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PROSPECTS FOR THE EXPLOITATION OF JORDANIAN OIL SHALE

J. O. JABER
S. D. PROBERT
O. BADR

Department of Applied Energy,
Cranfield University
Bedford, England

Oil shale is the major indigenous fossil-fuel in Jordan: its predicted reserves, of about 5 × 10^{10} tonnes, should be sufficient to satisfy Jordan's energy-requirements for several centuries. Jordanian oil shale has, on an average, a gross calorific value of between 5 and 7 MJ/kg, an oil yield of ~10 %, and a sulfur content of approximately 3 % by weight of the raw shale (i.e. 7 to 9 % of the organic matter content). Using the oil shale as the input fuel, a multipurpose production process (i.e. retorting, electricity generation, thermal water-desalination, chemicals production as well as mineral extraction) could achieve high utilisation-factors of both its chemical and energy potentials. In the long-term, oil shale is the only indigenous energy resource that could reduce Jordan's dependence on imported crude oil and hence ease the pressure on the national economy. The conversion of oil shale into a liquid or gaseous fuel and raw materials will be of decisive importance in attempts to secure the future of energy supplies. So national efforts devoted to the exploration for, and harnessing more economically, this energy resource, while limiting the associated adverse environmental impacts, should be accelerated.

1. The Problem and the Opportunity

In the Middle East, oil shale is a well-known resource, having been used since the Pharos period for such diverse applications as the production of mosaic tiles, for decorating places of worship as well as being burnt for lighting purposes. Lately, oil shale was used as a fuel during the early 20th century (i.e. during the period 1905 to 1915) after being mixed with wood and coal in order to operate the Hijaz Railway between Istanbul in Turkey and the holy city of Madinah in Saudi Arabia [1].

The first recorded report concerning the occurrence of oil shale in Jordan, was written by S. J. Blaick in 1930. Subsequently, several studies were undertaken in co-operation with international geological agencies, the most important of which were started in the mid-1960s by the Natural Resources Authority (NRA). These studies consisted of core-drilling and laboratory analyses to determine the organic and inorganic constituents as well as the calorific values of the oil shale deposits. However, the NRA terminated oil shale activities in late 1969, because it was predicted that the cost of the utilisation of such an energy resource would significantly exceed that of imported crude oil for the near future [2]. Nevertheless, during the 1970s and early 1980s, due to the sharp increases in unit crude oil prices, the importance of oil shale as an indigenous energy-resource awaiting exploitation increased considerably. As a result, the Jordanian Government, in co-operation with specialist foreign companies, launched several investigations to assess the technical and economic feasibility of utilising the national deposits of oil shale [3, 4]. The main conclusions of these studies were that Jordanian oil shale deposits could be retorted to produce liquid and/or gaseous hydrocarbon products; or combusted directly to generate electric power. Laboratory tests have demonstrated that the characteristics of the Jordanian oil shale are satisfactory for its direct combustion, with 96 to 98 % of its carbon content being burnt-out when fluidised bed combustion technology is employed [5, 6]. However, it was recognised that this technology is relatively new and unproved on a large-scale for burning oil shale. There are also associated problems, such as the large amounts of (e.g. cooling, make-up and cleaning) water required for the power plant, the significant risk of environmental damage and the high capital-costs involved [7]. Moreover, at present and for the immediate future, the unit cost of electricity generated via a turbine as a result of combusting oil shale would be much higher than that from burning imported oil. This is due to the relatively prevailing low crude oil unit prices. Thus, the Government adopted a "wait-and-see" policy, while meanwhile monitoring the technical as well as the economic advances world-wide in oil shale harnessing and use [8].

During the last two years (i.e. 1995 and 1996), due to the restructuring plan for the energy sector as well as the privatisation scheme being implemented for the electric-power sub-sector in Jordan, several offers have been forthcoming from international companies to utilise some of the oil shale resources. The proposals are for generating electric-power, as an independent power producer, for national consumption and/or export. The state-owned National Electricity Power Company would be expected to buy the generated electricity, provided it is cheaper per kWh than that obtainable from other sources on a long-term purchase agreement basis. The Government is now devising policies and technical guidelines to ensure such new schemes will be successful [9]. These will include considerations of :

- electricity tariffs through short- and long-term supply contracts;

- the percentage share, on the national level, that private power producers will be permitted in the electricity-generation industry; and
- the codes of practice necessary for the selection and licensing of private power companies to achieve the least possible cost for electricity generation while ensuring security of supply.

