}{I_{\text{conc}}}\right); n = \frac{1}{r} \\ 
\end{cases}$$ \hspace{1cm} (16)

$$V_{\text{purch}} = \begin{cases} M_{\text{TPP}} \cdot (I_{\text{conc}})^n; n = \frac{1}{r} \text{ when } Ad_r > Ad_{\text{perm}}; r = r + 1 \\ M_{\text{TPP}}; \text{ when } Ad_r = Ad_{\text{perm}} \\ 
\end{cases}$$ \hspace{1cm} (17)

**Inclusion of TPP fuel enrichment costs in the objective function**

The purchase of coal depends on the cleaning procedure and can be carried out in the following ways:

$$Z = \frac{N}{\eta_{\text{TPP}} \cdot Q_h^p \cdot (I_{\text{conc}})^r} \cdot (x + l \cdot S) + N_{\text{flot.}} \cdot \sum_{m=0}^{r} \frac{N}{\eta_{\text{TPP}} \cdot Q_h^p \cdot (I_{\text{conc}})^m \cdot M_{\text{thr.}}} \cdot 24 \cdot t_{\text{el.}} \rightarrow \min$$ \hspace{1cm} (18)

where $r$ - number of enrichment cycles, $M_{\text{thr.}}$ - throughput of
the flotation machine, \( N_{\text{flot}} \). - machine capacity, \( t_{\text{el.}} \) - tariff per kWh.

Below (Table 1), we present a study of how the dynamics of coal purchases change with increasing ash content and subsequent cleaning.

Table 1

<table>
<thead>
<tr>
<th>( Ad )</th>
<th>( d_{MFU} )</th>
<th>( Ad_{MFU} )</th>
<th>( k_{MFU} )</th>
<th>( M_{MFU} )</th>
<th>( Q_{MFU} )</th>
<th>( B_{MFU} )</th>
<th>( K_{MFU} )</th>
<th>( P_{MFU} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>87,60</td>
<td>7,80</td>
<td>1</td>
<td>3'558,60</td>
<td>2'160</td>
<td>4'637,36</td>
<td>3</td>
<td>3'749,76</td>
</tr>
<tr>
<td>20</td>
<td>87,60</td>
<td>13,24</td>
<td>1</td>
<td>3'558,60</td>
<td>2'160</td>
<td>4'637,36</td>
<td>3</td>
<td>3'749,76</td>
</tr>
<tr>
<td>25</td>
<td>76,74</td>
<td>11,79</td>
<td>2</td>
<td>3'117,33</td>
<td>4'320</td>
<td>5'293,79</td>
<td>6</td>
<td>7'499,52</td>
</tr>
<tr>
<td>30</td>
<td>67,22</td>
<td>10,72</td>
<td>3</td>
<td>2'730,70</td>
<td>7'920</td>
<td>6'043,34</td>
<td>11</td>
<td>13'749,12</td>
</tr>
<tr>
<td>35</td>
<td>58,89</td>
<td>10,09</td>
<td>4</td>
<td>2'392,17</td>
<td>7'200</td>
<td>6'898,57</td>
<td>10</td>
<td>12'499,20</td>
</tr>
<tr>
<td>40</td>
<td>51,58</td>
<td>10</td>
<td>5</td>
<td>2'095,54</td>
<td>8'640</td>
<td>7'875,07</td>
<td>12</td>
<td>14'999,04</td>
</tr>
<tr>
<td>45</td>
<td>45,19</td>
<td>10,53</td>
<td>6</td>
<td>1'835,69</td>
<td>10'080</td>
<td>8'989,81</td>
<td>14</td>
<td>17'498,88</td>
</tr>
<tr>
<td>50</td>
<td>39,58</td>
<td>11,79</td>
<td>7</td>
<td>1'608,07</td>
<td>7'920</td>
<td>10'262,34</td>
<td>11</td>
<td>13'749,12</td>
</tr>
<tr>
<td>55</td>
<td>34,68</td>
<td>13,91</td>
<td>8</td>
<td>1'408,67</td>
<td>12'240</td>
<td>11'715</td>
<td>17</td>
<td>21'248,64</td>
</tr>
<tr>
<td>60</td>
<td>26,61</td>
<td>10</td>
<td>10</td>
<td>1'080,98</td>
<td>13'680</td>
<td>15'266,31</td>
<td>19</td>
<td>23'748,48</td>
</tr>
<tr>
<td>65</td>
<td>20,42</td>
<td>7,38</td>
<td>12</td>
<td>829,52</td>
<td>15'120</td>
<td>19'894,17</td>
<td>21</td>
<td>26'248,32</td>
</tr>
<tr>
<td>70</td>
<td>17,89</td>
<td>13,91</td>
<td>13</td>
<td>726,66</td>
<td>15'840</td>
<td>22'710,25</td>
<td>22</td>
<td>27'498,24</td>
</tr>
<tr>
<td>75</td>
<td>12,02</td>
<td>8,49</td>
<td>16</td>
<td>488,47</td>
<td>18'000</td>
<td>33'783,88</td>
<td>25</td>
<td>31'248</td>
</tr>
<tr>
<td>80</td>
<td>9,23</td>
<td>13,90</td>
<td>18</td>
<td>374,84</td>
<td>19'440</td>
<td>44'025,20</td>
<td>27</td>
<td>33'747,84</td>
</tr>
</tbody>
</table>

