Energy self-sufficiency in motor fuel production from oil shale: economic and environmental considerations

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Abstract:

Nowadays, due to concerns on limited fossil resources and climate considerations, special attention is paid to evaluation of resource management in production processes. The objectives of the current study are (1) to quantify energy inputs and outputs of shale oil production using two retorting technologies – Kiviter and Petroter technology; (2) to analyse the energy return ratio with focus on energy self-sufficiency strategy of the production process and its economic and environmental implications. Four evaluation indexes are proposed: net external energy return (ratio of energy outputs to all external energy inputs), energy related self-sufficiency index (ratio of indigenous energy and total energy used in the system), exported energy money index (amount of exported energy divided by gross domestic product) and exported energy climate change index (amount of exported energy divided by shale oil production sector generated CO_2 emissions). The oil shale generated motor fuel production industry located in Estonia is selected for testing of the methodology. Results of the study show that the energy related self-sufficiency of the shale oil production is 67 %, while without efficient use of by-products the value is 17–24 % lower. The calculated net external energy return ratio of the Estonian oil shale derived motor fuel is 3.13:1 for 2013 that is lower than previously defined for the Alberta region (5.51:1) oil sands operations. The exported energy money index and the exported energy climate change indexes also show better performance: economic performance is 0.19 MJ/Euro in 2013 and 0.24 MJ/Euro in 2008 and the climate performance is 3.75 MJ/t CO_2 in 2013 and 2.8 MJ/ t CO_2.

Keywords:
Energy return on investment, Oil shale, Motor fuel, Energy self-sufficiency index, Non-conventional fuel.

1. Introduction

Climate and environmental considerations have stimulated countries to find alternatives to substitute traditional fossil based energy: one direction has pointed to wider use of renewable energy resources, second to analysis of unconventional fossil fuels and the third one, also joining the previous alternatives, is the improvement of energy efficiency at production, transmission and energy use stages.

Unconventional fossil fuel, as unconventional natural gas, oil sands and oil shale, are considered as comparative sources to replace fossil based fuels. At the same time, the environmental effect of such replacement is still debatable: additional efforts required for extraction, refining and synthesis of unconventional oil-based fuels in comparison with traditional ones. The European Union Fuel Quality Directive Article 7a [1] proposes a mechanism for elimination of carbon intensive conventional and unconventional fossil fuels through the analysis of life cycle based greenhouse gas performance of these fuels.

Shale oil is a complex combination of hydrocarbons obtained by thermal decomposition of organic matter contained in oil shale, called kerogen. It consists of hydrocarbons and heterocyclic compounds containing sulphur and oxygen [5] and nowadays the oil shale based fuel is produced in Estonia, Brazil, Marocco, Russia and China. In Estonia the liquid motor fuel is produced from local unconventional fuel (oil shale) and later is exported to Scandinavian and European countries, thus generating significant inputs to the gross domestic product (3.5 % in 2012) [2].

