Sustainable Mining Land Use for Lignite Based Energy Projects

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Abstract. This research aims to discuss complex lignite based energy projects economic viability and its impact on sustainable land use with respect to project risk and uncertainty, economics, optimisation (e.g. Lerchs and Grossmann) and importance of lignite as fuel that may be expressed in situ as deposit of energy. Sensitivity analysis and simulation consist of estimated variable land acquisition costs, geostatistics, 3D deposit block modelling, electricity price considered as project product price, power station efficiency and power station lignite processing unit cost, CO₂ allowance costs, mining unit cost and also lignite availability treated as lignite reserves kriging estimation error. Investigated parameters have nonlinear influence on results so that economically viable amount of lignite in optimal pit varies having also nonlinear impact on land area required for mining operation.

1. Introduction

With high fixed costs, optimal surface costs and transition to higher efficiency power generation became important issue to sustain high profitability of lignite based energy projects in a low carbon future. Joint analyses constitute a contribution to investment decision-making [1, 2, 3, 4] and sustainable land use so that no land is used without careful economic analysis. Lignite reserves represent a subset of resources, which could be mined economically with regard to realistic mining and economic conditions at the time of reporting. In order to identify lignite reserves at least the ultimate pit shell has to be designed [5]. Thanks to optimisation [6, 7] and modelling a graphical feedback of each scenario pit extents is given enabling precise cadastral visualization and analyses of occupied land, which might be helpful in terms of mining-induced displacement and resettlement [8]. Although research was performed for lignite deposit, it can be easily adapted to coal deposit simply by changing block model and some further adjustments.

2. Test model development

Estimation of the minable lignite reserves should be based on the spatial model of the lignite deposit and defined pit limits. Spatial modelling is crucial for both, simple and more complex geological structures such as multi-seam deposits [9]. To create lignite deposit economic block model, quality parameters were investigated. Under intrinsic stationarity assumption kriging estimation was performed. Kriging as estimation procedure gives the best linear unbiased prediction of the values and by assigning kriging weights, kriging variance (kriging error) is minimized [10].
Figure 1. Boreholes location, avg. spacing 400 m (a) and histogram of calorific value (kJ/kg) at moisture 50% (1 m composites) (b)

For quality parameters estimation purposes a block model with panels of $400 \times 400 \times 3$ meters was used that reflects average borehole spacing (figure 1) and vertical range of semivariograms. After performing estimation block model was adjusted to mining technology that is bench height of 12 m and $50 \times 50$ m block cell dimensions that represents average mining block exploited by a bucket-wheel or bucket-ladder excavator. Minimized kriging error is given by following formula:

$$\sigma_k^2 = \sum_{i=1}^{N} w_{ik} \cdot \overline{\gamma}(S_i, A) + \sum_{i=1}^{N} \sum_{j=1}^{N} w_i w_j \cdot \gamma(S_i, S_j) - \overline{\gamma}(A, A)$$

(1)

Where: $N$ - number of observations included in kriging procedure, $w_{ik}$ - $i^{th}$ observation kriging weight coefficient, $\overline{\gamma}(S_i, A)$ - average value of semivariogram for distance between sample $S_i$ and interpolation point (or block for average grade estimation) $A$, $\gamma(S_i, S_j)$ - value of semivariogram for distance between sample $S_i$ and $S_j$, $\overline{\gamma}(A, A)$ - average value of semivariogram for block $A$ (for point interpolation - equal to zero).

3. Lignite quality index adjusted to energy

Estimation in order to estimate lignite deposit value, quality index is introduced as part of lignite price formula (multiplication of quality index and base price) that was used by Polish lignite mine to estimate the price of lignite - product sold to power plant. Quality index enable to differentiate lignite through deposit.

$$Q_{\text{index}} = F(Q_A, A_A, S_A) = \frac{Q_A - A_A}{A_B} - \frac{S_A - S_B}{10}$$

(2)

Where: $Q_A, Q_B$ - actual and base lignite calorific value (kJ/kg), $A_A, A_B$ - actual and base lignite ash content (%), $S_A, S_B$ - actual and base lignite total sulphur content(%), $Q_B = 8850$ kJ/kg, $A_B = 12\%$, $S_B = 0.6\%$. As next step quality index was multiplied by factor that converts base tonne of lignite to energy that may be generated from it.

