UTILIZATION OF OIL SHALE RETORT GAS

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Abstract. *Production of shale oil yields a significant quantity of by-product gas that can have considerable value. The by-product, oil shale retort gas (OSRG), constitutes about ¼ of the energy input of the shale that is processed in a Galoter-based retort.*

The desirability of producing separate products from OSRG is confirmed. Even one single component – propylene – has a potential market value of up to US$250 million per year if produced on the scale that Eesti Energia (EE) is proposing to develop its oil shale project in Utah, USA. Used in its aggregate state as a simple fuel in a power plant, the same amount of OSRG has only about 5% of that value.

Keywords: *oil shale retort gas, gas processing, gas separation.*

1. Introduction

Oil shale retort gas (OSRG) can have numerous possible applications. Its various uses can be patterned after the principal author's prior experience with coal mine methane (CMM), another gaseous fuel that has multiple components and requires processing before it can be used in some applications. However, given the unique compositions of OSRG, many of its uses will be different from those of CMM.

The CMM utilization options with which the principal author has had direct experience during the last 30 years in that industry are shown in

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Table 1. In most cases, the author's experience has included the design, construction and operation of facilities to use CMM with the listed technologies. Only in the case of the last three options (propane substitution, CNG production and LNG production) has the experience been limited to planning and conceptual design without actual operating experience.

Table 1. Coal mine methane (CMM) utilization options

- Electricity generation using
  - Central station power plant
  - Internal combustion engines
  - Gas turbines
  - Fuel cells
- Processing of CMM for delivery of methane to a natural gas pipeline using
  - Pressure swing adsorption (PSA) for nitrogen rejection
  - Carbon dioxide removal with amine scrubbing systems
  - Oxygen removal
  - Gas dehydration and compression
- Direct combustion of methane in heaters for mine air heating
- Flaring of CMM to generate carbon offset (greenhouse gas) credits
- Replacement of propane use at a mine with CMM
- Compression of CMM to produce compressed natural gas (CNG), including
  - Use of CNG for on-site vehicle fuel
  - Sale of CNG to local markets
- Conversion of CMM to liquefied natural gas (LNG)

Given this varied background and experience, it is relatively straight-forward to define the various utilization options for OSRG. One needs only address the differences in composition between CMM and OSRG and understand the impacts that the differing compositions can have on possible utilization options.

It is important to note the differences in composition between CMM and OSRG. Only saturated hydrocarbons (HCs) occur in CMM, along with some inorganic gases like N_2, CO_2 and O_2. OSRG has the same HCs, but also generally contains hydrogen and some unsaturated HC gases, such as ethylene and propylene. OSRG also contains heavier HCs than does CMM.

The only current utilization of OSRG that has been reported is its use in a power plant [1]. This approach puts OSRG to use but this direct fuel approach does not necessarily exploit the resource in an optimal manner. The challenge is to utilize OSRG in applications where its use reflects the specific characteristics and higher value of the gas.

There are high quality components that are now simply burned for their heating value. As an example, the hydrogen in OSRG could be segregated out and used directly in a fuel cell or be used as an additive for upgrading raw shale oil into more refined products.

The authors expect to make this the first of several papers on the utilization of OSRG. Future articles will cover topics such as the economic analysis of OSRG utilization at specific sites in various countries and more detailed technical evaluations related to specific applications of OSRG, such

as its use in district heating applications. Economic analyses of OSRG utilization have to be site-specific since prices for various energy forms vary by country and even by region within countries.

2. Quantities of oil shale retort gas available from oil shale retorts

The amount of OSRG that is produced during oil shale processing varies by the process that is used. There is also variability for a given process, depending on the particular pieces of equipment being used.

There is even some variability by the source of data. Ots et al. [1] report that in the solid heat carrier (SHC) process OSRG accounts for about 18% of the energy output that is produced from oil shale.