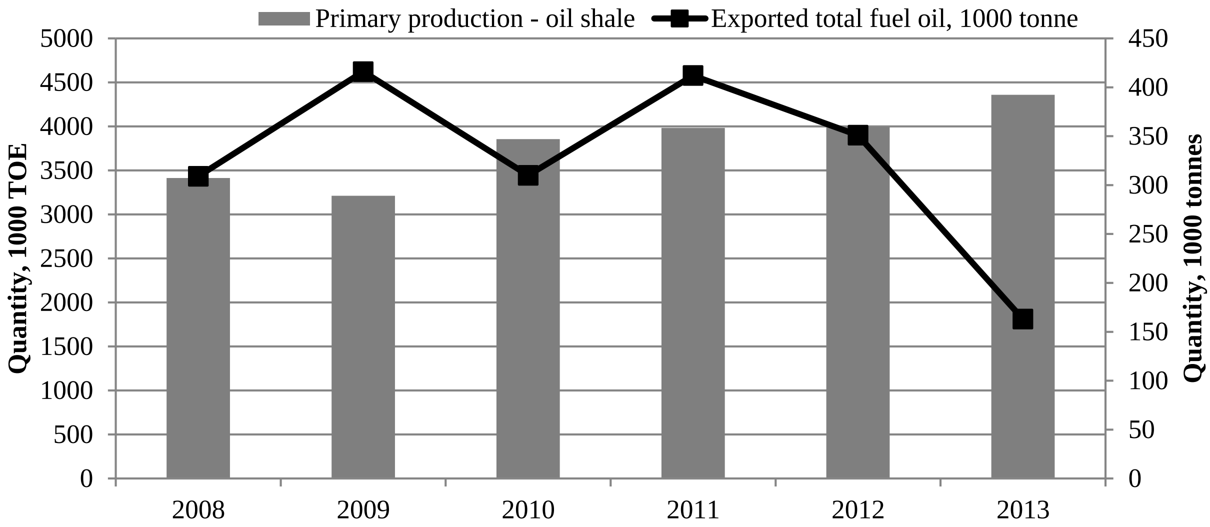

Fig. 1. Role of oil shale for Estonia in primary energy production and export of the oil shale derived motor fuel [3, 4].

Several shale oil production technologies are developed and industrially used [5-9]; the main differences defined between the technologies are (1) quality of raw oil shale and its fraction size, (2) execution of pyrolysis technology, (3) energy and environmental requirements of the final fuel [6, 7]. From an environmental point of view, the most significant distinguishing factor of oil shale based fuel oil production is its efficient use of process by-products [9, 10], as well as the ratio between the energy spent to extract and synthesize the fuel and the energy produced.

The traditional method used to quantify the relations between energy produced and energy required to produce that energy is an Energy Return on Investment (*EROI*) and a net energy ratio (*NER*) – the index showing the ratio of energy produced to energy costs [11-13]. In case of the oil shale industry, *energy produced* is described with the energy content of the produced oil shale based fuel, while *energy costs* entail the amount of energy spent during the life cycle of the oil shale derived motor fuel, e.g. extraction, transportation and processing of oil shale, synthesis and treatment of the produced motor fuel.

Several studies related to the oil shale industry were based on use of the *EROI* concepts. Indexes based analysis of *in situ* conversion process (ICP) of oil shale to liquid fuels in Colorado (USA) was performed by Brandt [13]: he defined the energy inputs and outputs of the ICP taking into account the full life cycle and computed two energy ratios – the external energy ratio (*EER*, the final refined product output divided to the primary energy input from the outside energy system) and net energy ratio (*NER*, all energy output to all energy input). The calculated values of *EER* were 15.8 and 2.4 for the lower case and higher case, respectively. The environmental effects were then expressed through the greenhouse gas emission factors of these two ratios and thus showed the effects at the industry-scale only. Bartis et al. analysed *Shell in-situ* oil shale conversion process and defined the ratio between the heat energy required to deliver the extracted fuel as 6:1 [15]. A comparative assessment of the *EROI* for different fuels (conventional and unconventional fossil fuels and also renewables based fuels) was performed by Hall et al [16]. The authors stated that the *EROI* of renewables and unconventional fuels are lower than traditional fossil fuels, e.g. 18:1 for global petroleum in 2005, 20:1 for dry natural gas in 2009, close to 75:1 to the USA coal in 2005 and 25:1 for coal in China in 2010. While Hu et al. [17] predicted that the EROI of China's oil and natural gas extraction will reach 9:1 in 2020 and coal 24:1 in 2020.

The findings of the above mentioned studies are limited only to the oil shale processing technologies explored in the USA and Canada and differ significantly from the liquid fuel production process explored in Estonia.

The aim of the current study is to analyse the net energy ratio of the Estonian oil shale processing industry, using two retorting technologies – Kiviter and Petroter, with a special focus on internal energy use and a self-sufficiency strategy in the industry. An additional objective is to formulate indexes characterising the environmental and macroeconomic advantages of the self-sufficiency issues in fuel oil production from oil shale.

The authors of the current paper also pay special attention to ecological emergy accounting principles formulated by Odum [18-20]. We referred to Odum's developed indexes which outlined the concepts of self-sufficiency indexes, however the scope was eliminated to energy concept only instead of emergy.

2. Methodology

2.1. Calculation model

The calculation model of the study is divided in several steps.

I. **Definition of the system boundary and the target product.** As stated by Cleveland et al., one of the significant issues in net energy calculations is a selection of the system boundary. Estonian shale oil production plant VKG Oil AS is selected as a case plant of the study. Two retorting technologies are exploited here – Kiviter and Petroter heat carriers. The joint retorting technology was introduced at the plant to improve the efficiency of resource use. Selection of the case industry is justified with the following objections. Firstly, an oil shale fraction unfitting requirement of Kiviter technology (i.e. less than 25 mm) is used in Petroter technology. Secondly, surplus heat and steam generated in one of the retorting units might be compensated by another unit. It was concluded that these objections give a good basis for the analysis of the self-sufficiency strategies. Thus the analysis is performed for the following production plant units: Kiviter retorting, Petroter retorting, coking unit, fuel mixing unit and distillation unit. Due to the fact that VKG Oil AS is a multi-product industry (the main products are motor fuel, heat, chemicals), the oil shale derived motor fuel is selected as a target product within the following study.