$$\text{ENERGY} = Q_{\text{index}} \cdot c$$

(3)

Where: $Q_{\text{index}}$ - lignite quality index, $c$ - factor 2.458 MWh/Mg for base lignite with calorific value of 8850 kJ/kg. As a result lignite deposit is converted into 'deposit of energy’ with assigned uncertainty.
given by function error \( mF_{Q_{\text{index}}} \) based upon kriging errors of lignite deposit quality parameters estimation. \( Q_{\text{index}} \) function error calculated in block model cell may be expressed by following formula:

\[
mF_{Q_{\text{index}}} = \sqrt{\left(\frac{\partial F}{\partial Q_A}\right)^2 m_{Q_A}^2 + \left(\frac{\partial F}{\partial A_A}\right)^2 m_{A_A}^2 + \left(\frac{\partial F}{\partial S_A}\right)^2 m_{S_A}^2} \]

\[
= \sqrt{\left(\frac{1}{8850}\right)^2 \sigma_{k-Q_A}^2 + \left(\frac{1}{200}\right)^2 \sigma_{k-A_A}^2 + \left(\frac{1}{10}\right)^2 \sigma_{k-S_A}^2}
\]

(4)

To prepare joint optimisation of lignite mine and power plant it is important to locate investment in existing cadastral land scheme. Analysed map includes about 6,000 land parcels that were grouped into 2 main categories as for urban and rural area. Within each category, there are 5 types of land use: residential, agricultural, build-up agricultural, forests and shrubs, and other (roads, infrastructure etc.). For each of 10 land use gamma probability density function of real estate free market transactions prices were plotted. Free market transactions data that were used were derived from Real Estate Turnover [11] prepared by Polish Central Statistical Office based upon descriptive characteristics of average transaction prices of premises at County level that comprises thousands of transactions. For simulations and sensitivity analyses 4 surface cost scenarios were used which include the no surface cost scenario for comparison purposes and also 50th, 60th and 95th percentile of surface cost scenarios. Importance of real estate surface cost was also investigated before [12, 13].

![Figure 2: Example of cumulative gamma probability function of residential lands prices within urban area, EUR/m² (a) and within rural area, EUR/m² (b).](image1)

Example of complete surface cost model derived from cadastral map and gamma probability density functions of real estate free market transactions prices is shown in figure 3b.

![Figure 3: Ultimate pit phases (a) with example of surface cost model as cadastral map applied in (b)](image2)
4. Results and discussions
In simulations and sensitivity analyses total number of 596 optimum pits were calculated with variable project parameters as shown in table 1. These 596 optimum pits extents can be used for precise cadastral visualization and analyses of occupied land for each scenario if required.

| Parameter | Sensitivity analysis parameters changes | Base project parameters | Parameter distribution used in simulation |
|-----------|----------------------------------------|-------------------------|------------------------------------------|
| Power plant efficiency, % | 0.37 0.41 0.42 0.43 0.44 0.45 | 0.45 | Gaussian 0.45 0.05 |
| Lignite processing cost, EUR/MWh | 9.78 10.23 10.69 11.14 11.6 12.00 | 12.05 1.14 12.51 13.42 13.87 14.33 |
| Energy price (product price), EUR/MWh | 45.48 50.03 54.57 59.12 63.67 68.22 | 68.22 11.37 72.76 77.31 81.86 86.41 90.95 |
| Emission allowances cost, EUR/CO₂ | 0 2.73 5.23 7.73 10.23 0.70 | Triangular 12.73 Min. 0.00 Max. 50.93 |
| Resource risk, [-] | 0.919 0.9352 0.9514 0.9676 0.9838 1.00 | Gaussian 1 0.081 |
| Unit mining cost, EUR/m³ | 1.65 1.7 1.74 1.79 1.84 1.88 | Gaussian 1.88 0.11 |

Table 2. Tornado diagrams data table, sensitivity analysis of project parameters ranges

| No. | Parameter | unit | min | base value | max |
|-----|-----------|------|-----|------------|-----|
| 1   | Energy price (product price) | EUR/MWh | 45.48 | 68.22 | 90.95 |
| 2   | Emission allowances cost CO₂ | EUR/CO₂ | 0.00 | 12.73 | 25.24 |
| 3   | Power plant efficiency | % | 37 | 45 | 50 |
| 4   | Resource risk | [-] | 0.919 | 1 | 1.081 |
| 5   | Lignite processing cost | EUR/MWh | 9.78 | 12.05 | 14.33 |
| 6   | Unit mining cost | EUR/m³ | 1.65 | 1.88 | 2.11 |

