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ACHIEVING RESILIENCE AND SUSTAINABILITY THROUGH INNOVATIVE DESIGN FOR OIL SHALE PYROLYSIS PROCESS MODEL

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Abstract. *Low international oil price, advance in renewable energy technology, development of energy storage technology and strict environmental regulations have presented encumbrance and opportunity for the current oil shale project development. Oil shale industry is at critical stage and facing challenges from competitive conventional energy, clean renewable energy and more strict environmental regulations. Through an innovative design of the oil shale pyrolysis process model by utilizing a developed new advanced technology, the oil shale project could improve its resilience and sustainability with excellent social and economic performance.*

This paper investigated the shale oil production process in terms of technology selection, utilization of resource, energy efficiency, oil yield, and mining to improve the resilience of oil shale project economic performance facing lower oil price. Innovative design options for the oil shale production process model were discussed from the following aspects: 1) itemized cost analysis and comparison of shale oil production technologies; 2) development of a new oil shale pyrolysis process model with combination of the existing vertical retort process (VRP) and horizontal rotary-kiln retort process (HRRP) technologies to improve the oil shale process economic gain; 3) discussion of innovative design options to improve the economic performance of the process by utilizing the current new advanced energy storage technology. Investigation of the applicability of the energy storage system (ESS) to the oil shale project was carried out with a sensitivity analysis of its cost-revenue.

Keywords: *vertical retort process, rotary-kiln retort process, shale oil cost, energy storage system, revenue.*

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1. Introduction

Oil shale is a sedimentary rock containing organic matter which can be converted to oil and gas through thermal cracking reaction also known as pyrolysis reaction. Oil shale can be regarded as an alternative oil and gas resource and a replacement energy of coal and other non-renewable fossil energy kinds. When the world oil price stays high due to the high demand and limited resource of conventional oil, oil shale has been regarded as an alternative source of fuel oil and thus gets more attention from energy industry.

However, due to the low global oil price since 2014, oil shale industry has suffered from lack of energy industry's and investors' attention. More than a dozen of oil shale plants/projects have ceased operation and development around the world due to the finance loss in the last five years. Maoming oil shale mine, which was one of the biggest oil shale industry centers in China during the 1960s, ceased development activity even with billions of tons of oil shale resource remained and has now been rehabilitated and converted into an industrial ecology park. The closure of Maoming oil shale mine is the result of the government's strict environmental policy, low world oil price, insufficient renewable energy technology development and uncertainty about oil shale technology.

Nevertheless, despite the low oil price there are a few oil shale plants that keep operating today with resilience at reasonable economic performance. These include five oil shale plants in China, three in Estonia, and one in Brazil. Taimu Mining Group (TMG) of China has kept its 40 retorts operating at full capacity all the time and is planning to put into operation three large-scale oil shale plants with a processing capacity of 8 million tons of oil shale per year. The innovative and resilient design for the oil shale production process model is a key to the industry's competitiveness.

There has been conducted significant research on shale oil production technology components such as gas heat carrier, solid heat carrier process and electrical heating process in terms of heating media, and vertical retorting and rotary-kiln retorting process in terms of current key retort equipment [1–8]. Each process technology exhibited unique advantages and some disadvantages from economic and environmental aspects. To make the oil shale production process resilient against low priced conventional crude oil, there is a long list of tasks to tackle, from mining technology [9], retorting technology [5], added value products [10] to waste treatment [11] and resource utilization [10]. All of these investigations have presented a new or improved methodology on each of individual process factors. Considering the oil shale production process includes mining, oil shale pretreatment, retorting, oil/gas recovery and upgrading, waste treatment and disposal, etc., this paper has taken a systematic approach to quantitative analysis of each step for the whole oil shale pyrolysis process and proposed its resilient model to exhibit competence from both economic and environmental aspect.

