Origins, compositions, and technological and environmental problems of utilization of oil shales

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Oil shale (OS) is a large global resource of low-quality fossil fuel. According to the World Energy Council (WEC), the total world resources of shale oil (SO) are conservatively estimated at 3.3 trillion barrels, or around 500 billion tonnes. During 2005 and 2006, over 4.1 billion tonnes of natural oil was produced yearly world-wide. Analyses show that world oil production will start to fall sometime during this decade and will never rise again, decreasing down to about 15% in 2050. The same will happen with the natural gas resources somewhat later, and with coal – much later. In the near and farther future the other main competitors of SO recovery are tar sands that are under development and hypothetic gas hydrates of ocean floor as a challenge. The present yearly SO production is around 0.5 million tonnes.

The expansion of SO recovery, e.g. onto the 10% level of the present oil production (400 million tonnes per year) would require construction of around 133 oil retorting plants producing 3 million tonnes per year (50 000 barrels per day) each and using 5.7 billion tonnes OS altogether. For this purpose, recoverable reserves of OS with Fisher oil yield of 9%, corresponding to the expected industrial retort oil yield of 7%, in the amount of almost 150 billion tonnes (as a minimum for 25 years of operation) are required. At the usual overburden to OS volume ratio between 1 : 1 and 3 : 1, the yearly amount of rock excavation would reach some 12–25 billion tonnes or around 5–10 km^3. When mining approximately 25 m thick OS seams (around 40 tonnes shale/m^2) in open pits, the area exhausted each year would reach some 100 km^2. Yearly around 5 billion tonnes or 3 km^3 of hot treatment mineral wastes should be allocated.

The WEC estimate (2005) of commercial-grade OS suggests the organic matter (OM) content of 13–23 wt%, which in the best cases corresponds to 8.5–15% Fisher oil yield, or to 7–12% oil yield by industrial retorting, or to 6.3–10.5 MJ/kg. No commercial technologies exist for complete utilization of OS of this grade – neither for oil retorting nor for burning in electric power plants. In Estonia, SO is produced from OS with oil yield over 13–16% and electric power is obtained by direct burning of OS, yielding 8.5 MJ/kg on average.

Oil shales are either shallow marine or fresh-water and salt lake sedimentary deposits. The mineral matter (MM) content of the WEC commercial-grade OSs varies between 77 and 87 wt%. Some national lists of OS deposits include even resources with Fisher oil yield as low as 3–5 wt% or OM content around 4–7% and MM up to 93–96%. National data on WEC commercial-grade resources are randomly available.

Depending on the element composition (C, H, N, O, S) of OM, its oil yield may range from 20 to 66%. The MM composition depends on the origin of OS. According to the MM composition, the three main types of wide-spread marine OSs are: a) calcareous (chalk, limestone), b) siliciclastic (claystone–siltstone–sandstone mixtures), and c) mixed calcareous–siliciclastic (marls) types. The MM of the largest salt lake Green River OM has a specific composition of alternating sodium plus Ca + Mg + Fe carbonate, plus silicate. Not depending on the composition of OM and bulk composition of MM, different marine OS-bearing basins and deposits may have or may not have high contents of sulphur (S) or a large spectrum of trace (including toxic and radioactive) elements.

Uniform and specific features of OS composition cause similar and different, presently mainly unsolved problems of OS utilization under various geological, environmental, and economic conditions.

Depending on the geological setting, and OS grade and composition, the problems to be solved or assessed before the industrial development are:

(1) the lower limit of energetic potential (percentage of OM and oil yield or caloric value) for the feasible OS utilization in oil retorting or in electric power plants or in their combination, and, consequently, the realistic assessment of resources and recoverable reserves;
(2) utilization and disposal of large amounts of mining and technological wastes, e.g. application of environmentally sound technologies for utilization of carbonate-rich, high-S, high trace element-bearing, silicate S and toxic element-bearing, etc. OS varieties;
(3) risks in solid waste management depending on compositional varieties of OS; e.g., somewhere in national OS overviews high contents of S, carbonates, and minor elements are mentioned as an additional value of resources, however, in practice the complex use of such materials may postpone their utilization for a long time;
(4) risks of air pollution due to large-scale surface mining processes, retorting, and power plants, especially having in mind the high carbonate, high-sulphur, toxic and radioactive component-bearing varieties of OS.

