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WHERE TO WITH JORDANIAN OIL SHALES

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In this paper, different ways for developing indigenous oil shale resources and their important role in reducing the dependence of Jordan on imported oil are assessed. Also, the Government's plan and strategy with respect to premature or short sighted and loose energy policy is discussed. Oil shale is the major indigenous fossil fuel in Jordan, and it is not utilised at present. During the next few years, a commercial oil shale complex could be developed in the country to produce shale oil and/or electricity substituting for imported crude oil and petroleum products. The future beneficial use of the vast oil shale deposits depends not only on the development of suitable process economics but also on the availability of suitable environmental controls. Thus, oil shale's future will be a mixture of promise and risk. Oil shale can still be considered Jordan's most extensive domestic fossil-fuel source well throughout the 21st century and beyond. However, the Government's position is not clear enough with regard to what should be done in order to utilise the oil shale resources in a wise way. So, comprehensive scientific research, feasibility studies, legislation and best practices codes as main parts of a national energy plane should be addressed and developed in order to decide about the most suitable technology for Jordan.

Introduction

In 1999, the last year for which statistics are published, the total energy needs of Jordan were approximately 4.75×10^6 toe of which imported oil supplied 94 % and the remaining came from natural gas (4.5 %) and renewable sources (1.5 %) [1]. The annual imported crude oil bill was approximately 600×10^6 US$, representing about 7.5 % of Jordan's gross domestic

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product, about 14 % of the total commodities imports; and 30 % of the domestic commodities exports [2, 3]. As can be seen, even a slight increase in oil prices in the international market can have severe impacts on the local economy.

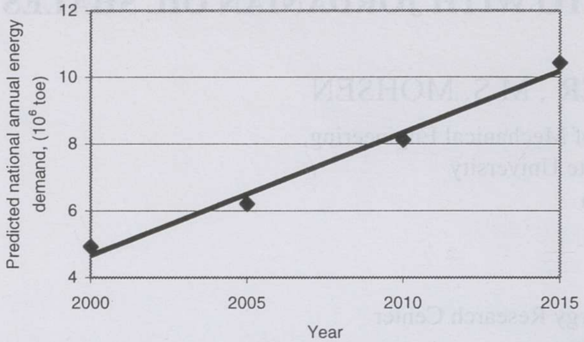

Fig. 1. Predicted annual rate of fuel consumption

From previous investigations and published reports, the national energy demand is expected to be around 10×10^6 toe in 2015 – see Fig. 1 [2, 4]. Electricity demand is predicted to grow at an average annual rate of about 6 %, with the maximum peak demand reaching approximately 2200 MW. In 1999 the maximum demand was about 1100 MW – see Fig. 2 [5–7]. Without exploitation of indigenous energy sources, such as oil shale, the energy bill most probably be around 1800×10^6 US$ per annum by 2015, when the annual rate of fuel consumption in Jordan will have been approximately doubled, however, the exact value depends on the crude oil international unit price. Thus there is an urgent need to start a national programme aiming to improve energy efficiency and utilise local energy resources, where their technical and financial performance are attractive.

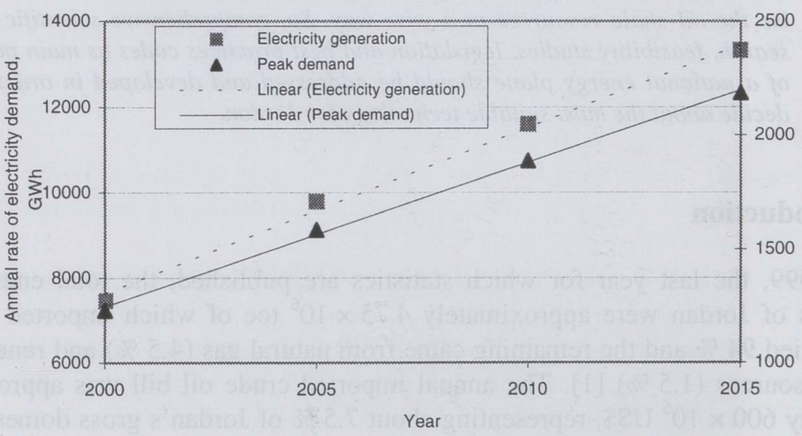

Fig. 2. Projected electricity consumption and maximum load demand

There is little information available about processing of Jordanian oil shales, and most of available and published data are either concerned with geological aspects or pre-feasibility studies. This is most probable because there has been only little interest in developing this resource, due to the prevailed low crude oil unit prices during the last 15 years, compared with those for the final energy produced from oil shale. Equally important is the lack of know-how and seriousness as well as the intention of consequent governments in developing such a vital resource: one government supported the idea of producing shale oil, but the next one preferred direct combustion of oil shale in order to generate electricity and so on. So there has been no firm and published plan based on the results of scientific investigations concerning Jordanian oil shales.

However, recently and due to a sharp increase in the price of crude oil, there is a growing interest in developing oil shale deposits, especially those in the central part of Jordan. For example, few months ago the Government, represented by the Ministry of Energy and Mineral Resources (MEMR), has signed a memorandum of understanding with a specialised Canadian firm, SUNCOR, which aims to develop the Ellujjun oil shale deposit and mainly produce shale oil [8]. SUNCOR will employ the Alberta Taciuk retorting technology, which is originally developed in Canada. This is similar to the one that has been used, on pilot scale, for processing the Stuart oil shale in Queensland, Australia [9]. However, the Taciuk process is still unproven on commercial scale and associated with operating and environmental problems needing a lot of work before being available for safe and reliable commercial applications.

This paper discusses different ways for utilising the local oil shale resources and their vital role in reducing the dependence on imported oil. The Government's dilemma regarding what to do with oil shale and national energy policy is discussed. Also the paper looks at energy consumption in Jordan and the future major potential use of oil shale – generation of electricity or producing liquid and gaseous fuels.

Local Oil Shale Deposits

Besides the limited reserves of natural gas from the Al-Risha field in the north-eastern corner of Jordan, close to the Iraqi border, the vast oil shale deposits represent the only other indigenous fossil fuel resources. The latter exists predominantly in the central, i.e. south of the capital Amman, and north-western parts of the country. Based on micro-palaeontological studies and stable carbon-isotope determinations, it is generally believed that these deposits were formed in the shallow marine environment, which prevailed in the Middle East region about 140 million years ago during the Cretaceous age [10]. However, other geological surveys have concluded that the oil shale was formed during the Maestrichtian to Palaeocene ages [11].