2. Mining

2.1. Mining cost and technology

Mining, the first step in the shale oil production process, represents a significant cost for some oil shale projects depending on geological conditions, and may account for up to 50% of the total cost of shale oil production. Mining cost varies depending on the amount and quality of oil shale resource and could be reflected on the final oil price, which is \$3/barrel to \$60/barrel shale oil production. There are a few factors that determine the mining cost, including the location and depth of the oil shale seam, geological conditions, mining technology used and the oil content of the resource, to be reflected on the oil production cost per barrel.

Generally, there are two kinds of oil shale mining technologies – open pit mining and underground mining. Open pit mining normally costs much less than underground mining, for some oil shale projects, the mining cost could be as low as \$3/barrel for large-scale commercial open pit mining while the cost of underground mining is unlikely less than \$15/barrel as shown in Table 1.

Table 1. Estimation of mining cost, \$/barrel shale oil production

	Open pit mining	Underground mining
Min	3	15
Max	> 25	> 60

2.2. Future mining methodology

With many years of oil shale mining operation, the methodology has been developed and improved [9]. The cost of oil shale mining could be diluted or reduced by enhancing product value such as increasing oil yield. However, improvement in mining technology through automation or robotization may significantly contribute to the reduction of mining cost. Currently robot cost is very high and seems not very cost effective. However, unmanned mining operation or robotic mining technology represents the future of mining technology and the oil shale industry could benefit significantly from reduced mining cost, improved efficiency, safety, quality, accuracy enhancement of the robot technology and wide application through mining industry. With the application of robot mining technology, the mining cost of oil shale is expected to be reduced in the long-term vision and thus could help oil shale industry to be more competitive with conventional crude oil.

3. Oil shale pretreatment and retorting

3.1. Crushing and drying

Oil shale extracted out of the mine needs to be crushed into smaller particles of certain size range required by the retorting process. Oil shale crushing is the second stage after mining and its cost varies significantly depending on oil shale moisture (including free and bonded water) and mineral contents as well as particle size required by the retorting process. Normally crushing oil shale into finer particles costs significantly more because of the high energy consumption caused by the circulation and equipment wearing and maintenance, which also depend much on the mineral content of oil shale. It is hard to calculate the exact cost of crushing for oil shale of certain particle size as fine particles may be a byproduct of the coarse crushing process. However, the crushing process may cost up to $3.49/ton as estimated by computer modelling [12]. The cost of crushing of fine oil shale feed may be three times higher than that of coarse oil shale feed in consideration of energy, productivity, mechanical equipment wearing and maintenance.

Fresh oil shale from the mine contains some water, including free and bonded water. Normally the retorting process requires oil shale water content below 15% and excess water in oil shale feed needs to be removed by the drying process before directing to the retort. The drying cost is dependent on the water content of oil shale and the energy efficiency of the drying process. The cost of drying may be in the range of $1–$10/barrel shale oil production roughly but depends significantly on the water content and oil yield of oil shale.

3.2. Retorting process

Retorting plays a significant role in oil shale pyrolysis process to produce shale oil and gas from oil shale by heating it up to about 500 °C. The variety of available retorting technologies and operation skills exhibit significant cost difference between different retorting processes depending on oil yield, requirement for pretreatment, utilization of oil shale, operation and maintenance, technology and equipment cost.

There have been developed and operated commercially more than 10 retorting technologies [13]. Each retorting process reveals its advantages and disadvantages over other technologies and this can be represented in the shale oil production cost. With the advance of technology development, current operating technologies can be classified into two types: vertical retort process (VRP) and horizontal rotary retort process (HRRP). The VRP process represents a set of retorting processes which process lump oil shale feed vertically using the direct or indirect hot gas heating methods such as Fushun retorting process, modified Fushun retorting process, Petrosix, Paraho, Sanjiang (SJ) retorting process, etc. The HRRP process represents a set of processes that process fine oil shale feed horizontally through a rotary retort using the direct hot solid heating or indirect hot gas heating methods such as Alberta Taciuk Process (ATP) process, Enefit process, Petroter process, UTT process, etc.

This study estimated the cost of VRP and HRRP based on commercial projects prior to 2015. The basis of commercial cost estimation is confidential and is not available in detail for commercial confidentiality reasons.