2. Oil Shale Reserves

Besides the limited reserves of natural gas in the north-eastern corner of the country, large deposits of oil shale represent the only other indigenous fossil fuel naturally occurring in Jordan. The latter exists in the central (i.e. south of the capital Amman) and north-western parts of the country - *see* Fig. 1. In general, the oil shale seam's thickness increases as one proceeds northwards to reach, on the average, ~350 (± 50) m in the Yarmouk district near Irbid. Based on micro-palaeontological studies and stable carbon-isotope ratio determinations, it is believed that these deposits were formed in the shallow marine environment, which prevailed in the Middle East about 140 million years ago (i.e. during the cretaceous age) [10]. However, other geological surveys have concluded that oil shale was formed during the maestrichtian to palaeocene ages [11].

The criteria dictating whether or not the oil shale deposits will be exploitable economically depend on the processes which would be employed. In the case of retorting, the organic matter content in the oil shale has to exceed ~5 % by weight. While, for direct combustion, it has been suggested that the shale should have a minimum gross calorific value of 3.14 MJ/kg [12]. Based on the first of these criteria, there are about 24 known surface and near-surface oil shale deposits in the central region of Jordan: these shallow reserves provide, even now, a potentially viable energy resource. The total proven reserves of these deposits have been estimated to exceed 5×10^{10} tonnes of oil shale (i.e. equivalent to at least 5×10^9 tonnes of crude oil) [2]. At the present national rate of primary-energy consumption (i.e. $\sim 4 \times 10^6$ tonnes of oil equivalent in the year 1995), these reserves alone would be capable of meeting Jordan's energy demands for the next millennium. The most important oil shale deposits occur at Wadi Maghar, Wadi Thamad, Attarat Um Ghudran, Juref Ed-Drawish, El-Lajjun, Sultani, Khan Ez Zabib and Siwaga - *see* Fig. 1. These deposits have an average stripping-ratio (i.e. the ratio of the vertical thickness of the overburden to that of the deposit) of about unity (i.e. 1 : 1), which is considered to be favourable from the mining point-of-view as well as the associated costs of extraction. Table 1 summarises what information is available concerning the important features of these deposits.