There are 24 known outcrops and near-surface oil shale deposits in Jordan. These proven reserves have been estimated to exceed 40×10^9 tonnes of oil shale, which is equivalent to about $3–4 \times 10^9$ tonnes of crude oil [2]. At the present annual rate of national primary-energy consumption, 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 [12]. These deposits have an average stripping ratio (of about unity) of the vertical thickness of the overburden to that of the associated oil shale deposit which is considered to be favourable from a cost-of-extraction point-of-view.

National Need for Oil Shale as an Energy Resource

Jordan has experienced temporary shortages of mineral-oil products on several occasions; the last one being during the Gulf War in the early 1990s [13]. Given the likelihood of the increases in energy and electricity demands in the future and the rapid depletion of fossil-fuel reserves world-wide, the risk of future fuel shortfalls in Jordan is relatively high. Also, the rising cost of oil imports and Jordan'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 difficulties. So, the solution to Jordan's fuel-shortage problem should be based on: better long-term energy management and developing indigenously available fossil-fuel resources, such as oil shale, because renewable energy for the immediate future will be financially viable only for specific applications and particular locations.

The indigenous oil shale has a potential major role to play by reducing Jordan's dependence on imported crude oil and petroleum products, which involves a strategic security-of-supply risk and imposes a serious burden on the national economy. In the longer term with the foreseeable exhaustion of world's crude oil reserves and higher oil prices, such a dependence on imports could lead to even more serious economic difficulties for Jordan. Also, oil shale harnessing projects are most likely to be established in remote areas, close to the deposits. These, by providing employment and training opportunities for the labour force, would help to reduce the differences in social equity between the rural and urban regions of the southern Jordan.

The importance of oil shale, for Jordan, as an energy source, depends on the final costs and attractiveness as compared to conventional fuels. However, since crude oil and petroleum products, and in the near future natural gas, are imported and cause a heavy burden on the national economy, they are likely to be discouraged as fuels for electricity generation. Renewable and new energy sources also have great potential but the related economics and technical limitations will delay the use of such sources for many years to come. However, these are unlikely in the near or medium future, i.e. within next two decades, to equate to more than 10 to 15 % of the rate of national electricity generation, because of the higher cost per unit of energy produced from renewable energy than that obtained from conventional resources [14]. Thus, oil shale would be left as the only option as an indigenous energy source in Jordan that should be developed to meet the growing demand.

Economic Evaluation of Oil Shale's Potential

In general, oil yield and/or the calorific value of Jordanian oil shales are relatively high, approximately 10 % by weight and about 5–6 MJ kg^{-1}, respectively [15]. Based on recent experimental investigations, the average oil yield is around 100 litres per tonne of shale, depending on the pyrolysis conditions and type of shale [16].

Besides the organic matter, Jordanian oil shale deposits contain metals, such as uranium, molybdenum, vanadium, chromium, cobalt and nickel, in low concentrations, as well as aluminium and iron in higher concentrations [17]. These metals have strategic significance in the international market. A preliminary estimate is that rare metals worth at least 30 US$ per tonne, exist in the typical oil shale. However, other assessments suggest that an additional 30 US$ worth of aluminium and 10 US$ worth of iron are present in each tonne of oil shale [18, 19]. If all these metals were to be recovered, their total value would exceed that of the shale oil, which is around 15 US$ per tonne of shale, based on 100 litres of crude shale oil being derived from a tonne of oil shale and 25 US$ being paid per barrel of oil. In the case of Jordanian oil shales, it has been estimated that the total potential of such resource would be about 45(±5) US$ per tonne, based on current prices of crude oil and metal oxides, and an average recovery ratio of about 80 % for most probable products from the shale. However, when crude oil prices rise to reach 30 US$ per barrel, then this potential would be higher, i.e. at least 50(±5) US$ per tonne, depending on the actual unit price.

In addition, the newly established companies for exploiting oil shale will provide the employees and their families with adequate facilities, such as housing, and general-services, e.g. education and medical-care, as fringe benefits. Also, workers at the proposed plant will not build only mining, processing and transportation systems, but a whole town complete with housing and commercial services, cultural activities as well as social and political systems. Such new settlements would offer better living standards as well as profitable and long lasting business and employment opportunities for local residents. In addition, the property cost is expected to be about ten times more than prevailing rates for the surrounding areas because of the underlying oil shale. Also local and central governments would benefit through taxes, which may be levied on oil shale property, wages, sales, companies income and on the final products. It is expected that such an industry would create at least between 10^3 and 1.5×10^3 jobs, including mining operations, on a permanent basis and a few more temporarily [20]. This means that the national economy would grow, thence, such an industry would help the whole country to prosper.

Main Methods to Obtain Energy from Oil Shale

The following discussion highlights the important issues of oil shale processing technologies:

Retorting

The main interest world-wide has been directed to the pyrolysis processes in which organic matter recovery could be done underground, i.e. *in situ*, or above ground, i.e. *ex situ*. In situ retorting offers several operational, economic and environmental advantages over the *ex situ* processing [21]. However, above ground processing, generally, allows better control of the retorting conditions, which leads to higher yields of final products.

Retorting is a thermal pyrolysis process, which takes place in a closed vessel called retort, where the oil shale is heated, directly or indirectly, at a temperature of between 400 and 600 °C in order to extract its organic content as shale oil and fuel gas [22, 23]. The shale oil, which is usually highly viscous and has high content of sulphur and nitrogen, depending on the quality of the feed stock, may be upgraded in a refinery to produce synthetic fuels or further processed to yield chemical products. It can also be consumed directly, without any extra treatment, as a fuel for electricity generation and industrial applications. Oil shale retorting is a well-developed technology: it has been used for decades in many countries, e.g. Estonia and China on a commercial scale and semi- or near-commercial scales in the USA and Australia, to yield shale oil [24, 25]. However, these methods tend to be inefficient with respect to liberating the organic content of oil shale. State-of-the-art technology can extract, on average, between 70 and 80 % of the organic matter; the remainder being locked in the spent shale as a residual char [26, 27].

Equally important is the chemical composition of the shale oil produced, which has consequences for its safe handling, transport and indeed its end use in combustion systems. It is reported that the presence of aromatic compounds in the shale oil will increase the rate of soot and other pollutant emission to the environment [28]. Several investigations concerning the associated health hazards of employing liquid fuels derived from the pyrolysis of oil shale have shown that such a fuel contains polycyclic aromatic compounds. The latter represent a group of chemicals over which there is a big concern due to the fact that a large number of these compounds are considered carcinogens [29–34]. The presence of carcinogenic compounds in the shale oil, especially in high concentration, will limit its usage as a potential fuel to substitute for crude oil and petroleum products. This significant health hazard, together with the necessity for the disposal of vast amounts of retorted shale resulting in groundwater contamination, can lead to serious adverse environmental impacts.

