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Energy related sustainability analysis of shale oil retorting technologies

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Abstract

The research proposes an energy related performance evaluation method of shale oil production industry based on definition and analysis of energy balance indicators. Shale oil production quantitative data of the Viru Keemia Grupp Oil AS plant located in Kohtla Järve (Estonia) is used for the analysis. Results are summarised in the form of a comparative analysis of indicators of two shale oil production technologies (Kiviter and Petroter). Developed indicators are a useful tool for improvement of fuel production technological processes and for accessing the resource efficiency of potential alternative retorting technologies.

Keywords: motor oil; Kiviter; Petroter; retorting; energy related; indicators

1. Introduction

European Union initiates regular greenhouse gas emissions cutting actions for implementation in the energy production field to minimise climate change effects[1]. Such actions stimulate development of renewable energy technologies and low emission technologies of coal, conventional and unconventional oil resources. Oil shale is considered as a promising conventional oil alternative and, according to the requirements of the European Union Fuel Quality Directive, production and transportation of oil shale based fuels needs to be performed in a sustainable and environmentally sound manner [2].

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Progress towards defined sustainable energy sector policy goals are frequently measured with combined environmental, technical, economic and social indicators. The Organisation for Economic Co-operation and Development (OECD) structures the initial green growth measurement indicators in four thematic groups [3,4]:
- environmental and resource productivity: carbon and energy productivity, resource productivity, multi-factor productivity.
- economic and environmental assets: renewable and non-renewable stocks, biodiversity and ecosystems.
- the environmental dimension of quality of life: environmental health and risks, environmental services and amenities;
- economic opportunities and policy responses: technology and innovation, environmental goods and services, international financial flows, prices and transfers, skills and training, regulations and management approaches.

The supplementary group helping to track the effects of green growth policies and to measure the growth contains indicators describing socio-economic context and the characteristics of growth based on economic growth and structure, productivity and trade, labour markets, education and income, socio-demographic patterns. The proposed OECD indicators are flexible enough to be adapted to different national contexts [4].

Analysis of the role of indicators for assessment of sustainable development in the European Union performed by Cornescu and Adam [5] proves the necessity to develop an assessment model with several levels (“Environmental – Economic – Social”) of indicators, also described by Kalnins et al. [6,7], where each component is firstly evaluated separately and during the second round evaluation – combined in a joint evaluation model. The authors also conclude that the sustainable development indicators vary from region to region and from one industry sector to another.

Previous reviews have provided a detailed description of existing sustainability assessment indicators, its applicability, strength and limitations [8–10] and most of them emphasize the role of energy production and CO2 emission generation fields in sustainability assessments. Mathematical models on the discovery and depletion of oil resources (incl. oil shale and oil sand) are described by Brandt [11] and include pre-curve, curve-fitting, simulation, bottom-up and economic models. Due to the limited number of countries which have oil shale reserves, sustainability assessment of the oil shale sector is not widely researched. A three level assessment matrix considered to be applied for Estonian oil shale mining industry was developed by Šommet [12]; assessment module includes a set of economic, environmental and socio-cultural indicators resulting in Mining Sustainability Index. Sustainable development economic, environmental and social issues related to oil shale mining industry are summarized by Shen et al. [13]; X. Han et al. [14] performed a detailed analysis of issues related to oil shale utilization for semi-coke production.

The aim of this study is to define energy balance indicators for assessment of shale oil production at the Viru Keemia Grupp Oil AS (VKG Oil AS) plant located in Kohla Järve (Estonia). Special attention in the research is paid to allocation of inputs to partitioning the input flows of the retorting process to the final product system.

2. Methodology

2.1. Description of case industry

VKG Oil AS is the subsidiary of Viru Keemia Grupp AS, and its main area of activity is thermal processing of oil shale (producing semi-coke from oil shale in gas generator plants) and re-processing crude shale oil and total phenols retrieved from crude oil shale oil and phenol water into various products (different grade fuel oils, electrode coke, phenols, etc.).