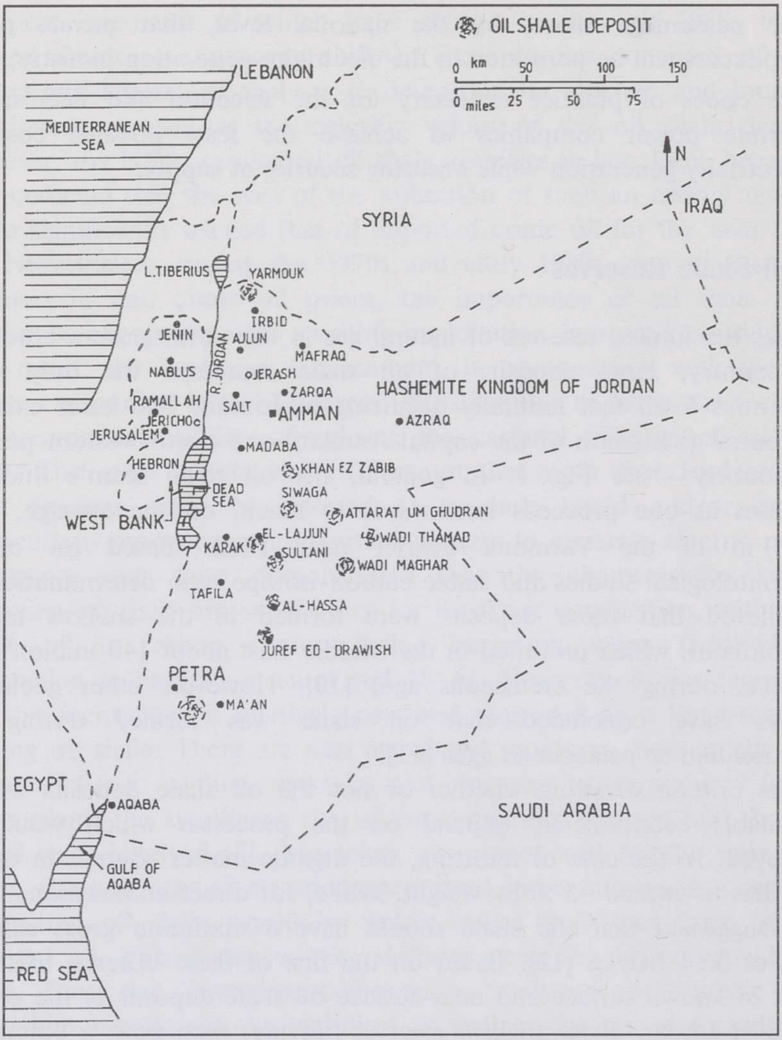

Fig. 1. Locations of the oil shale deposits

Besides these deposits, there are several near-surface occurrences with good prospects of economic recovery via open-pit mining near Ma'an and Petra. Other locations, with great potential for underground mining include the Yarmouk deposit near Irbid. However, as yet, these occurrences have not been studied sufficiently (i.e. only little information is currently available about their properties) to enable us to make worthwhile predictions concerning when they would be financially viable to exploit. In addition, in the Al-Hassa phosphate open-cast mine, oil shale beds of ~5 m thickness overlie the phosphate-rich rocks. The phosphate is mined on a large-scale, yet the raw oil shale (at an annual rate of approximately 5 million tonnes) is being wasted with the overburden and this deserves immediate attention.

Table 1. **Characteristics of Oil Shale Deposits in Jordan [13]**

Location	Area (10^6 m^2)	Mean deposit thickness (m)	Overburden thickness (m)	Stripping ratio	Oil content (%)*	Proven reserves (10^6 tonnes)
Wadi Maghar	29.0	40.0	41.0	1.02 : 1	6.80	31,600
Wadi Thamad	150.0	136.0	60.0	0.44 : 1	10.0	11,400
Attarat Um Ghudran	226.0	45.0	53.0	1.17 : 1	11.0	11,300
Juref Ed-Drawish	150.0	64.0	48.0	0.75 : 1	6.00	8,506
El-Lajjun	20.5	30.0	26.0	0.87 : 1	10.5	1,196
Sultani	75.0	31.6	69.0	2.18 : 1	7.50	989
Khan Ez Zabib	-	-	-	-	7.00	-
Siwaga	-	-	-	-	7.00	-

Note: * Average oil content by weight.

Table 2. **Characteristics of Oil Shales from Different Deposits Worldwide [8, 11, 14, 15]**

Characteristic	Jordan	Morocco	China	USA	France	Brazil	Estonia
Moisture content, (%)*1	2.5	10.0	13.0	6-10	7.0	5.3	8-10
Gross calorific value, (MJ/kg)	7.5	4.6	6.28	7.5	5.65	5.6	12.5
Ash content, (%)*1	55.0	64.0	71.0	67.0	75.0	79.0	45-60
Oil yield, (%)*2	8-12	7.0	7.0	10.0	13.0	7.0	19-21
Elemental analysis of organic matter, (%)*1							
C	73.0	46.2	55.4	80.5	55.0	68.0	77.4
H	8.6	8.4	9.2	10.3	6.5	10.5	9.6
O	8.0	40.4	32.2	5.8	30.7	15.0	11.2
N	1.4	-	1.8	2.4	1.3	3.0	0.3
S	9.0	5.0	1.4	1.0	6.5	3.5	1.5

Notes: *1 Average content by weight.
*2 Percentage by weight according to Fischer assay.

3. Oil Shale Analysis

Like other naturally occurring organic sediments, oil shale has greatly varying compositions and properties, which depend on the location of the deposits and the process of their formation. The content of organic matter, which is the main reason for our commercial interest, in oil shale may range up to 50 % by weight of a sample and the content of inorganic matter may vary between approximately 30 % for very rich shale and 95 % for very lean shale. It is clear that ash content and composition of oil shale vary from one deposit to another, and even within the same seam. This introduces further difficulties into the accurate comparison with other shales and prediction of the composition of the final products. However, these values can serve as a useful guide. The oil shale deposits at El-Lajjun, Sultani and Juref Ed-Drawish have been well surveyed and investigated thoroughly: their physical and chemical characteristics, as compared with shales from some other important deposits in the world, are shown in Table 2.