There are many retorting methods, such as Lurgi [35, 36], Petrosix [37], Union [38, 39], Fushun [40, 41] and Alberta Taciuk [9], available in the international market. However, careful behavioural analysis should be carried out before selecting any of these methods, because the techno-economic performance of any retorting process depends on the chemical and physical characteristics of the oil shale deposit: what is suitable for Canada or any other country may not be good for Jordan.

Direct Combustion

Direct combustion of oil shale offers an opportunity to generate electricity in commercial utility-power plants. The combustion of pulverised oil shale in Estonia has been used for electricity generation since 1924, when the Tallinn Thermal Power Plant, with a capacity of 22 MW, was modified to burn this fuel [42]. During the 1960s and 1970s, the Baltic Power Plant, 1624 MW, and Estonian Thermal Power Plant, 1610 MW, were commissioned [43].

The plant required for combustion of pulverised oil shale is, in principle, similar to that for pulverised coal, with slight modifications in feeding and ash-handling equipment. However, the combustion behaviour of oil shale is different from that of coal, because oil shale contains much more oxygen and sulphur than coal does. Also, as its mineral content is several times higher than that of coal, more ash is formed when oil shale is burnt. Experience in Estonia has indicated that pulverised oil shale burns faster than pulverised coal, because the heat generated during combustion of the volatile matter of the oil shale is greater than that of the fixed carbon [44].

In employing pulverised oil shale combustion, there are serious operational problems including low availability of the boilers as a result of fouling and slagging as well as water and air-pollution problems [45–49]. Thermal efficiency of commercial pulverised oil shale plants is about 29 %, without flue-gas clean-up, and they have an availability of only 50 % [50]. So these were main reasons behind the decision of the Estonian Government not to expand the electric-power generation capacity until the present method of pulverised oil shale combustion is improved [51]. The common problems of fouling and corrosion of the heat-exchange surfaces by ash and slag deposits are enhanced in the presence of alkali metals, sulphates and chlorides in the raw shale. Usually the alkali metals and chlorides have higher corrosion activities compared with those of sulphates [52]. Corrosion causes a sharp drop in the system's thermal efficiency as well as its availability. Intensification of regular cleaning could not mitigate this problem: whatever happens the boiler's output will always be lower than its design value [53]. In general, such technology for firing solid fuels including oil shale has proved to be technically inefficient, economically unacceptable and environmentally disastrous [42, 54, 55]. Thus, it is hardly surprising that this technology has only achieved a slow market penetration.

More stringent emission-control requirements and the need to generate electric power and/or heat for industrial processes, from fossil fuels, with higher efficiencies and lower costs, have led to new technologies being introduced, such as fluidised bed combustion (FBC). In 1960, Ruhrgas-Lurgi built two FBC units for combustion of oil shale to generate steam and electricity. The unit capacity was 360 tonnes of oil shale per day, with spent shale being used for cement production [56].

FBC is an energy-efficient and environmentally-friendly technique for burning low-grade solid fuels with high sulphur content and low calorific values including: tars; industrial, agricultural and municipal wastes; poor-quality coals [57, 58]; and oil shale [59]. In FBC, oil shale is combusted in a bed of solids fluidised by high-velocity primary air. The off-gases and the entrained solids, i.e. fly ash, are separated in cyclones and the collected solids are returned to the bed. Heat is extracted from the furnace and from the flue gases before they are cleaned up and released to the atmosphere via the stack, and used to produce superheated steam, which will drive a conventional steam-turbine to generate electricity [60–66].

Preliminary tests performed indicate that a FBC is capable of burning high ash as well as high sulphur content oil shales successfully, with high combustion and boiler efficiencies of 95–98 and 75–80 %, respectively [36, 67, 68]. It is concluded that emission rates from FBCs are low and there is no need for flue-gas clean-up down stream except for particulates, which could be collected easily by employing approved systems such as bag-filters or electrostatic precipitators [69,70]. At present, there are only two FBCs fuelled by oil shale. These are a demonstration cogeneration plant, in Israel, with an installed capacity of 50 tonnes of steam per hour [71] and a full commercially operating unit in China, with a steam flow of 1750 tonne per hour [72]. Experience gained in these countries concerning electricity generation by using oil shale showed that a FBC, with carbonates ($CaCO_3$ and $MgCO_3$) in the inorganic part of oil shale, is suitable for burning sulphur-rich and low-grade oil shale such as those available in Jordan [70]. Due to the encouraging results and experience gained from a demonstration plant, the board of directors of the Israel Electric Corporation Ltd., approved a project to build a commercial oil-shale-fired power plant with a nominal installed capacity of about 75 MW [73].

Gasification

Gasification, unlike retorting, aims to increase the calorific value per unit mass of the resulting fuel gas: this is achieved by removing unwanted constituents, mainly ash, thereby producing a gaseous fuel, which is cleaner and easier to handle. Oil shale gasification is a relatively simple process requiring extraction of the volatile compounds of the shale through pyrolysis, followed by partial combustion of the remaining char. This series of reactions produces a fuel gas, with CO and H_2 as the major constituents, together with small amounts of CO_2, N_2, CH_4 and H_2S. Because the gasifier would operate at elevated temperatures in a reducing atmosphere, there will be neither oxides of sulphur nor of nitrogen in the product gas [74].

Gasification of oil shale can be achieved in one of two ways: with the heat supplied directly, by partial oxidation of the feed stock or indirectly through an external heat-source and/or heat exchanger. Direct heating is the basic process applied in pressurised coal-gasifiers, and oxygen is used to achieve high temperatures required for efficient gasification. However, such an operation is relatively costly, especially for commercial-scale plants. So a promising opportunity for such an application is the fluidised-bed gasifier, which uses air instead of oxygen to produce a fuel gas with a relatively low energy content. An important key feature of the indirectly-heated gasifiers, which operate usually at relatively low temperatures of about 700 to 850 °C, is that they can produce a high-calorific gaseous fuel, without the use of oxygen, which is costly.