Main production stages in the technological process of thermal processing of shale oil include:
- Oil shale preparation;
- Thermal processing of oil shale;
- Removal and storage of solid waste (semi-coke) generated during oil shale processing;
- Condensing and separation of vapour and gas products;
- Processing of liquid products [15].

General description of VKG Oil production units is provided in Fig.1.
Kiviter technology corresponds to a gaseous heat carrier technology and oil shale with the size of 25 – 125 mm and with the minimal heating value of 10 MJ/kg is used in the retorting process. The heat for the process is 750-950°C. The retort gas yield per ton of processed oil shale is ~400 – 500 Nm³/t and the lower calorific value of the retort gas is ~2.1 MJ/Nm³ and higher. The by-products of Kiviter technology are crude shale oil, retort gas, phenolic water and lower quality oil shale [15].

Oil shale fraction with the size of 0-25 mm and with calorific value of ~8.5 MJ/kg is used in the solid heat carrier or Petroter retorting technology. Lower calorific value of oil shale used in Petroter retorting technology results to lower oil yield (~12.5%) comparing to Kiviter retorting (~17%). The heat necessary for the process is gained in the equipment from waste carbon in solid residue. The pyrolysis process of the solid heat carrier occurs in the reactor at ~500°C and due to small fraction of oil shale used in process, residence time of oil shale in pyrolysis process is lower. The by-products of Petroter technology are also retort gas and phenolic water [15].

Analysed system is characterised as a set of energy related production and supply parameters of oil shale thermal processing (in Fig. 1 referred to the Petroter and Kiviter units)– input and output fuel (oil shale), input secondary energy (electricity and steam), output fuel (motor oil fractions), output secondary energy (steam – for the Petroter unit only).

2.2. Evaluation methodology

The methodology developed and presented in the paper allows us to evaluate environmental sustainability performance of shale oil production in combined Petroter and Kiviter retorting technologies.

The methodological framework of the research is illustrated in Fig. 2. VKG Oil AS plant operational data is acquired from technical and environmental monitoring reports for the time period 2009–2011. The boundary of the system is limited to oil shale retorting process only. According to Jorgenson et al. [16], sustainable human well-being has dynamic relationships with energy use. At the same time, the energy sector is a core element to transition
to sustainable and clean environment [17]. Based on these arguments, the selected functional unit of the present research is 1 tonne of market ready motor oil produced.

According to the technological process of shale oil production (see Fig.1), the following input flows were analysed:
- Technological oil shale delivered from Ojamaa mining site.
- Electricity and steam used in the retorting technologies comes from the CHP plant belonging to Viru Keemia Grupp AS.

Output flows analysed in the study are limited with motor oil fractions: light middle shale oil, heavy shale oil, generator gas, semi-coke waste.

3. Results and discussion

Input flow of retorting technologies are characterised with input oil shale delivered to the plant from Ojamaa mining site. As stated before, different fractions of the oil shale are used in the Petroter and Kiviter retorting technologies. General characteristics of the oil shale for both technologies are given in Table 1.

Table 1. Characteristics of oil shale used in the Petroter and Kiviter retorting technologies.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Kiviter</th>
<th>Petroter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower calorific value</td>
<td>[MJ/kg]</td>
<td>12.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Humidity</td>
<td>[%]</td>
<td>11</td>
<td>10.7</td>
</tr>
<tr>
<td>Oil shale carbonate content</td>
<td>[%]</td>
<td>12.5</td>
<td>18.9</td>
</tr>
<tr>
<td>Ash content</td>
<td>[%]</td>
<td>41.9</td>
<td>45.3</td>
</tr>
</tbody>
</table>

It should be emphasized that the motor oil production industry at VKG Oil AS is a multi-product industry; while a target product is motor oil, efficient use of by-products and optimisation of technological process resulting in the production of such products as retorting gas and semi-coke gas, bitumen, oil coke, phenols, resins, heat and electricity (for internal needs and to the market). Therefore the role of data allocation is crucial for the definition of performance indicators. The input and output parameters are normalised to 1 MJ of motor oil fraction – diesel (for the Petroter only), light middle shale oil, heavy shale oil and generator gas. These are the fractions exiting the
retorting unit as final products and after treatment in fuel mixing unit and distillation unit are considered as market ready oil products.