The cost estimation is helpful to develop a more cost effective oil shale pyrolysis process model. The estimation of retorting process cost in shale oil production has been itemized and each item has been estimated individually for cost of oil production except the oil yield as shown in Table 2. The lower oil yield in VRP resulted in oil loss of up to 30% more than in HRRP, becoming a disadvantage for the former. Except for the lower oil yield, VRP can only utilize lump oil shale and up to 30% of fine oil shale could not be utilized in this process. Lower oil shale utilization rate and lower oil yield are the main cost disadvantages for VRP. In all other aspects, the cost of shale oil production through the VRP process was lower.

Table 2. Summary of estimation of itemized shale oil production cost

		VRP	HRRP
Pretreatment	Crushing, $/barrel	0.5–3	1–6
	Drying, $/barrel	0–10	0–10
Retorting process	Oil yield, %	60–90	> 90
	Utilization of oil shale, %	< 70	100
	Operation and maintenance, $/barrel	5–20	10–30
	Technology and equipment, $/barrel	5–30	15–40
	Oil recovery	5–20	10–30

In the worst cases such as deep underground mining operation, complicated geology conditions, lower oil grade, high water content, either the VRP or HRRP process could cost even more than $80/barrel which is not competitive with conventional crude oil, except with implementation of new technology and production of commercial mineral or chemical products of high added value. Combining the advantages of both VRP and HRRP could reduce the shale oil production cost.

3.3. TMG process model configuration

A new oil shale pyrolysis process model by combining VRP and HRRP processes has been developed by Taimu Mining Group to make use of the advantages of lower cost of VRP technology and higher oil shale utilization rate and higher oil yield of HRRP process as shown in Figure 1.

As seen from the figure, the TMG process model exhibits the following advantages by combining the VRP and HRRP processes:

- 100% utilization of oil shale with minimum pretreatment cost;
- 100% utilization of the thermal energy of semicoke to produce power for the process;
- obtaining higher oil yield, above 90%;
- estimation of the overall shale oil production cost at $25–$30/barrel.

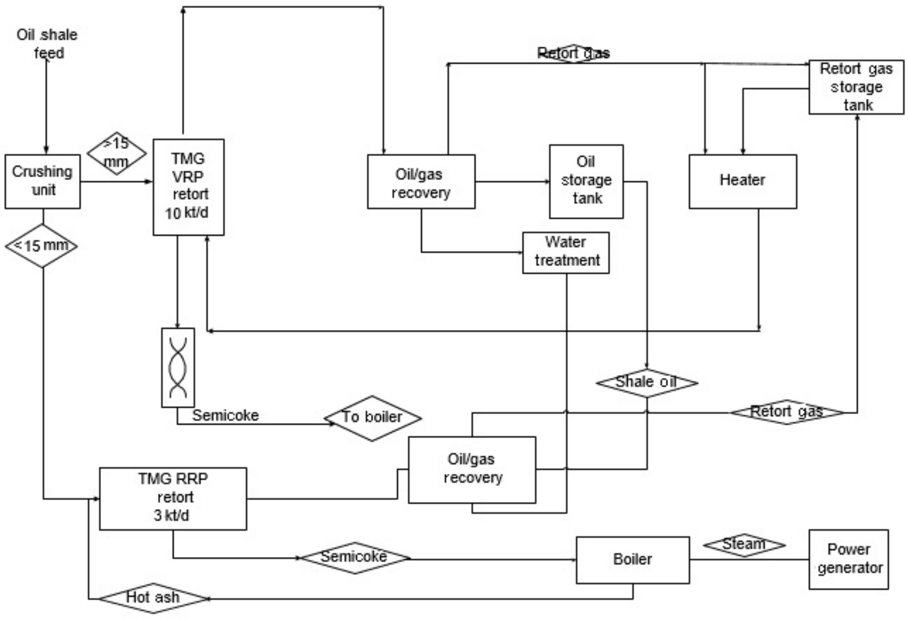

Fig. 1. TMG process model configuration design.