The potential of an oil shale formation, as an oil source, depends on its organic matter content and how much of this can be converted to oil in a retorting process. The latter is a function of the C/H ratio or the amount of hydrogen in the organic matter, which is the key factor in producing liquids during oil shale retorting processes. As seen from Table 2, all shales have high ash contents (from 45 to 79 %) and high carbon contents as well. The Estonian oil shale is the richest (i.e. has the highest organic matter content and therefore the highest calorific value). The Estonian, Brazilian, American and Chinese shales are suitable for retorting to produce shale oil, because they have high hydrogen contents in their kerogen constituents.

The oil yield and the potential gross calorific value of the Jordanian oil shales are good on the average (i.e. ~10 % by weight and 7.5 MJ/kg, respectively). Based on a Fischer assay, the average oil yield is approximately 100 to 120 litres per tonne of shale (i.e. two tonnes of oil shale, which would occupy approximately the same space as an office desk, would yield more than a barrel of oil). A study [16] conducted to determine the effects of the composition for various supplies of oil shale (taken from the El-Lajjun deposit) on its calorific value, found that it increases with rising carbon and sulphur contents and decreases with increasing calcium carbonate content: the overall correlation is represented by

$$\textbf{Gross calorific value} = 352.44(S)^{0.257}\,(C_{organic})^{1.141}\,(CaCO_3)^{-0.066}$$

where S, C and $CaCO_3$ are expressed as percentages by weight, and the gross calorific value is expressed in kilojoules per kilogramme of the oil shale.

To a high degree of accuracy, it is also possible to estimate the gross calorific value of a sample from the El-Lajjun oil shale deposit, using a linear correlation with its organic content, because a high correlation coefficient (i.e. ≥ 0.98) exists between them.

Gross calorific value = 534(Organic matter content) + 2.99
where the organic matter content is expressed as a percentage by weight of the oil shale, and its gross calorific value is in kilojoules per kilogramme of the oil shale.

Besides the organic matter, Jordanian oil shale deposits contain certain valuable metals (e.g. uranium, molybdenum, vanadium, chromium, cobalt and nickel) in low concentrations, as well as aluminium and iron in relatively high concentrations. These metals have strategic significance in the international market. A preliminary estimate is that the valuable metals in a tonne of typical shale are worth at least 30 US$. However, other estimates suggest that an additional 30 US$ worth of aluminium and 10 US$ worth of iron per tonne of shale exist [17]. If all these metals were to be recovered, the metals value will exceed that of the shale oil which lies between 10 and 12 US$ per tonne of shale (based on ~100 litres of crude shale oil being derived from a tonne of oil shale and 20 US$ being paid per barrel of oil). The principal inorganic compounds in oil shale deposits are calcium carbonate ($CaCO_3$) and silica (SiO_2) - *see* Table 3.

These trace elements become concentrated and enriched, after the shale has been retorted or burned in fluidised bed combustors, on the surfaces of small ash particles (i.e. spent shale). Thus, recovery of some of these valuable metals is recommended and would improve the economic performance of any future oil shale utilisation plant. Compared with other oil shales, from other parts of the world, the moisture content of the Jordanian shales is relatively low. Thus local shales incur lower costs for crushing and grinding as well as lower heat losses when combusted directly for electricity generation or retorted to yield shale oil.

Table 3. **Average Values for the Major Inorganic Constituents of Oil Shale Deposits in Central Jordan [13]**

Element	Concentration (% by weight)
$CaCO_3$	30-35
SiO_2	10-26.3
SO_3	4.3-4.8
Al_2O_3	2.8-3.8
P_2O_5	1.5-3.5
Fe_2O_3	1.1-1.5
MgO	0.2-0.95
Sr	0.07-0.12
Zn	0.019-0.065
Cr	0.022-0.035
V	0.01-0.027
Ni	0.01-0.017
Cu	0.007-0.0115
Ba	0.0035-0.0115
Mo	0.002-0.0095
U	0.0017-0.003
As	0.001-0.0017

Jordanian oil shales bear quite a similar resemblance to the Colorado (USA) shales. However, the organic matter of the former contains a considerable amount of sulfur (i.e. on average 2.5 to 3 % by weight of the raw shale or ≤ 9 % by weight of the organic content) which requires the use of special methods for processing. The high sulfur contents of the produced shale oil or hydrocarbon gases would increase the upgrading and utilisation costs. Nevertheless, such a high concentration of sulfur might make its recovery, as a by-product commodity, economical. However, in all the shales, the Ca/S molar ratio is large enough (i.e. ~4.5 for Jordanian shales, 2.7 for the Estonian shale and 6.4 for oil shale from Colorado, USA) for effective sulfur retention (i.e. >90 %) to occur, during combustion when fluidised bed technology is employed.