II. **Inventory analysis and allocation.** During the second step, collection of the input and output flows (materials and energy) was performed based on the life cycle inventory principles: (1) process flow diagrams outlining the modelled product developed and analysed; (2) site-specific data for the processes, which are included in a study system (See Fig. 2) and a flow diagram covering the whole life cycle of the production process, are collected (where necessary are also measured) at the case industry; (3) the units of the input and output unified; (4) calculation and allocation procedures applied to quantify relevant inputs and outputs of the analysed product system. Based on the production scheme (see Fig. 1), the following input and output energy flows are defined during the inventory audit at the industry (see Table 1). Data on amounts of the resources, energy, waste and fuels used at the industry are collected from the industry's regular direct measurement reports. Materials and energy required to build up the oil shale processing plant are not included in the study: it is assumed that the energy and material inputs will be similar to other oil shale processing industries thus might be neglected.

Table 1. General input and output energy flows at the analysed oil shale processing industry

	Category	Original unit	Unified unit
Inputs			
oil shale, natural gas	Resources	tonne, m^3	MJ
electricity, steam	Energy	MWh	MJ
By-products			
generator gas, distillation residue, drainage oil, semi-coke gas, coking gas, coking distillate, kek	Fuel	MJ, tonne	MJ
Outputs			
shale oil, gasoline, diesel light fuel, heavy fuel	Fuel (final product)	tonne	MJ
Waste			
semi-coke waste	Waste	tonne	MJ

III. **Definition of the indexes and calculation of the values.** Four indexes are proposed to evaluate the energy self-sufficiency of the motor fuel production from the oil shale (see Table 2): net external energy return on investment, energy related self-sufficiency index, exported energy money index and exported energy climate change index.

Table 2. Description of the indexes used in energy related self-sufficiency analysis

Index	Abbreviation and unit	Description
Indigenous energy	*I*, MJ	Flow of internal energy available within the system, incl. fuels, resources, energy
Imported energy	*F*, MJ	Flow of imported (external) energy from outside system, incl. fuels, resources, energy
Exported energy	*Y*, MJ	Flow of exported energy from the indigenous system to the outside system in the form of final and semi-products
Total energy used	*U*, MJ	Total energy used to support the studied system ($I+F=U$)
Net external energy return	*NEER*, (-)	Ratio of energy outputs to all external energy inputs
Energy related self-sufficiency index	*ESI*, (-)	Ratio of the indigenous energy (I) and the total energy used in the system (U)
Exported energy money index	*EMI*, MJ/Euro	Amount of exported energy (Y) divided by the gross domestic product (GDP)
Exported energy climate change index	*ECCI*, MJ/tCO_2	Amount of exported energy (Y) divided by the shale oil production sector generated CO_2 emissions (C)

Within the current study, the parameters *I*, *F*, *Y* are described as follows:

- *I* includes oil shale processing by-products (retorting gas, generator gas, steam and oil) generated and later used within the system;
- *F* is represented with natural gas for start-up of the CHP plant, electricity from the CHP plant and the oil shale coming from the mining site;

- different types of motor fuel fractions (diesel, light fuel, heavy fuel, bitumen), kek and also heat delivered to the market are defined as exported energy flow *Y*.

Traditionally a net energy return index (*NER* describing the net energy output to all energy inputs) is used for defining the efficiency of energy use. However, when the objective of a study is focused on analysis of the self-sufficiency of an industry, the *NEER* provides better description – it characterises the proportion of the energy produced to the external energy spent. Thus in the framework of the current study, it reflects the amount of motor fuel produced to the energy delivered to the industry from outside.

ESI is defined as a proportion of the indigenous energy (energy available within the system and recovered from efficient use of by-products), *I,* and the total energy used in the system, *U*. Thus, the *ESI* is defined within the value range from 0 to 1: a low *ESI* value (closer to 0) represents low self-sufficiency, a value closer to 1 demonstrates high self-sufficiency. The indigenous system is described as units belonging to VKG Oil AS; technological units outside the VKG Oil AS (even if some belongs to VKG AS) are defined as an external system and therefore the energy and products flows delivered to or from the indigenous system are called, accordingly, imported and exported.