According to energy balances made on data provided by Eesti Energia (EE) on their web site (http://www.energia.ee/en/oil/oilandgas/enefit140 Retrieved 17 June 2011) OSRG can even represent more than 18% of the total energy produced from shale. The current production of OSRG from two Enefit-140 units is about 40 MM m^3/yr. The next generation of EE retorts, the Enefit-280, will yield almost twice that amount of OSRG per retort. The Company reports that the Enefit-140 retorts consume about 1 MM tons of oil shale to produce this much OSRG. Using their reported heating value of 47 MJ/m^3 for OSRG and 8.3 MJ/kg of oil shale one can calculate that OSRG represents 23% of the energy fed to the units. Considering heat losses from processing, that would mean that OSRG represents even more than 23% of the total energy products produced by the two retorts.

Given these calculations, one can observe that OSRG represents a considerable energy source from an oil shale retorting project and its effective and efficient utilization can have a significant impact on the total plant and its efficiency.

3. Oil shale retort gas composition

Knowing the composition of OSRG shows that it contains many valuable components. Some of the constituents have a much higher value if they could be segregated and used separately, rather than being consumed as a part of the aggregate OSRG product.

Since both EE and Viru Keemia Grupp (VKG) have retorting processes that are variations of the Galoter process, it is reasonable to expect that the composition of the OSRG from these processes will be somewhat similar to that of the Galoter process.

A typical Galoter OSRG composition is presented in Table 2 [2].

The OSRG from the Galoter process has a heating value of 46 KJ/m^3. The OSRG from the Enefit-140 has a similar heating value which is reported to be 47 KJ/m^3, as noted above. This might have one conclude that the compositions are virtually identical. However, the composition of the OSRG

Table 2. OSRG composition

Component	Composition, vol. %	
CO_2		1.7
H_2S		Traces
C_nH_m		26.3
$\quad$ C_2H_4	12	
$\quad$ C_3H_6	8.9	
$\quad$ C_4H_8	5.4	
O_2		0.8
CO		8.6
H_2		14.5
C_nH_{2n+2}		24.1
$\quad$ CH_4	14.4	
$\quad$ C_2H_6	6.3	
$\quad$ C_3H_8	2.2	
$\quad$ C_4H_{10}	1.2	
N_2		24
		100

from the Enefit-280 differs from that of the Galoter process in some aspects [3]. According to VKG, this also applies to the OSRG from the VKG units. For the purposes of this article these differences are not important. The differences may not even be important when one makes pre-feasibility studies for separating the various components. The most important factor is that all of the constituents are identified, not necessarily their exact concentrations. There will be variations in the OSRG composition even as a commercial plant is operated, either through variations in operating parameters, or some changes in the oil shale that is fed to the system. So, one should not be distracted by attempting to define a precise OSRG composition at this time.

It is notable that at least one source claims that, although the type of process that is used for shale oil production alters the composition of OSRG, the type of oil shale that is fed to a given process may not have as significant an influence on the OSRG composition. Taciuk [4] states that the gas composition is "… remarkably similar for different oil shales." He tested various oil shales from Jordan, Utah, Fushun (China), Australia and Estonia under similar processing conditions. The OSRG produced was quite similar for all tested oil shales. This is not a generally accepted conclusion since Sieger [3] concluded that the composition of the OSRG produced from different oil shales is different due to the high influence of the solid heat carrier. The amount of such variability has not been defined so it may, or may not, have an impact on the design of a commercial OSRG separation plant.

4. Component separation options

Many processes are available for separating gaseous components from a mixture. Only physical separation processes are considered for component segregation here since any chemical modifications would alter the composition of OSRG. Chemical processes will be considered in the Utilization options section below.

The categories of gas separation processes are presented in Table 3.

Table 3. Gaseous component separation processes

A. Compression
B. Membrane
C. Adsorption
D. Absorption
E. Distillation
F. Expansion and refrigeration processes

More detail regarding each of these options is provided in the following sections.