In 1986, a study conducted in co-operation with the Chinese Oil Shale Co. showed that Jordanian oil shales (i.e. from the El-Lajjun deposit) can be effectively processed in the Chinese Fushun retort, with a relatively high recovery rate of ~85 % of Fischer assay [18]. Also during the late 1980s, and in close co-operation with the Japan Oil Shale Engineering Company, a sample from the El-Lajjun deposit was tested in a pilot plant (i.e. simple indirectly-heated retorting and gasification unit as well as a fluidised bed combustor for the oil shale fines for the purpose of electricity generation). The results of these co-operation programmes have demonstrated that Jordanian oil shale can be processed successfully to produce shale oil or generate electricity [19, 20]. However, further detailed technical and economical feasibility studies are still needed, and the proposed process to be employed needs to be optimised.

4. The National Need for Using Oil Shale as an Energy Resource

Unfortunately, Jordan possesses only relatively small reserves of conventional fossil fuels. Its indigenous crude oil and natural gas supplies satisfy only approximately 4 % of the current annual national primary-energy demand. Without the exploitation of indigenous oil shale, this level is unlikely to increase in the national energy mix, unless new discoveries of crude oil or natural gas are found, which are unlikely to happen. Consequently the country is almost exclusively dependent, and it will continue to be for the immediate future, on imported crude oil.

Thus the indigenous oil shale has a potentially major role to play, but it is unlikely to provide a total solution for Jordan's energy requirements. Oil shale utilisation nevertheless can reduce the dependence on the imported crude oil and petroleum products, which involves a security of supply risk as well as impose a serious burden on the national economy. In 1995, the annual imported-oil bill was approximately 4.75×10^8 US$ (i.e. representing ~10 % of the GDP), and, without the exploitation of indigenous oil shale, it may be around 1.15×10^9 US$ per annum by the year 2010, depending on the international crude oil unit price, when the annual rate of fuel consumption in Jordan will probably have doubled [21]. And in view of the foreseeable rapid depletion of the world's oil reserves, this may lead to serious economic difficulties locally.

Jordan has experienced temporary shortages of oil products on several occasions, the last one being during the Gulf War in the early 1990s. Given the likelihood of the increases in energy (especially electricity) demand for years to come, the risk of future shortfalls is likely to be greater. The rising cost of oil imports and the country's increasing dependence on them have already contributed significantly to trade-balance problems, inflation, decline of real income per capita, and other economic and social problems.

So, it can be concluded that the solution to Jordan's energy-shortage problem should be based on:

- developing indigenously-available energy resources, such as oil shale, because renewable energy is likely to be financially only viable for specific applications and particular locations;
- seizing the feasible economic opportunities to save energy; and
- better long-term energy-and-environmental planning and management.

Among the potential supplements to petroleum products and natural gas supplies are synfuels (i.e. synthetic liquids and gases made from oil shale or other types of fossil fuel). Several processes for making these fuels as well as the direct generation of electricity from oil shale have been successful commercially in various countries (e.g. Estonia, Russia and China). Other processes have been researched and developed and are approaching commercial readiness (e.g. in Australia, Japan and USA). So the utilisation of oil shale as a fuel source is no more just a theoretical possibility. Similar oil shale deposits, and even lower-grade ones, have been utilised for many years in other countries.

Oil shale projects should be established in remote areas (i.e. close to a deposit). These would help to reduce the differences in social equity between the rural and urban regions in the southern part of Jordan. They would also provide work and training opportunities for the labour force.