Monetary effect of the industry's self-sufficiency to the national economy (defined with the GDP) is formulated in the exported energy money index (*EMI*) definition; it shows how much energy produced to the system's export is generated per one Euro. The higher *EMI*, the higher productivity of the system's efficiency is reached.

Similar to the *EMI*, the environmental efficiency of the system is described with the exported energy climate change index (*ECCI*): it shows how much energy produced for the system's export needs is generated per one tonne of CO_2 emissions generated by the shale oil production industry in the country. Moving towards a sustainable production system, EMI needs to increase, i.e. more final shale oil products are produced per 1 tonne of CO_2.

In the next chapters, the proposed methodology will be applied for assessment of the shale oil production at the VKG Oil Plant AS.

2.2. Description of a case industry

As stated before, an Estonian motor oil production industry VKG Oil AS is selected as a case industry for the study. The boundaries of the analysed system are outlined in Fig. 2.

Time boundary of the study is 1 year – calculated parameters and indexes are based on the input data for 2013.

Energy required for the plant's infrastructure and equipment development are not included in the study.

As shown in Fig.1, the mining of oil shale, transportation of oil shale to the processing plant as well as transportation of the by-products and co-products to storage or utilisation sites is not included at this stage. This is based on the following considerations:

- According to Siirde et al. [9], the highest energy related life cycle effect (93-95 %) of motor fuel processing corresponds to the retorting, condensation and distillation phases of the motor fuel production, the effect of energy use for the mining and transportation is 5-7 %.
- The transportation distance between the mining site and thermal processing unit does not exceed 12 km, and from the thermal processing unit and storages – 3 km. Thus the fuel and energy requirements are assumed to be within the 5-7 % as stated before.
- By the moment, the residues of the oil shale thermal processing (ashes) are landfilled, thus the energy requirements of its processing will include transportation to the landfill site only. The energy embodied in the ashes are calculated as wasted energy.