The plant’s monitoring data are used for further analysis. Retorting of the oil shale in the Kiviter technology occurs at the plant in three departments. Definition of the indicators (incl. all the analysis steps defined in Fig. 2) are completed at each department separately and then a cumulative indicator is determined (see Table 2). To ensure a comparative analysis, the illustrated indicators are normalised to the common calorific values of the shale oil fractions.

Table 2. Quantitative allocated indicators describing the retorting of the oil shale at VKG Oil AS.

<table>
<thead>
<tr>
<th>Indicator (input parameter per output parameter describing final motor oil fraction), MJ/MJ</th>
<th>Kiviter</th>
<th>Petroter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technological oil shale per light middle shale oil fraction</td>
<td>0.955</td>
<td>1.271</td>
</tr>
<tr>
<td>Electricity per light middle shale oil fraction</td>
<td>0.006</td>
<td>0.016</td>
</tr>
<tr>
<td>Steam per light middle shale oil fraction</td>
<td>2.751·10⁻⁷</td>
<td>7.712·10⁻⁶</td>
</tr>
<tr>
<td>Return gas per light middle shale oil fraction</td>
<td>0.178</td>
<td>-</td>
</tr>
</tbody>
</table>

| Technological oil shale per heavy shale oil fraction | 0.932 | 1.289 |
| Electricity per heavy shale oil fraction | 0.006 | 0.015 |
| Steam per heavy shale oil fraction | 4.528·10⁻⁷ | 7.768·10⁻⁶ |
| Return gas per heavy shale oil fraction | 0.293 | - |

| Technological oil shale per diesel fraction | - | 1.266 |
| Electricity per diesel fraction | - | 0.012 |
| Steam per diesel fraction | - | 7.695·10⁻⁶ |

| Technological oil shale per gasoline fraction | - | 1.288 |
| Electricity per gasoline fraction | - | 0.015 |
| Steam per gasoline fraction | - | 7.769·10⁻⁶ |

The comparative analysis of the results demonstrates:

- Relatively high resource efficiency (use of oil shale) of the retorting technologies at VKG Oil plant - from 0.932 MJ input/MJ output to 1.289 MJ input/MJ output of final product. The Kiviter retorting technology requires less amount of input oil shale than Petroter; and production of heavy shale oil in the Kiviter retort relates to the process with the highest oil shale consumption per MJ of heavy shale oil produced.

- Use of secondary energy (steam) delivered from the outer system is minimal in case of both retorting technologies. This is justified with a fact that oil shale thermal processing (retorting) takes place without the use of external fuels. The heat necessary for the process is gained from the waste carbon existing in the oil shale.

Retort gas produced as by-product in the Kiviter technology is efficiently re-used in the technological process – as an additional fuel for retorting that improves the overall efficiency of the retorting technology.

4. Conclusions

Estonia’s mid- and long-term national energy sector development strategy encourages the development of low emission and sustainable oil shale industry and it will play a significant role in meeting energy security targets.

Viru Keemia Grupp Oil AS implements regular improvements of oil shale processing activities to reduce environmental pollution and to improve economic performance of the plant. However limited research was introduced before to analyse complex progress towards sustainable development of the plant. The present research is
aimed at definition of sustainability indicators for shale oil production industry with a focus on energy balance indicators.

Energy related performance indicators, allocated to the final products, were proposed and quantified within the paper. Despite the opinion about low efficiency of resource use for motor oil production from oil shale, the results of the current paper show high transformation efficiency. That also proves that the efficiency of motor oils (heavy and light middle shale oil, diesel and gasoline fraction) production are highly depends on technological possibilities of retorting technologies to utilise “waste products” of the process to effective products.

Acknowledgments

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References