5. The Proposed Oil Shale Plant

Oil shale reserves can be developed and exploited as an indigenous source of energy. A prospective and increased financially attractive utilisation of this resource is based on a multipurpose production approach (i.e. leading to shale oil and gaseous fuel, electricity generation

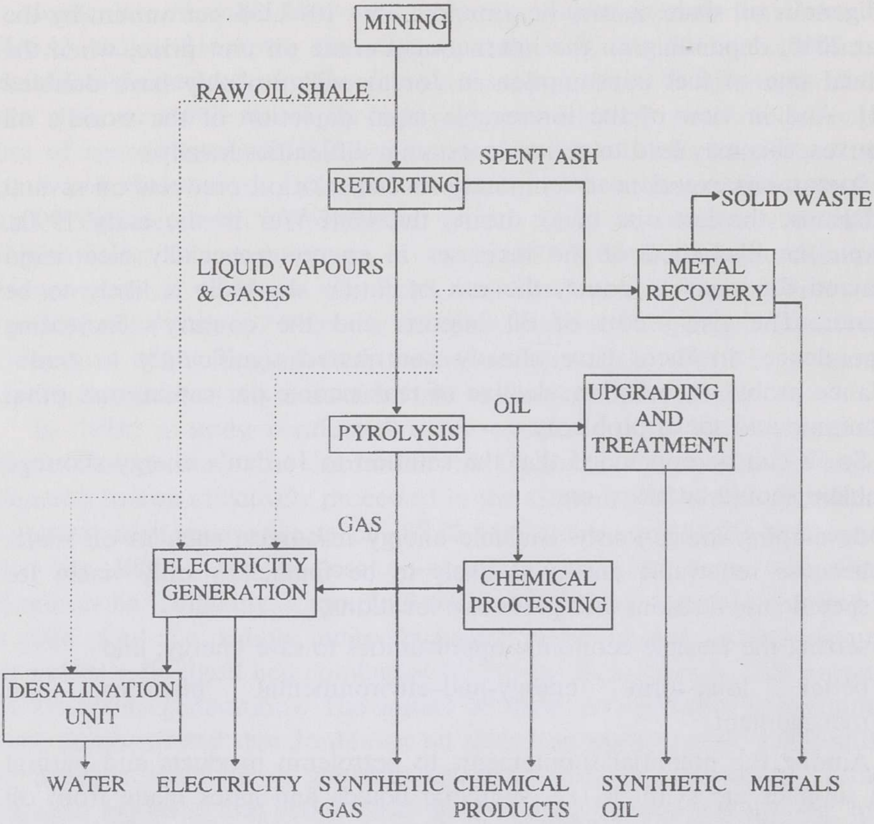

Fig. 2. Multiproduction scheme of oil shale processing.
—— multipurpose production process, ········ direct combustion path

and water desalination as well as chemical and mineral extraction) - *see* Fig. 2.

The general trends in oil shale utilisation are synthetic fuel and chemicals production and/or electricity generation. However, both retorting and direct combustion of oil shale have their drawbacks: the temperature of combustion is limited by the melting point of the ash or the mineral content and its tendency to form hard deposits, which result in fouling and/or corrosion of the processing equipment. These deposits also decrease the heat transfer rates and hence reduce the system's capacity and efficiency. In the case of retorting, oil shale is processed in the temperature range between 450 and 550 °C, where the maximum oil yield is achieved, but with a relatively low quality of shale oil being produced (i.e. a high pour-point as well as relatively large contents of nitrogen, oxygen and sulfur) [22]. A rise in the retorting temperature will improve the quality of the products. However, the oil yield will then be reduced and the inorganic matter would melt at higher temperatures and so adversely affect the whole process. This is the reason why it is proposed to combine the two utilisation methods (i.e. retorting and direct combustion) into an optimal multipurpose production process, which will achieve high rates of oil recovery as well as more effectively harness the chemical, energy and mineral potentials of the Jordanian oil shale.

Such a process is based on multistage processing: in the first stage, the oil shale is retorted to yield the maximum amounts of shale oil and hydrocarbon gases: the heat source for the process being the spent shale (i.e. from directly-heated retort). Then, in the second stage, these products are subjected to another thermal decomposition phase to produce high calorific-value gaseous fuel and oil. The latter can be processed further to produce high-value chemical products or synthetic oil. The produced gases are used to fuel the process and to generate electricity via a combined-cycle gas turbine as well as a thermal water-desalination unit, which will supply the required freshwater for the plant and neighbouring area. On the other hand, oil shale fine particles (i.e. produced during the preparation and crushing of oil shale lumps) and the spent shale from the retorting process can be burnt in a fluidised bed combustor for the same purpose. The finally-produced synthetic gases can also be conveyed to different customers by pipeline. Moreover, it may be financially viable to recover some of the trace metals because they become so concentrated in the spent shale: the eventually-produced ash can be used as a raw material for the building and construction industries. Such an approach will enhance the economic feasibility of oil shale harnessing.