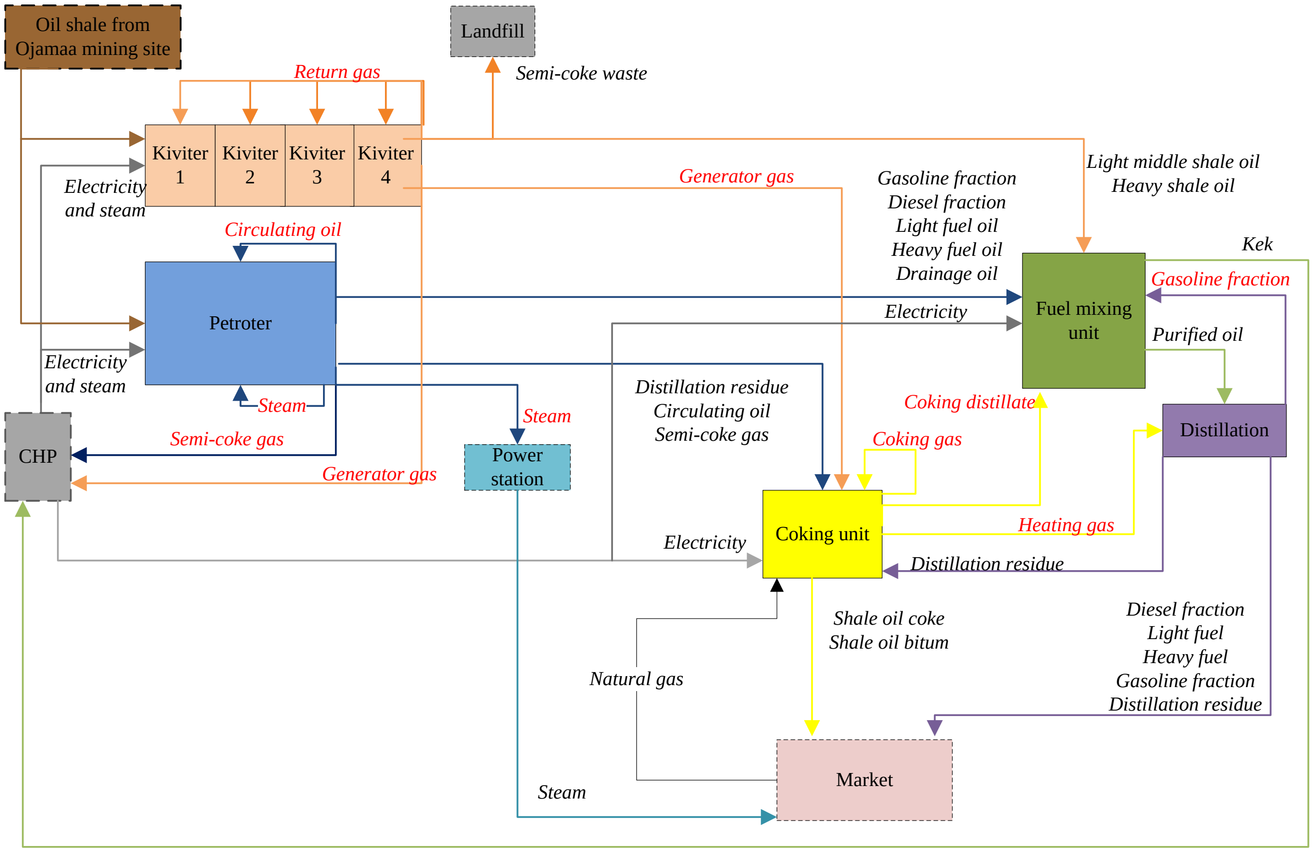

Fig. 2. Principal scheme of motor oil production input and output flows at VKG OIL AS (units outlined in dash pattern (mining site, CHP, Power station, market, landfill) are located outside the study boundary and are defined as external units).

Nevertheless, it is assumed that only the oil shale corresponding to the parameters of Ojamaa mining site is used at the plant (see Table 3).

Table 3. Parameters of the oil shale from Ojamaa mining site used in the Kiviter and Petroter retorting technologies [8]

Parameter	Unit	Kiviter	Petroter
Lower calorific value	[MJ/kg]	12.5	8.3
Moisture	[%]	11	10.7
Oil shale carbonate content	[%]	12.5	18.9
Ash content	[%]	41.9	45.3

A short description of the processes within the analysed units is as follows:

- Thermal processing or retorting of oil shale, delivered from Ojamaa mining site, is performed with two technologies – Kiviter and Petroter retorting. Kiviter technology corresponds to a gaseous heat carrier technology and oils shale with the size of 25 – 125 mm and with the minimal heating value of 10 MJ/kg is used in the retorting process [9]. If the fraction of oil shale is below 25 mm and its calorific value is about 8.5 MJ/kg, the oil shale is processed in a solid heat carrier or Petroter retorting technology. Higher calorific value of the oil shale used in Kiviter technology provide a higher oil yield (around 17%) in comparison with the Petroter where the achieved yield is ~12.5%. The greatest part of the energy required for the thermal processing is gained from the oil shale itself; electricity and steam from the VKG AS CHP is used in a small amount and only for initiation of the process.

- Fuel preparation system involves coking and fuel mixing units. The purpose of the oil preparation and purification processes is the secondary purification of heavy oil and light middle oil received from gas generators by removal of mechanical additives (heavy oils 10–15%, light middle oils 0.6–0.8%), ash (heavy oils 5–7%), water and – partially – salts (chlorides).
- After passing through the oil preparation system, total purified oil shale oil (with light coke distillate) is sent to distillation system, consisting of two consecutive columns. In the first column water and partial gasoline fraction is separated from total oil at 115–160°C. In the second column oil is heated up to 340–380°C and separated into five fractions: gasoline fraction, boiling range 80–210°C; diesel fraction, boiling range 160–250°C; light mazut, boiling range 230-320°C; heavy mazut, boiling range 320-360°C; distillation residue, boiling range 300–360°C and higher [2].
- Resulting fractions are further sent to the oil storage to produce finished goods. Most of the distillation residue is used for production of electrode coke and bitumen. A majority of generated gasoline fraction is used for liquefaction of heavy oil in oil preparation system [9-10].

3. Results and discussion

The resulting self-sufficiency descriptive parameters and the indexes are provided at the level of each production unit defined in Fig.2 (retorting of oil shale in Kiviter and Petroter units, fuel mixing unit, coking unit and distillation unit) and the level of shale oil production system (acc. to the boundaries defined in Fig.2). In addition, normalisation of the parameters *I*, *F*, *Y*, *U* to a unify unit (MJ) is performed to ensure effective analysis; calorific values of the inputs and outputs are used as a basis for unification. The results of the calculation are given in Table 4.