Where \( Ad \) is ash content, %; \( d_{MFU} \) - a fraction of the initial fuel mass after fuel enrichment, %; \( Ad_{MFU} \) - ash content after enrichment step, %; \( k_{MFU} \) - number of enrichment iterations; \( M_{MFU} \) - is the final mass of fuel after enrichment, tons; \( Q_{MFU} \) - is the amount of energy consumed for fuel enrichment, kWh; \( B_{MFU} \) - should be procured with the calculation of the loss of fuel during enrichment, tons; \( K_{MFU} \) - the number of MFU-25s for round-the-clock operation; \( P_{MFU} \) - the cost of electricity consumed, UAH.

Examples

Transportation problem. To solve the problem, three TPPs were taken: A1, A2, and A3, with Zaporizhzhia TPP, Vuhlehirsk TPP, and Burshtyn TPP as examples. These TPPs operate on coal.
Since the specific heating value of coal is taken as 31 MJ/kg, the fuel consumption will be as follows.

### Table 2

<table>
<thead>
<tr>
<th>TPP</th>
<th>Installed capacity, MW</th>
<th>Coal consumption, kg/s</th>
<th>Consumption of million tons/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁</td>
<td>3’600</td>
<td>290,32</td>
<td>9,16 = V₁</td>
</tr>
<tr>
<td>A₂</td>
<td>3’600</td>
<td>290,32</td>
<td>9,16 = V₂</td>
</tr>
<tr>
<td>A₃</td>
<td>2’400</td>
<td>193,55</td>
<td>6,10 = V₃</td>
</tr>
</tbody>
</table>

The Ukrainian mines were considered as a prototype of suppliers in the transportation problem (information was taken from statistics for 2008 and 2009).

### Table 3

<table>
<thead>
<tr>
<th>Year</th>
<th>UAH million</th>
<th>Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>127,1801847</td>
<td>45,53740265</td>
<td>B₁ Volynvuhillia</td>
</tr>
<tr>
<td>744,1657721</td>
<td>733,8540063</td>
<td>B₂ Lvivvuhillia</td>
</tr>
<tr>
<td>66,7066685</td>
<td>19,85776548</td>
<td>B₃ Myrnoigrad-vuhillia</td>
</tr>
<tr>
<td>101,2467087</td>
<td>34,75224867</td>
<td>B₄ Selydiv-vuhillia</td>
</tr>
<tr>
<td>185,097695</td>
<td>65,47338679</td>
<td>B₅ m. Dobropillya</td>
</tr>
<tr>
<td>62,04281552</td>
<td>64,4617811</td>
<td>B₆ m. Sosnivka</td>
</tr>
<tr>
<td>61,55088996</td>
<td>19,52413427</td>
<td>B₇ m. Ugledar</td>
</tr>
<tr>
<td>71,45735598</td>
<td>80,15046498</td>
<td>B₈ m. Alexandria</td>
</tr>
<tr>
<td>628,2408455</td>
<td>585,0998432</td>
<td>B₉ m. Pavlohrad</td>
</tr>
</tbody>
</table>

The option of a fuel shortage in the domestic market was also considered. In this case, the possibility of importing coal from South Africa was taken into account. The average cost per tonne for 2020 on CIF port of Odesa was taken as the price, which was equal to UAH 2'724.96. The average distances from the ports of the Odesa region to TPPs A₁, A₂, and A₃ are 555 km, 845 km and 764 km, respectively.

The transportation problem was solved by taking into...
account daily deliveries.

It was assumed that coal from South Africa was purchased for the supply, which turned out to be of poor quality with a high ash content of 50%. Consequently, twice as much coal would be needed to be delivered via this route. Given the high coal consumption due to high ash content, TPP A3 lacks 4.06 thousand tons per day. By using source B2, it turned out that the coal from this mine also has a high Ad=30%. Of the 8.125 thousand tons produced daily, only 5.6875 thousand tons are useful fuel, excluding ash impurities. Due to the shortage of 4.06233 thousand tons of ash-free fuel, the actual carbon demand, including ash content, will be 5.80333 thousand tons. It is worth noting that neither the purchase price nor the transportation costs are affected in this scenario, as the actual weight remains unchanged.