Pressurised gasification is preferred to atmospheric gasification from the thermodynamic losses point-of-view. These losses, associated with compressing the fuel gas before it is injected into the gas-turbine's combustor, are higher than those associated with compressing the fluidising air. However, this benefit would involve operational problems, such as feeding the raw oil shale to the pressurised reactor, and losses of inert gas if a lockhopper mechanism is used as the sealing device [75].

Burning the low-calorific gaseous fuel produced by oil shale gasification in industrial turbines or external combustion chamber with a gas turbine inlet temperature of 1250 °C at a pressure ratio of 10–15 is capable of achieving plant heat rates of about 7.8 (±0.1) × 10^3 kJ per kWh produced at relatively low capital cost [76–78]. The simple combined-cycle arrangement is more environmentally-friendly because less pollutants per kWh of electricity generated would be produced compared with FBC or pulverised fuel technologies. In general, the high efficiencies of the combined cycle gas turbine system can mitigate the conversion losses incurred in gasifying oil shale, and so still deliver a high overall efficiency as well as provide economically the superior environmental performance required. This would make using the integrated gasification combined-cycle system attractive for base-load electricity generation.

To sum up, current trends in oil shale utilisation are limited to either the production of synthetic fuel and chemicals or generation of electricity. 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 of oil shale and its tendency to form hard deposits, which result in fouling and/or corrosion of the processing equipment. These deposits also lead to lower heat-transfer rates and hence reduce the system's capacity and efficiency. In the case of retorting, oil shale is processed at a temperature of about 500 °C, at which the maximum shale oil yield is achieved, but it would then be of relatively low-quality: high pour point as well as relatively large contents of nitrogen, oxygen and sulphur. A rise in the retorting temperature will improve the quality of the end product, but the oil yield will then be reduced. So, it is suggested that one should combine the two utilisation methods into an optimal multi-purpose production process, which will achieve high rates of oil recovery as well as harness the chemical, energy and mineral potentials of the Jordanian oil shale. Also, gasification is an acceptable technical solution for processing high-sulphur oil shales: it is even more economic than the direct combustion of the shales [68]. Thus, due to its relatively high sulphur content, the gasification of Jordanian oil shale is expected to be cheaper and technically more viable compared with oil shale retorting.

Published Reports and Feasibility Studies

The first recorded report concerning oil shale in Jordan was written by S. J. Blaick in 1930. Subsequently, several studies by the Natural Resources Authority (NRA), involving core drilling and laboratory analyses to determine the constituents and the calorific values of the oil shales were undertaken [79]. However, the NRA terminated such activities in 1969, because it was predicted that the cost per harnessed kWh incurred via the utilisation of Jordan's oil shale, for the foreseeable future would significantly exceed those achievable using imported crude oil [80]. Nevertheless, after the first oil shock due to the overall rise in crude oil unit prices, interest in the Jordanian oil shale, as an indigenous energy-resource, rose considerably. As a result, the Government, in co-operation with specialised foreign companies, initiated several investigations to assess the technical and economic feasibilities of utilising the national deposits of oil shale [81, 82].

In 1986, a study conducted in co-operation with the Chinese Oil Shale Co., showed that Jordanian oil shales excavated from the Ellujjun deposit could be processed effectively in a Chinese Fushun retort with a relatively high recovery-rate of the organic content of about 85 % as measured by the Fischer assay [39]. Also, during the late 1980s, in close co-operation with the Japan Oil Shale Engineering Company, a sample from the Ellujjun deposit was tested in a pilot plant, which consists of a simple indirectly-heated retorting unit in conjunction with a FBC plant for the oil shale fines, for the purpose of electricity generation [83]. The preliminary result was that Jordanian oil shale could be processed successfully to produce shale oil or generate electricity. However, detailed technical design and commercial-feasibility studies are still needed to optimise the process.

More few pre-feasibility studies were conducted by different consultants during the 1980s and the main technical conclusions of these studies were that Jordanian oil shales could be retorted to produce liquid and gaseous hydrocarbon products; or burnt, thereby releasing heat which could be used to generate electricity [84]. However, it was recognised that FBC is relatively new as well as unproven, with respect to its financial viability, for burning oil shale in a large-scale plant for long periods. There are also associated problems, such as large amounts of water usually required for the processing plant; the significant risks of environmental damage as a result of harnessing oil shale; and the high capital costs incurred [85]. Moreover, during the late 1980s and 1990s, the unit cost of electricity generated via burning oil shale and a turbine or producing shale oil was concluded to be far more than that achieved using imported oil instead, due to relatively low crude oil prices. Thus, during the 1990s the Government has adopted a "wait-and-see" policy, while meanwhile monitoring the world-wide technical and economic advances in oil-shale harnessing and use [86].

During the last few years, due to the restructuring of the energy sector, as well as the privatisation of the electric-power sub-sector in Jordan, several offers have been forthcoming from international companies to utilise some of the oil shale deposits. The proposals are for producing shale oil and/or generating electricity for national consumption and/or export. The state-owned National Electricity Power Company would be expected to buy generated electricity, provided it is cheaper per kWh than that obtainable from any other source, on a long-term-purchase agreement basis.

Recently MEMR has signed an agreement with a specialised Canadian firm, SUNCOR. This aims to develop the Ellujjun oil shale deposit in order to produce mainly shale oil by employing the Alberta Taciuk retorting technology [2, 5, 8]. However, no details are made available to the public about the agreement, both from the financial or technical point of views.

Future Energy System Developments Involving Oil Shale in Jordan

Annual electricity consumption is increasing at a relatively high rate of about 6 %, which is attributed to the increasing dependency on such a flexible and clean form of energy that can be generated from a wide variety of fuels and sources. This will pose a real challenge for Jordan in trying to satisfy its growing energy and especially electricity demands, while simultaneously reducing the adverse impacts on the economy, the environment and social life.

There are two main routes for developing oil shale fired electric power plants. The first is based on the Rankine cycle, and the second on the Bryton cycle. The efficiency of the first option would be approximately similar to that achievable with the coal-fired systems: based on limited experience with a FBC which burns oil shale, less than 30 % and it may reach 32 % for the best scenario [73]. But the net efficiency can be increased dramatically to about 42 % when a combined cycle arrangement is used as in a Pressurised Fluidised-Bed Combustor (PFBC) [87–90]. The alternative way of achieving direct firing is to operate a FBC and a gasifier, which feeds fuel gas to a combined-cycle system, char and fines would be circulated to the FBC for combustion, in order to more fully exploit the available energy potential. Hence the final efficiency will be raised. Improving the efficiency of a system reduces the fuel consumption as well as the production of pollutants, which are generated for a specific power output. It also has the advantage of minimising adverse environmental impacts along the whole fuel-supply train: mining, handling and crushing as well as storage and transportation of raw oil shale or final products.