The proposed method has the following advantages compared with either retorting or the direct combustion of oil shale:

- Multipurpose production is economically attractive, because it allows high recovery ratios for the organic matter and the production of valuable, high-quality chemical products (e.g. benzene, ethylene and thiophene).
- The process is expected to be highly efficient.
- It can be controlled to produce high calorific-value gaseous and liquid products.
- It can be employed in any part of Jordan because the gaseous and oil products as well as water may be transported elsewhere relatively easily by pipelines or road trucks. However, the energy used for such conveyance should be minimised.
- The environmental impacts are minimised because of the high efficiency of the resource use in the multipurpose production approach.

Due to its relatively high sulphur content, the gasification of Jordanian oil shale tends to be cheaper compared with the retorting of it, which aims to produce liquid fuel. The resulting gas is easily cleaned and can be burnt in a combined-cycle gas turbine to generate electricity at high thermal efficiencies (i.e. ~50 %). This proposed scheme for utilising Jordanian oil shale appears to be the most promising method for power generation from such a solid fuel. However, it requires high capital investments, but it has a better technical and economic performance compared with the direct combustion or retorting of oil shale. Negotiations with multinational companies for the establishment of a private oil shale electric power plant in central Jordan (near El-Lajjun or Sultani) are under way. The preliminary estimate for the required investment for a 150 MW plant lies between 3×10^8 and 3.5×10^8 US$.

5. Conclusions

A vast deposit of oil shale exists in Jordan. The current proven reserves are about 5×10^{10} tonnes. It is approximately similar in composition to the shales of western Colorado in USA. In general, Jordanian oil shale deposits are:

- high in organic matter content;
- surface or shallow reserves, which make them suitable to be exploited by surface mining (i.e. by open-pit) methods; and
- located near the needed infrastructure facilities, such as the desert highway and big energy-consuming companies, like Phosphate Mines, Potash Co. and the South Cement Factory.

The deposits can be developed and utilised as an indigenous source of primary energy (i.e. for the production of synfuels and/or electricity), chemicals and building materials. So a long-term national policy of research and development to utilise this resource should soon be initiated and enacted upon.

The chemistry, as well as the technical and environmental aspects of oil shale processing, are well understood and several technologies (i.e. retorting to produce liquid and gaseous fuels or direct combustion to generate electricity) have been developed on a commercial scale or are near commercial readiness and nearly financially viable. Moreover, Jordanian oil shale deposits contain high concentrations of organic sulfur and small amounts of trace metals: these become more concentrated in the spent shale after being retorted or combusted. Thus, the recovery of sulfur and some of these valuable metals by employing the multiproduction approach would greatly enhance the economics of the utilisation programmes. Such an option may be considered to be a worthwhile possibility for the implementation of a sustainable resource development programme. However, the viability of the oil shale extraction and shale oil production are related to crude oil prices on the international market, and the Government's energy policy in Jordan. The additional costs of the oil shale processing would probably be acceptable because of the guaranteed long-term indigenous energy-supply stability that this resource provides for Jordan. However, this needs the Government's will to make appropriate commitments. Therefore, and in order to resolve any techno-economic uncertainties related to the utilisation of the Jordanian oil shales (either via retorting or direct combustion for generating electricity) and to justify any investments in this field, a pilot plant should be constructed soon. Such plant is a necessary step towards establishing a full-scale commercial plant.

Oil shale processing (i.e. retorting or combustion) may cause serious environmental impacts (e.g. landscape desecration, dust, toxic flue gases, odours, ash disposal and waste water). However, such problems can be avoided or successfully solved by the integration of planning and environmental management of the oil shale projects. The extraction and subsequent utilisation of oil shale in Jordan would result in:

- significant financial savings as a result of the lower oil imports;
- reducing the current deficit and national trade-balance problems; and
- the creation of jobs.

Finally, oil shale resources in Jordan are enormous. The technology is ready for their commercial application, and the private sector is interested in their exploitation. The need for the development of an oil shale industry in Jordan, in order to ease the dependence on imported energy, especially in the medium- and long-term, is vital to the national interest.

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