Three MFU-25 mechanical flotation machines were installed, and the recovery procedure was carried out three times. At each stage of cleaning, the concentrate will be 67.2% of the initial mass, and the tailings will be 32.8%. In the above problem, given the initial ash content of 30% for 100 tons of coal, the cleaning process will produce a concentrate with an ash content of 10.8% for 67.2 tons. The production capacity of the MFP-25 is 67.2 tons of enriched fuel per hour, resulting in a daily output of 1'612.8 tons from 2,400 tons of supplied coal.

With a capacity of 30 kW per unit, the enrichment equipment has a total capacity of 90 kW, consuming 2'160 kWh per day.

The electricity tariff for thermal power plants in Ukraine is UAH 0.67/kWh. Thus, the cost of processing 2'400 tons of coal per day, based on the average electricity cost of 173.6 kopecks per kWh, is UAH 3'749.76.

A comparison of objective functions (15) and (18) for the
transportation problem shows that fuel enrichment to an ash content of 30% is more profitable than relying on regular repairs and replacement of equipment at TPPs. In addition, taking into account the operation of the K-300 turbine for 10 years, the savings amount to an average of more than UAH 25.5 million.

As a result, the ash content has decreased from 30% to 24.1%, and the total weight of fuel has decreased from 100 tons to 87.6 tons.

Table 4

<table>
<thead>
<tr>
<th>transportation problem with consideration of ash content</th>
<th>carbon content</th>
<th>real volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>348,45</td>
<td>124,77</td>
<td>68,64</td>
</tr>
<tr>
<td>1,652,38592</td>
<td>1,631,363195</td>
<td>365,4681826</td>
</tr>
<tr>
<td>757,6973391</td>
<td>1,096,359289</td>
<td>1,001,767503</td>
</tr>
<tr>
<td>182,78</td>
<td>54,42</td>
<td>663,97</td>
</tr>
<tr>
<td>277,42</td>
<td>95,24</td>
<td>960,39</td>
</tr>
<tr>
<td>507,17</td>
<td>179,43</td>
<td>1,672,46</td>
</tr>
<tr>
<td>169,99</td>
<td>17,71</td>
<td>23,30</td>
</tr>
<tr>
<td>168,65</td>
<td>53,51</td>
<td>607,45</td>
</tr>
<tr>
<td>195,79</td>
<td>219,61</td>
<td>428,72</td>
</tr>
<tr>
<td>1,721,48</td>
<td>1,605,28</td>
<td>8,451,18</td>
</tr>
<tr>
<td>25,08705259</td>
<td>25,08705259</td>
<td>16,72470172</td>
</tr>
</tbody>
</table>

Analysis of the optimal plan (Table 4).
1) From the 1st mine, all the cargo should be sent to the 3rd TPP.
2) From the 2nd mine, all the cargo must be sent to the 3rd TPP.
3) From the (2*) port warehouse, all the cargo must be sent to the 3rd TPP.
4) From the 3rd mine, the cargo must be sent to the 2nd TPP (1.073928417 thousand tons), to the 3rd TPP (1.660318158 thousand tons)
5) From the 4th mine, the entire cargo must be sent to the 2nd TPP.
6) From the 5th mine, all the cargo should be sent to the 2nd TPP.
7) From the 6th mine, all the cargo must be sent to the 3rd TPP.
8) From the 7th mine, you need to send all the cargo to the 3rd TPP.
9) From the 8th mine, you need to send all the cargo to the 3rd thermal power plant.
10) From the 9th mine, it is necessary to send the cargo to the 1st TPP (25.08705259 thousand tons), to the 2nd TPP (13.150658419 thousand tons)
11) At the 9th mine, 2 tons of cargo remained unclaimed.
    The optimal plan is degenerate, since the base variable \( x_{104} = 0 \).

**Abrasive damage to pipes and reduced service life**

In terms of chemical composition, the main component of ash and slag is silicon dioxide \((\text{SiO}_2)\), which makes up 45-60% of the composition, along with other oxides, such as aluminium oxide \((\text{Al}_2\text{O}_3)\), which makes up 15-25%, iron oxides \((\text{Fe}_2\text{O}_3)\) - 5 - 15%, calcium oxide \((\text{CaO})\) - 1.5-4.5%, potassium oxide \((\text{K}_2\text{O})\) - 2.0-4.5%, as well as other oxides, which are usually present in minimal amounts not exceeding one percent [6].