Advanced oil shale based electric power generation systems would offer the potential for the immediate future to meet the increasing electricity demand by using the locally available and abundant oil shale deposits. Such an approach has the advantage of reducing dependence on imported oil. In addition, it will help in preserving premium fuels, natural gas and crude oil, for applications such as in chemical industries in which their natural advantages can be exploited more appropriately.

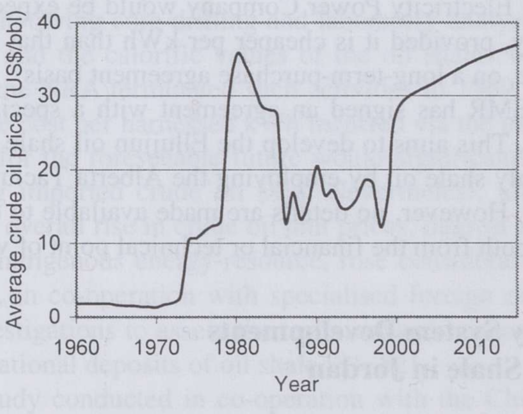

Fig. 3. Development of oil prices in the international market (Arabian light crude oil)

Now one of the most significant aspects of any energy review, which in the case of Jordan partially culminated in the Government's energy master plane [91], has to be the cost of final unit of energy, especially electricity production, from alternative energy sources and/or types of generating systems and fuels. This is not a new debate and there is fierce input from those with related interests and the position, in general, is not clear. For example, in the case of electricity planning the predicted cost of generation from a particular system is highly dependent on the future fuel prices. The latter is very difficult to predict due to various factors: fluctuations of crude oil prices during last 40 years and expected prices during the next 15 years can be seen in Fig. 3. But, indeed, the higher the unit prices and the tighter the supplies of crude oil and/or natural gas, the greater the interest in oil shale resources will be in the future.

Research and Development Concerning Oil Shale in Jordan

Unfortunately, only a few researches have been done concerning processing of Jordanian oil shales, and all of these studies were carried out on laboratory scale. The Table summarises the published papers, which can be traced in the literature, concerning different aspects of Jordanian oil shales [11, 15, 16, 33, 34, 74, 77, 78, 92–107]:

Scientific Articles about Jordanian Oil Shales

Subject	Number of articles*	Oil shale deposit
Elemental analysis and calorific value determination	3	Ellujjun
Composition analysis (organic and inorganic)	2	Ellujjun and Sultani
Reserves	2	Most of occurrences
Direct combustion	2	Ellujjun
Pyrolysis	4	Ellujjun and Sultani
Extraction	2	Ellujjun
Kinetic analysis	5	Ellujjun and Sultani
Drying	2	Ellujjun and Sultani
Gasification	2	Ellujjun
Process description	1	–
Environmental impacts	2	Ellujjun or Sultani
Ash utilisation	3	Ellujjun

* These represent what can be traced in the oil shale literature.

As one can see, the total number of published articles is very low, about 25 papers, and concern only two types of shales. Such a poor outcome of technical research in oil shale development and utilisation can be attributed to the lack of Government's support and know-how or scientific interest among research institutions in Jordan. However, most of the reported research studies, especially in the field of oil shale processing, were carried out by Jordanian researchers abroad. These were conducted on experimental laboratory-scale research rigs, which have certain limitations, such as small size of equipment. The latter allows for only a small amount of oil shale and particle sizes to be used, hence, the optimal processing conditions cannot be determined due to the system limitations. Thus the final results, as in all experimental work employing laboratory-scale devices, cannot be scaled off and can be used only as preliminary indicators. In order to reach representative figures, applicable in the technical and economic feasibility studies, the experiments should be conducted following the proven scientific path: first on bench scale, then in pilot and finally semi-commercial and commercial plants. Thus, oil shale research studies should be given a high priority and the required support in all scientific institutions in Jordan.

Conclusion

Based on the results of preliminary analyses and experimental work of the previously mentioned research studies about Jordanian oil shales, there are several key points that should be studied thoroughly in order to ensure the achievement of high source utilisation factors and energy-recovery ratios. Consequently, only financially and environmentally feasible oil shale developments should be implemented in the future. The most important scientific investigations and research work that should be carried out in order to support the establishment of a sustainable local oil shale industry are those related to evaluation of deposits and mining techniques; retorting technologies; gasification processes; environmental assessments of various utilisation methods; and spent ash and water treatment and requirement.

To sum up the contents of this article, it can be said that oil and natural gas will remain the prime fuels used in different sectors, and these will be major competitors to oil shale development world-wide and particularly in Jordan. Because crude oil and petroleum products, and in the near future natural gas, are imported and cause a heavy burden on the national economy, their long-term use as fuels for electricity generation is likely to be discouraged. Restorable energy sources and other new fuels also have a great potential but the related economics and technical limitations will delay the use of such sources for many years to come. Thus, oil shale would be left as the only option as an interim indigenous energy source in Jordan. However, the future of oil shale utilisation does not look bright at this moment because of economic conditions, but this is expected to change in the near future due to the increasing crude oil prices.