Depending on the physical and economic geographical setting, environmental measures for the assessment of (potential) OS mining sites should consider:

(1) global-scale factors of OS utilization according to physical geographic zonality: tropical and subtropical humid and arid zones, temperate zones, arctic zones;
(2) primary ecosystem qualities, e.g. a) species richness of terrestrial vertebrates, b) proximity to locations of sensitive species, c) surface water and riparian habitat zones;
(3) proximity to human settlements;
(4) groundwater resources: aquifers, their recharge rate, and depth to groundwater;
(5) surface slope, etc.

Recently, a number of energetic and oil companies have expressed their interests in the experimental and commercial use of OS. However, during the last decades the world has got more densely populated. Understanding the responsibility for the protection of natural equilibrium in the lithosphere, hydrosphere, and atmosphere has set new limits for the technological developments. Our message is that adequate developments in the R&D of the assessment of OS resources and recoverable reserves, depending on environmentally sound mining and utilization technologies, have to be achieved in using the energetic potential of OS technologies. Specific sides of settings of each OS basin, deposit, and reserve and their compositions have to be considered. Presently, at the very beginning of a new era of OS developments, a simplistic manner of treatment of these developments is rather a rule than exception.

In the world OS overviews, the Estonian kukersite and *Dictyonema* shale reserves are assessed on the basis of their energetic value. In practice, the environmentally acceptable technologies exist for the kukersite OS. Large-scale utilization of the *Dictyonema* shale as well as of the Alum Shale of Sweden has so many negative sides listed among the above potential environmental restrictions and concerns that the inclusion of such resources in world OS potential is completely misleading. Actually, many OS basins and deposits are presently assessed inadequately from the positions of large-scale developments. Examples of huge development challenges with certain specific OS compositions are resources of the lacustrine Green River Basin (USA) and marine S- and trace element-bearing OS in the Cretaceous–Palaeogene basins in the Mediterranean Region.

Estonia has gained experience related to environmental problems caused by the weathering of two different types of OS wastes. Estonian *Dictyonema* shale was exposed to atmospheric conditions during open mining of phosphates, being a part of the overburden. The main negative impacts on the environment included generation of acid water as a long-term process lasting for hundreds of years, and spontaneous combustion of the open mine heaps during a couple of tens of years after mining. Estonian kukersite does not generate acid water. Its main impact on water bodies is an elevated concentration of sulphates. However, spontaneous combustion of enrichment heaps has also been observed.

The Estonian cases can be effectively used as case studies in the geoenvironmental modelling of OS utilization already during the exploration of the deposit and planning of oil shale mines. From the aspect of water pollution, the critical issue is the mineral composition of OS, as well as of the surrounding rocks. Oil shale always contains pyrite, the oxidation of which generates acid drainage. Thus, the content of acid buffering carbonate minerals, which is low in Estonian *Dictyonema* shale and high in kukersite, is the main determining factor of the water pollution. Regarding spontaneous combustion, the way in which the shale is disposed is most relevant. The disposal in high heaps with steep slopes creates the most favourable conditions for spontaneous combustion.

Oil shale burning in power plants and treating in chemical factories lead to specific sets of mineral reactions for each OS type. Still, in Ca-rich shales the processes of change are calcium dominated, so the ashes of power plants contain minerals analogous to cement clinker. The ashes harden fast under atmospheric conditions and generate alkaline water, whereas the ashes of Ca-poor shales do not harden significantly, generate dust problems, and can be potentially used as filling material. Heavy metals in Ca-rich carbonate mining heaps are probably less hazardous than in Ca-poor OS, and the same stands for the residues of these different types of OS.

Geoenvironmental modelling makes it possible to predict environmental impacts of OS utilization in more detail on the basis of the characteristics of each individual OS, the surrounding rocks, and deposit type and setting, including hydrogeological conditions.