4. Application of the energy storage system in the oil shale plant

Recent developments and advances in energy storage technologies are making their use a viable solution to the application of the oil shale project for power purposes. The economic analysis of the energy storage system has been made for power industry [14–17] except oil shale industry. ESS can store energy and then release it at a proper time. Due to flexibility, this technology is applicable to the oil shale project that can benefit from it economically and environmentally. The costs of ESS consist of installing, operation and maintenance expenses, while the oil shale project could economically benefit from revenues of the system, including energy price arbitrage, reduction of transmission access cost, and deferment of facility investment. Therefore, this paper carried out the cost-revenue sensitivity analysis of the energy storage system for stage 3 of the TMG oil shale project as shown in Figure 2.

Three cases were studied assuming the oil shale project power cost could benefit from the energy storage system 50%, 25% and 10% of total power cost of stage 3 of the TMG oil shale project. The cost of the system can be economically viable and bring economic effect for stage 3 of the TMG oil shale project with ESS cost at no more than $400 k/MW in case of assuming the system could bring minimum 10% saving (reasonable minimum saving assumed) of total power cost saving for the TMG stage 3 project. If the ESS revenue increases more assuming ESS could bring up to 50% of total power

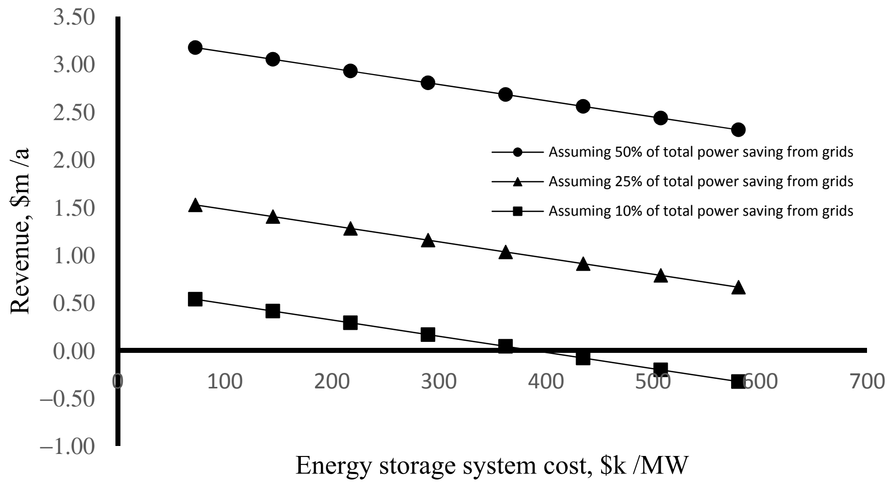

Fig. 2. Cost-revenue sensitivity analysis of the energy storage system of TMG oil shale project.

cost saving for stage 3 plant, the system could be economically feasible even at higher cost, up to more than \$1m/MW. However, it is difficult to achieve the 50% of total power cost saving with the current ESS technology, as its application in the oil shale project at the current high cost is of little economic gain. Nevertheless, the cost of ESS is likely to drop significantly with the advance and development of the system in the next years, and it is highly probable that ESS could be integrated into future oil shale projects which would economically benefit from it and bring the shale oil production cost down.

5. Discussion and conclusions

This study estimated the itemized cost of oil shale pyrolysis process and developed a combined vertical retorting and horizontal rotary-kiln retorting process model which manifested advantages of energy efficiency, higher oil yield and higher oil shale utilization rate and resulted in the reduction of shale oil production cost. It would be possible to achieve a very competitive cost of shale oil production, \$25–\$30/barrel.

This study also explored the possibility of reducing the cost of oil shale mining by using an advanced robot mining technology in the future. The geological conditions of oil shale resource should be well studied to select the most suitable and economic mining methodology. The reduction of the mining cost could help an oil shale project to exhibit better economic performance and alleviate environmental problems.

The cost-revenue sensitivity analysis of integrating the energy storage system with the oil shale pyrolysis process showed that the development of the system and its application to the said process could significantly help to reduce the shale oil production cost if the system cost was reasonable. Thus, a more detailed study of the applicability of the energy storage system should be carried out for each individual oil shale project.

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