REFERENCES

1. Energy 1999 – Facts and Figures / Ministry of Energy and Mineral Resources. – Amman, Jordan, 2000.

2. Annual Report 1999 / Ministry of Energy and Mineral Resources. – Amman, Jordan, 2000.
3. Statistical Yearbook 1999 / Department of Statistics. – Amman, Jordan, 2000.
4. *Jaber, J.O., Probert S.D.* Energy demand, poverty and the urban environment in Jordan // Applied Energy. 2001. Vol. 68. P. 119–134.
5. Annual Report 1999 / National Electric Power Company. – Amman, Jordan, 2000.
6. Web site of National Electric Power Company: www.nepco.com.jo/ 2001.
7. *Jaber, J.O., Mohsen, M.S., Probert, S.D., Elees, M.* Future electricity demands and greenhouse gas emissions in Jordan // Applied Energy. 2001 (accepted and in press APEN 633).
8. Al-Rai Daily Newspaper, 6 February, Vol. 30, No. 11108. Amman, Jordan, 2001.
9. Web site of Southern Pacific Petroleum N. L.: www.sppcpm.com/ 2001.
10. *Speers, G.C.* Ellujjun Oil Shale Deposit, Jordan. Report No. EPR/R 7005 / British Petroleum Company. – London, UK, 1969.
11. *Abu Ajamieh, M.* An Assessment of the Ellujjun Oil Shale Deposit / Natural Resources Authority. – Amman, Jordan, 1980.
12. Natural Resources Authority, Basic Information on Oil Shale in Jordan. – Amman, Jordan, 1995.
13. Annual Reports 1990 & 1991 / Ministry of Energy and Mineral Resources. – Amman, Jordan, 1991 and 1992.
14. *Mustafa, I., Bsieso, M., Bakri, W., Jebril, Z., Anani, F.* Renewable Energy in Jordan: Share in Total Energy-Mix / The Higher Council for Science and Technology. – Amman, Jordan, 1993.
15. *Anabtawi, M.Z., Nazzal, J.M.* Effect of composition of Ellujjun oil shale on its calorific value // Testing and Evaluation. 1994. Vol. 22, No. 2. P. 175–178.
16. *Jaber, J.O., Probert, S.D., Williams, P.T.* Influence of particle size, grade and pyrolysis temperature on the oil yield from Jordanian oil shales // Oil Shale. 1999. Vol. 16, No. 1. P. 197–221.
17. Annual Reports 1993–1999 / Natural resources Authority. – Amman, Jordan, 1991–2000.
18. *Gluskoter, H.J., Cahil, R.A., Miller, W.G., Ruch, R.R., Shimp, N.F.* An Investigation of Trace Elements in Coal, Aspects for Fuel Conversions, EPA-600/2-76-149 / Environmental Protection Agency, Washington D. C., USA, 1976.
19. *Maremäe, E., Taal, H.* Metal extraction from alum shale ashes under the effect of ammonium sulphate // Oil Shale. 1991. Vol. 8, No. 4. P. 337–341.
20. M. Bsieso. Personal communication. National Energy Research Center, Amman, Jordan, 2001.
21. *Tissot, B.P., Welte, D.H.* Petroleum Formation and Occurrence. – Springer-Verlag, New York, 1978.
22. *Allred, V.D.* Oil shale retorting phenomenology // Oil Shale Processing Technology / V.D. Allred (ed.). The Center for Professional Advancement, New Jersey, USA, 1982.
23. *Hunt, V.D.* Synfuels Handbook. – Industrial Press, Inc., New York, USA, 1983.

24. *Speight, J.G.* Fuel Science and Technology Handbook. – Marcel Dekker, Inc., New York, USA, 1990.

25. *Lee, S.* Oil Shale Technology. – CRC Press, Inc., Boca Raton, Florida, USA, 1991.

26. *Yen, T.F.* Science and Technology of Oil Shale / The Center for Professional Advancement, New Jersey, USA, 1976.

27. *Lyon, R.K., Hardy, J.E., Stell, R.* The domino theory of steam gasification of spent shale // Fuel. 1985. Vol. 64, No. 5. P. 714–716.

28. *Longwell, J.P.* Polycyclic aromatic hydrocarbons and soot from practical combustion systems // Soot in Combustion Systems and its Toxic Properties / J. Lahaye and G. Prado (eds.). Plenum Press, New York, USA, 1983.

29. *Schmith-Collerus, J.J., Bomono, F., Gala, K., Leffler, L.* Polycondensed aromatic compounds (PCA) and carcinogens in the shale ash of carbonaceous spent shale from retorting of oil shale // Science and Technology of Oil Shale / T.F. Yen (ed.). Newcastle University, Ann Arbor Science Publishers, Ann Arbor, Michigan, USA, 1976.

30. *Rovere, C.E., Crisp, P.T., Ellis, J., Bolton, P.D.* Chemical characterization of shale oil from Condor, Australia. // Fuel. 1983. Vol. 62, No. 11. P. 1274–1282.

31. *Bett, G. Harvey, T.G., Mathseon, T.W., Pratt, K.C.* Determination of polar compounds in Rundle shale oil // Fuel. 1983. Vol. 62, No. 12. P. 1445–1454.

32. *Williams, P.T., Nazzal, J.M.* Polycyclic aromatic compounds in oils derived from the fluidised bed pyrolysis of oil shale // J. of Analytical and Applied Pyrolysis. 1995. Vol. 35. P. 181–197.

33. *Nazzal, J.* The presence of polycyclic aromatic hydrocarbons in the pyrolysed shale oil // Proc. Intern. Conf. of Energy Systems, 25–28 September 2000. University of Jordan, Amman, Jordan.

34. *Nazzal, J.* Influence of pyrolysis temperature on the products of Jordan oil shale in a semi-continuous fluidised bed reactor // Proc. Conf. of Arab Energy and Sustainable Development, 28–30 October 2000. Syrian Engineers Association, Damascus, Syria.

35. *Marnell, P.* Economic data for a 50,000 bpd Lurgi/Ruhrgas shale oil plant // Synthetic Fuels Processing: Comparative Economics / A. H. Pelofsky (ed.). Marcel Dekker, Inc., New York, USA, 1977.

36. Lurgi GmbH, Oil Shale Retorting by the Lurgi-Ruhrgas (LR) Process, Document No. 1560e/2.88, Frankfurt am Main, Germany, 1988.

37. *Casavechia, L.C., Novicki, R.E.M., Martignone, W.P., Goldstein, L., Pecora, A.A.B., Lombardi, G.* Design and operation of an oil shale circulating fluidized bed boiler pilot plant // Proc. 11th Intern. Conf. on Fluidized Bed Combustion, 21–24 April 1991, Montreal, Canada.

38. *Reeg, C.P., Randle, A.C., Duir, J.H.* Uncal's Parachute Creek oil shale project // 23rd Oil Shale Symposium. Colorado School of Mines, Golden, Colorado, USA, 1990.

39. *Bayrer, R.L.* Appraisal of current projects in synthetic fuels technology // Fuel. 1991. Vol. 70. P. 1327–1329.

40. *Dehong, P., Jialin, Q.* Oil shale activities in China // Oil Shale. 1991. Vol. 8, No. 2. P. 97–105.

41. *Shuyuanl, L., Jialin, Q.* A Mathematical model for evaluating fluidized bed combustion efficiency of oil shale // Oil Shale. 1992. Vol. 9, No. 2. P. 97–102.

42. *Volkov, E.P.* New developments in oil shale technology // Proc. 17th Congr. of the World Energy Council "Energy and Technology: Sustaining World Development into the Next Millennium", 13–18 September 1998, Houston, Texas, USA.

43. *Ots, A.A.* Formation of air-polluting compounds while burning oil shale // Oil Shale. 1992. Vol. 9, No. 1. P. 63–75.