For the purposes of the analysis, we will assume that the average ash content of Donbas coal is 15-20%. Assuming that \(\text{Ad} = 20\%\), and quartz \((\text{SiO}_2)\) makes up 60% of the ash content, we have \(\text{Ad} = n_{\text{SiO}_2} + n_{\text{rock}} = 12\% + 8\% = 20\%\).

Using the example of TPP A1 turbines: two K-300-240-2 and two K-325-23.5 turbines with a total electric capacity of 317 MW and 337.3 MW, respectively, the total capacity of the four turbines will be \(W = 1308.6\) MW. Assuming that the efficiency of the TPP is 40%, the consumption of "ideal coal fuel" for TPP A1 will be 379.91 tons per hour. Consequently, the electricity generated per day, assuming 40% efficiency and combustion of "ideal" fuel, will be \(q = W \times 40\% \times 24 = 12\,565.56\) MWh.

For Donetsk G-grade coal, the fuel consumption is \(B = 25.08\) tons/d, where 80% = 31.3545 tons/d. At \(\text{Ad} = 20\%\), consisting of 12% abrasive material and 8% rock, the ash content is compensated by increasing the volume of fuel burned, thereby maintaining the same turbine power, resulting in \(q = 12\,565.56\) MWh/day. The abrasive wear per ton of dry
coal \( \delta_{(d.c.)} \) will be 3.003 nm/t.d./t.a., so \( \delta_{(d.c./day)} \) per day will be 3.003 nm/t.d./t.a. * 31.3545 t.d./day = 94.1575635 nm/d.

If we convert the mass of carbon into the amount of substance for the reaction, the amount of carbon is 932.479 moles. The same amount of oxygen is needed to form carbon dioxide, which means that four times as much nitrogen is needed, based on the above assumption.

\[
932.479 \, C + 932.479 \, O_2 + 3729.916 \, NO_2 = 932.479 \, CO_2 + 3729.916 \, NO_2
\]

\[
v_{CO_2} = 932.479 \, \text{moles} \Rightarrow m_{CO_2} = 41.037 \, \text{kg};
\]

\[
v_{NO_2} = 3729.916 \, \text{moles} \Rightarrow m_{NO_2} = 171.595 \, \text{kg}
\]

\[
\rho_{SiO_2} = 2.65 \, \frac{g}{cm^3} \Rightarrow V_{SiO_2} = 633.96 \, cm^3
\]

\[
\rho_{Fe_2O_3} = 5.24 \, \frac{g}{cm^3} \Rightarrow V_{Fe_2O_3} = 106.87 \, cm^3
\]

\[
\rho_{CaSiO_3} = 2.915 \, \frac{g}{cm^3} \Rightarrow V_{CaSiO_3} = 192.11 \, cm^3
\]

\[
\rho_{CO_2} = 1.9768 \cdot 10^{-3} \, \frac{g}{cm^3} \Rightarrow V_{CO_2} = 20.741 \cdot 10^6 \, cm^3
\]

\[
\rho_{NO_2} = 1.45 \, \frac{g}{cm^3} \Rightarrow V_{NO_2} = 118.276 \cdot 10^3 \, cm^3
\]

\[
V_{cons.} = v \cdot \rho
\]

\[
V_{cons.} \approx 20,860 \cdot 10^6 \, \frac{cm^3}{s} = 20,860 \, m^3/s
\]

The ash removal rate of 31.23% was obtained. When burning coal with an ash content of 20%, of which 12% is abrasive, the boiler tubes wear out in 6.2 years (with a normal service life of 10 years).

**Conclusions.** This study addresses the issue of ash impurities and their abrasive impact on thermal power plant (TPP) equipment. By considering the financial aspects of equipment failures, including repair and replacement costs, as well as additional fuel purchases, the importance of fuel enrichment to reduce TPP costs was emphasized. The analysis showed that, despite the initial costs associated with enrichment, the extended equipment life as a result of reduced wear and tear outweighs the investment.

In addition, the analysis of the optimal plan for the
transportation problem provided valuable information on the distribution of cargo between different mines and thermal power plants. The identified optimal plan ensures efficient use of resources and transportation, contributing to cost optimization in the overall supply chain.

By implementing fuel enrichment strategies and optimizing freight distribution, thermal power plants can achieve significant cost savings, extend equipment life and improve operational efficiency. These findings contribute to ongoing efforts in the energy sector to improve the financial sustainability and reliability of thermal power plants.

It is important to keep in mind that this study focused primarily on the financial perspective and did not take into account operational constraints related to scheduled maintenance and grid capacity. Traditionally, TPPs do not have the laboratory infrastructure to test every batch of fuel, but periodic deviations in fuel quality from documented specifications require methods for timely detection.

Future research could explore methods for accurately determining the need for fuel enrichment given periodic fluctuations in fuel quality.

References:


ENERGETICS