Table 4.Results of the self-sufficiency indexes of the motor oil production from the oil shale

Parameters and Indexes	Abbreviation and unit	Value
Indigenous energy*	I, MJ	$6.21 \cdot 10^5$
Imported energy*	F, MJ	$3.06 \cdot 10^5$
Exported energy*	Y, MJ	$9.59 \cdot 10^5$
Total energy used*	U, MJ	$9.27 \cdot 10^5$
Net external energy return	*NEER*, (-)	3.13
Energy related self-sufficiency index	*ESI*, (-)	0.67
Exported energy money index	*EMI*, MJ/Euro	0.19
Exported energy climate change index	*ECCI*, MJ/t CO_2	3.75

* allocated to final products values

The *NEER* of the Estonian oil shale processing industry is 3.13:1 considering the surface mining and retorting in Kiviter and Petroter technologies. As stated before, the external energy flow in this case is represented with electricity delivered from the CHP, natural gas required for production of heating gas in the coking unit and the main input flow – the oil shale from the mining site. However, this division of the imported inputs corresponds only to the current boundary of the study – in reality, the mining site and the CHP belongs to VKG AS, therefore expansion of the studied area can stimulate increase of the indigenous energy flow and reduce the exported energy flow (as far as some part of the exported energy goes back to the CHP). According to Brandt et al. [21], the energy return ratio of the Alberta oil sand derived refined product was in the range of 10.25-5.51:1 from 1970 to 2010.

The total energy consumption required to produce 110 340 tonnes of different motor fuel fractions (diesel, light fuel, heavy fuel, bitumen), kek and also heat delivered to the market (represent also exported energy flow) is $2.40 \cdot 10^{10}$ MJ. Imported energy flow ($7.05 \cdot 10^{9}$ MJ) in this case is represented with electricity delivered from the CHP, natural gas required for production of heating gas in the coking unit and the main input flow – the oil shale from the mining site.

The energy related self-sufficiency index for the VKG Oil plant AS is relatively high – 67 %. This factor can be used as a measure of the sustainability of the production system: the higher the value, the higher the ability of the plant to utilise internal energy flows and reduce the wasted energy (amount of wasted energy is 1.78 % from the total energy input). The reasons for the high *ESI* value are matching the arguments of the indigenous energy flow, i.e. efficient use of the by-products and effective combination of the Petroter and Kiviter retorting technology. An initial calculation showed that the self-sufficiency index of the VKG Oil AS plant is 17–24 % higher than in non-combined oil shale retorting plants.

Economic performance of the motor oil production from the oil shale, described with the *EMI*, is 0.19 MJ/Euro. Compared to the industry operational data for 2008, the *EMI* was 0.24 MJ/Euro. On the broader scale, the *EMI* value is very sensitive to policy changes and political processes in the country [12]. When comparing to the income generated by the shale oil industry to GDP over the last 5 years, it can be seen that the value fluctuates from 2.8 % to 3.9 % from total GDP.

Shale oil production sector environmental performance, defined as the exported energy climate change index (*ECCI*), is 3.75 MJ/tonne of CO_2. Generated CO_2 emissions (*C*) used for the *ECCI* calculation are gained from the national greenhouse gas emissions report of Estonia and corresponds to 623 018 tonnes of CO_2 per year. In comparison with the *ECCI* value for 2008, the climate effect of oil shale processing is decreased for 26 % due to modernisation of oil shale pyrolysis process and optimisation of the by-products reuse.

Conclusions

Industry based analysis of production process of fuel oil from Estonian oil shale via Petroter and Kiviter retorting is performed in the paper. A methodology for definition of self-sufficiency indexes of fuel production plant was introduced. Self-sufficiency of the motor oil production is characterised with four indexes – net external energy ratio, energy related self-sufficiency index, exported energy money index and exported energy climate change index. The Estonian oil shale based motor fuel production plant was selected as an evaluation object. The results of the study demonstrated good applicability of the indexes for definition of the self-sufficiency potential of the plant.

Further work needs to focus on the following tasks:

- expansion of the analysed system through inclusion of mining site, landfill, power station and CHP units;
- definition and calculation of sustainability index for oil shale based motor fuel production;
- comparison of direct and allocated input and output indexes;
- expansion of the system's scope – from energy accounting to emergy accounting.

Acknowledgment

This work has been supported by the European Social Fund within the researcher mobility programme MOBILITAS, MJD455.

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