44. *Jianqiu, W., Qi, Z.* Comparison of combustion behaviour between oil shale and coal under atmospheric and elevated pressure // Oil Shale. 1991. Vol. 8, No. 3. P. 210–219.

45. *Etlin, S.N., Rudco, L.A.* Effect of air in the oil shale region on the population's health // Oil Shale. 1990. Vol. 7, No. 3-4. P. 174–181.

46. *Sidorkin, V., Kniga, A., Rakitina, N.* The opportunity of NO_x emissions reduction for the pulverized oil shale fired boilers // Oil Shale. 1991. Vol. 8, No. 4. P. 355–359.

47. *Klimova, E.* Modelling of transfer and impact on eco-systems of emissions from oil shale power plants in Estonia // Oil Shale. 1993. Vol. 10, No. 1. P. 67–78.

48. *Liblik, V., Kundel, H.* Pollution sources and formation of air contamination multicomponential concentration fields of organic substances in North-Eastern Estonia // Oil Shale. 1995. Vol. 13, No. 1. P. 43–64.

49. *Mandre, M., Liblik, V., Rauk, J., Rätsep, A., Tuulmets, L.* Impacts of air pollutants emitted from the oil shale industry on conifers // Oil Shale. 1996. Vol. 13, No. 4. P. 309–324.

50. *Öpik, I., Prikk, A.* The 41 MWe LLB CFB-biler as model for 200 MWe oil shale blocks // Oil Shale. Vol. 13, No. 3. 1996. P. 239–245.

51. *Barabaner, N.I., Kaganovich, I.Z.* Oil shale production and power generation in Estonia: Economic and environmental dilemmas // Energy Policy. 1993. Vol. 21, No. 6. P. 703–709.

52. *Ots, A.A.* Utilisation of high calcium oxide and alkali metal content fuel at the thermal power plants // Oil Shale. 1990. Vol. 7, No. 3-4. P. 321–310.

53. *Tiikma, T.* Thermal operation of oil shale boiler furnaces // Oil Shale. 1994. Vol. 11, No. 4. P. 325–329.

54. *Öpik, I.* Scenarios for shale oil, syncrude and electricity production in Estonia in the interim 1995–2025 // Oil Shale. 1992. Vol. 9, No. 1. P. 81–87.

55. *Klimova, E.* Impacts of oil shale power plants on environment in Estonia // Oil Shale. 1993. Vol. 10, No. 1. P. 67–78.

56. *Plass, L., Beibwenger, H., Anders, R.* Large size power plants working according to the atmospheric and pressurised CFB technology // Proc. 11th Intern. Conf. on Fluidized Bed Combustion, 21–24 April 1991. – Montreal, Canada.

57. Personal Communication. Foster Wheeler Energy International, Inc., Pyroflow CFB Technology: The Global Clean Energy Alternative, Foster Wheeler Energy Services, San Diego, California, USA, 1997.

58. *Palit, A., Mandal, P.K.* Fuel and ash characterisation of Indian coal for their suitability in fluidized bed combustion // Proc. 13th Intern. Conf. on Fluidized Bed Combustion, 7–10 May 1995. Orlando, Florida, USA.
59. *Abdulally, I.F., Reed, K.* Experience update of firing waste fuels in Foster Wheeler's circulating fluidized bed boilers // Proc. 13th Intern. Conf. on Fluidized Bed Combustion, 7–10 May 1995. Orlando, Florida, USA, 1995.
60. *Yerushalmi, J. Wohlfarth, A., Schwartz, M., Luria, S.* Power from oil shale // Modern Power Systems. February 1988. Vol. 17. P. 27–29.
61. *Howard, J.R.* Fluidized Bed Technology: Principles and Applications. – Adam Hilger, Bristol, UK, 1989.
62. *Dixit, V.B., Mongeon, R.K.* Design and economics for an advanced circulating fluidized bed concept targeted for the small industrial markets // Proc. 11th Intern. Conf. on Fluidized Bed Combustion, 21–24 April 1991. Montreal, Canada, 1991.
63. Foster Wheeler Energy International, Inc., Largest CFB Set to Enter Service in Nova Scotia / Foster Wheeler Energy Services. – San Diego, California, USA, 1993.
64. Foster Wheeler Energy International, Inc., Fluidised Bed Combustion: Turow Serves as a Model for Central Europe / Foster Wheeler Energy Services. – San Diego, California, USA, 1995.
65. Foster Wheeler Energy International, Inc., Foster Wheeler Update, A Newsletter about Advanced Energy Technology / Foster Wheeler Energy Services. – San Diego, California, USA, 1996.
66. *Grace, J.R., Avidan, A.A., Knowlton, T.M.* Circulating Fluidized Beds. – Blackie Academic & Professional, London, UK, 1997.
67. *Johnk, C., Friedman, M.A., Andrews, N.W.* Early experience with Nova Scotia Power's Point Aconi Station, 165 MWe Ahlstrom Pyroflow CFB // Proc. 13th Intern. Conf. on Fluidized Bed Combustion, 7–10 May 1995. Orlando, Florida, USA, 1995.
68. *Kashirskii, V.* Problems of the development of Russian oil shale industry // Oil Shale. Vol. 13, No. 1. 1995. P. 3–5.
69. *Barnes, J.E.* Pyroflow CFB: The modern way to burn coal // 1993 Pittsburgh Coal Conference. Pittsburgh, Pennsylvania, USA, 1993.
70. *Alliston, M.G., Probst, S.G., Wu, S., Edvardsson, C.M.* Experience with the combustion of alternate fuels in a CFB pilot plant // Proc. 13th Intern. Conf. on Fluidized Bed Combustion, 7–10 May 1995. Orlando, Florida, USA, 1995.
71. *Holopainen, H.* Experience of oil shale combustion in Ahlstrom Pyroflow CFB-boiler // Oil Shale. Vol. 8, No. 3. 1991. P. 194–209.
72. Foster Wheeler Energy International, Inc., Reference List, Circulating Fluidized Bed Boilers. – San Diego, California, USA, 1997.
73. *Schaal, M., Podshivalov, V., Wohlfarth, A., Schwartz, M.* FBC to burn oil shale in the Northern Negev //Modern Power Systems. 1994. Vol. 14, Issue 9. P. 25–28.
74. *Jaber, J.O., Probert, S.D.* Reaction kinetics of fluidised bed gasification of Jordanian oil shales // Intern. J. Thermal Sciences. 2000. Vol. 39. P. 295–304.