Figure 4 and 5 show tornado diagrams of performed sensitivity analyses for energy contained in ultimate pit (TWh) as well as ultimate pit net value (million EUR). Left, green tornado diagram represents scenario with no surface cost, middle (blue) scenario with 50th percentile of surface cost (47 million EUR) and right (red) scenario with 95th percentile of surface cost (374 million EUR). Bar numbers from the left side of the graph, correspond to data table 2.
Figure 4. Tornado diagrams of energy contained in ultimate pit, TWh. Left with no surface cost scenario, middle with 50th percentile of surface cost (47 million EUR) and right with 95th percentile of surface cost (374 million EUR). Bar number corresponds to data table 2.

Figure 5. Tornado diagrams of ultimate pit net value, million EUR. Left with no surface cost scenario, middle with 50th percentile of surface cost (47 million EUR) and right with 95th percentile of surface cost (374 million EUR). Bar number corresponds to data table 2.
Figure 6. Change in ultimate pit net value and relative impact of project parameters. 50th percentile of surface cost

As observed in figure 6 in 50th scenario of surface cost project is most sensitive to energy (product) price changes. It can be observed that 1% change in energy price generates 2.5% change in project net value. Similar to power plant efficiency which has third most important impact on lignite mining project where 1% change in power plant efficiency generates 1.5% change in project net value in analysed ranges. While increasing surface cost up to 95th percentile there is a slight change in relative impact of project parameters on optimum pit energy resources where power plant efficiency and mining unit cost swap their places (figure 7).

Figure 7. Relative impact of project parameters on optimum pit resources (contained energy). 50th percentile of surface cost (left graph) 95th percentile of surface cost (right graph)

Due to performed simulations (figure 8), each calculation of optimum pit was calculated from unique set of project parameters given by their distributions in table 1. It can be observed that project gives 95% of probability to obtain net value of 1.20 billion EUR in 60th percentile of surface cost scenario and 1.28 billion EUR in 95th percentile of surface cost scenario. Also there is only 5% chance to obtain net value of 6.0 billion EUR in 60th percentile of surface cost scenario and 5.52 billion EUR in 95th percentile of surface cost scenario.
Analyses show that project is most sensitive to energy (product) price changes what implies the most significant changes in occupied land area. In figure 9, outlines of ultimate pit extents for two surface cost scenarios are presented as calculated in sensitivity analyses. Green outline corresponds to 0th percentile as no surface cost scenario whereas red outline corresponds to 95th percentile of surface cost. Letters a, b and c correspond to different levels of energy (product) price (a - 45.48 EUR/MWh, b - 68.22 EUR/MWh, c - 90.95 EUR/MWh). More results are covered in table 3.

### Table 3. Sensitivity analyses results (results for figure 9 pit extents outlines).

| Parameter                        | Surface cost scenario | Product (energy) price |
|----------------------------------|-----------------------|------------------------|
|                                  |                       | a - 45.48 EUR/MWh      |
| Optimum pit area                 | 0th (green outline)   | 14.3 km2               |
|                                  | 95th (red outline)    | 11.2 km2               |
| Contained energy in optimum ultimate pit | 0th (green outline) | 246.0 TWh              |
|                                  | 95th (red outline)    | 192.3 TWh              |
| Project net value                | 0th (green outline)   | 0.86 billion EUR       |
|                                  | 95th (red outline)    | 0.52 billion EUR       |

5. Conclusions
Lignite open pit mining electricity generation project has many uncertainties that can be properly identified only in combination of financial, geological, real estate, technical and optimisation assessment. With high fixed costs, optimal surface costs and transition to higher efficiency power
generation became very important issue to sustain high profitability of lignite based energy projects in a low carbon future. Multi parameter analysis might be helpful not only to extractive industry executives but to determine sustainable mining land development in dense urban area. Resulting optimum pit outline can include ID of cadastral land parcels, which might be helpful for decision makers and further studies.

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