75. *Miles, T.R., Miles, T.J.* Reliable Feed Systems for Thermochemical Conversion, Research in Thermochemical Biomass Conversion. – Elsevier Applied Science, London, UK, 1988. P. 1156–1169.
76. *Solomon, P.R., Serio, M.A., Cosgrove, J.E., Pines, D.S., Zhao, Y., Buggeln, R.C., Shamroth, S.J.* A coal-fired heat exchanger for an externally fired gas turbine // J. Engineering for Gas Turbines and Power. 1996. Vol. 118, No. 1. P. 22–31.
77. *Jaber, J.O., Probert, S.D., Williams, P.T.* Gaseous fuels derived from oil shale for heavy-duty gas turbines and combined-cycle power generators // Applied Energy. 1998. Vol. 60. P. 1–20.
78. *Jaber, J.O.* Oil shale to empower industrial gas turbines // Proc. Conf. of Arab Energy and Sustainable Development, 28–30 October 2000, Syrian Engineers Association. Damascus, Syria, 2000.
79. *Ja'uni, W., Bsieso, M.* Oil shale utilisation technology // The Third Jordanian Scientific Week / The Higher Council of Science and Technology. – Amman, Jordan, 1995.
80. Annual Reports, 1985–1992 / Natural Resources Authority. – Amman, Jordan, 1986–1993.
81. Lurgi GmbH, and Natural Resources Authority, Technical and Economic Feasibility of a Large-Scale Oil Shale Retorting Complex / Natural Resources Authority. – Amman, Jordan, 1986.
82. Bechtel National Inc. and Jordan Electricity Authority, Prefeasibilty Study: Oil Shale Utilization for Power Production in the Hashemite Kingdom of Jordan, Contract No., LAC-5724-C-5126-000. – Amman, Jordan, 1989.
83. *Harada, K.* Research and development of oil shale in Japan // Fuel. Vol. 70, No. 11. 1991. P. 1330–1341.
84. Annual Reports, 1985–1992 / Ministry of Energy and Mineral Resources. – Amman, Jordan, 1986–1993.
85. World Bank, Jordan Energy Sector Study, Report No. 7984-JO. – Washington, D.C., USA, 1990.
86. Annual Reports, 1994–1998 / Ministry of Energy and Mineral Resources. – Amman, Jordan, 1995–1999.
87. *Harrison, T.* Where to with coal // Mining Technology. July/August 1993. P. 201–204.
88. *Khartchenko, N.V.* Advanced Energy Systems. – Taylor and Francis, Washington, DC, USA, 1998.
89. *Dechamps, P.J.* Combined Cycle Off-Design Performance : Lecture notes presented at the Combined Cycle Gas Turbines Short Course, 18–22 May 1998, School of Mechanical Engineering, Cranfield University, UK. 1998.
90. *Dechamps, P.J., Croix, P.J., Mathieu, P.H., Pilidis, P.* Influences of syngas properties on the performances of aero-derivative and industrial gas turbines // ECOS 92 Conference, 1992, Sarragoza. P. 433–440.
91. Arab Bank Center for Scientific Research, Terms of Reference for Consultancy Services for the Preparation of a Master Plan for the Energy Sector in Jordan / Arab Bank. – Amman, Jordan, 2001.

92. *Jaber, J.O., Probert, S.D.* Non-isothermal thermogravimetry and decomposition kinetics of two Jordanian oil shales under different processing conditions // Fuel Processing Technology. 2000. Vol. 63. P. 57–70.

93. *Jaber, J.O.* Gasification potential of Ellujjun oil shale // Energy Conversion and Management. 2000. Vol. 41. P. 1615–1624.

94. *Jaber, J.O., Probert, S.D.* Predicted environmental and social impacts of the proposed oil shale integrated tri-generation system // Oil Shale. 1999. Vol. 16, No. 1. P. 2–29.

95. *Jaber, J.O., Probert, S.D.* Exploitation of Jordanian oil shales // Applied Energy. 1997. Vol. 58. P. 161–175.

96. *Jaber, J.O., Probert, S.D.* Oil shale integrated tri-generation system: the technology and predicted performance // Oil Shale. 1999. Vol. 15, No. 1. P. 3–30.

97. *Jaber, J.O., Mohsen, M.S.* Behaviour of two Jordanian oil shales at drying // Oil Shale. 2001 (accepted and in press).

98. *Tamimi, A.,Uysal, B.Z.* Drying characteristics of oil shale. Energy. 1992. Vol. 17. No. 3. P. 303–308.

99. *Haddadin, R.A., Mizyed, F.A.* Thermogravimetric analysis kinetics of Jordan oil shale // Industrial Engineering Chemistry, Process, Design and Development. 1974. Vol. 13. P. 332–336.

100. *Ahmad, N.T., Abou-Arab, T.W., Azzam, S.* The combustion of oil shale using fluidised bed combustor // World Renewable Energy Congress, 11–16 September 1994. Reading, UK.

101. *Hammad, M., Zurigat, Y.* Fluidized bed combustion unit for oil shale // Proc. 1st Jordanian Mechanical Engineering Conference, 25–28 June 1995. Jordan Engineers Association, Amman, Jordan, 1995.

102. *Hamdan, M.A., Khraish, Y., Al-Dabbas, M.A.* Combustion of shale oil // Proc. 1st Jordanian Mechanical Engineering Conference, 25–28 June 1995.

103. *Anabtawi, M.Z., Uysal, B.Z.* Extraction of Ellujjun oil shale // Separation Science and Technology. 1995. Vol. 30, No. 17. P. 3363–3373.

104. *Anabtawi, M.Z.* Comparison between continuous stirred tank reactor extractor and Soxhlet extractor for extraction of Ellujjun oil shale // Separation Science and Technology. 1996. Vol. 31, No. 3. P. 413–422.

105. *Kablan, M.M., Alkhamis, T.M.* An experimental study for a combined system of tar sand, oil shale and olive cake as a potential energy source in Jordan // Biomass and Bioenergy. 1999. Vol. 17. P. 507–515.

106. *Alkhamis, T.M., Kablan, M.M.* A Process for producing carbonaceous matter from tar sand, oil shale and olive cake // Energy. 1999. Vol. 24. P. 873–881.

107. *Suliman, M.R., Awwad, M.T.* The Use of Oil Shale Aggregates as a Pavement Material : Internal Report / Amman College for Engineering Technology; Al-Balqa Applied University. Amman, Jordan, 2000.

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