4.1. Compression

Some of the OSRG components can be separated from the rest of the mixture by simple compression. This takes advantage of the varying boiling points and vapor pressures for each of the components. The easiest to separate out will be the heaviest HCs: butane, butylene, propane and propylene. Butane and butylene will become liquids at pressures less than 500 kPa and remain such up to temperatures of 38 $^{\circ}$C (100 $^{\circ}$F). Propane and propylene require higher pressures: 1400 and 1800 kPa, respectively. These are again the pressures that are needed in order to maintain a liquid phase for these components for temperatures up to 38 $^{\circ}$C (100 $^{\circ}$F).

4.2. Membrane

Another simple approach to gas separation is to use membranes that allow the smaller molecule to pass through a membrane and be separated from larger molecules that cannot pass through the membrane. In some cases, such as for high temperature hydrogen membranes, there are even chemical reactions that take place during the separation, but the basic principle still holds that the larger molecules cannot pass through the membrane.

Hydrogen membranes have received considerable study due to the emphasis to consider using hydrogen as an energy delivery mode. The research has been focused on membranes made of metals, molecular sieve carbons, zeolites, and ceramics. The metallic membranes are sensitive to some inorganic gases like carbon monoxide and hydrogen sulfide. OSRG could have significant amounts of H_2S and CO so these constituents need to be considered during the hydrogen membrane design. The metallic membranes

also require a higher pressure differential since the flux through those membranes is proportional to the square root of the pressure differential across the membrane whereas the flux in non-metallic membranes is directly proportional to the differential pressure. A significant advantage for metallic membranes is that they can yield a very high purity product, > 99.9% pure hydrogen. An overview of hydrogen separation membranes is provided in an article by Adhikari and Sandun [5].

Membranes can be considered for other separations from OSRG as well. Such separations are generally based on the simple concept that the gaseous molecules have differing diameters. Table 4 provides a list of diameters for some of the gases in OSRG. As is noted for ethylene in Table 4 [6, 7], all the heavier HCs in OSRG have diameters larger than 4 Å. That will make any membrane separation of the smaller components from the heavier HCs listed in Table 4 quite straightforward.

Table 4. Molecular diameters

Gas	Diameter, Å
CO_2	3.9
CO	3.7
C_2H_4	4.2
H_2	3.0
CH_4	3.8
N_2	3.8
O_2	3.5

4.3. Adsorption

Having gas adsorb onto the surfaces of adsorbents is a very common way of separating constituents from a mixture of gases. Various gas components are adsorbed onto the solid surfaces in different proportions than they exist in the gas phase. By cycling the pressure administered to the adsorbent and using various process "rinse" steps, one can selectively remove components from a mixed gas stream. The use of pressure cycling leads to the process name, pressure swing adsorption (PSA). In CMM projects the PSA process has been applied successfully on a commercial basis to remove nitrogen from the CMM mixed gas that is produced from a coal mining operation. That leaves a pipeline quality stream of methane that can be delivered to a conventional natural gas pipeline system. PSA processes should be useful with OSRG as well.

4.4. Absorption

4.4.1. Lean oil absorption

Absorption is a physical process where all gases in a mixture make contact with a liquid and certain gaseous components go into the liquid solution and are separated from the non-dissolving gas components. In the natural gas

industry, heavy HC liquids such as nonane, decane and heavier are used to extract light HCs from non-HCs in a gas stream. The process is operated at ambient temperatures if only heavy HCs are to be extracted from the gas phase. Adding refrigeration to the system allows for extraction of lighter HCs such as ethane and propane.

4.4.2. Carbon dioxide removal

Many of the gas processing steps will be adversely affected by the existence of carbon dioxide (CO_2). As an example, there is the risk that the CO_2 could form solids in refrigeration processes described below and those solids could build up and plug the piping in the process equipment.

The most common method of CO_2 removal is through the use of amines[1] in a scrubbing system. The amine solvent absorbs CO_2, along with any other acid gases. CO_2 is then vented into the atmosphere as it is stripped from the amine before the latter is sent back to the scrubbing column. The amine systems will also remove any hydrogen sulfide (H_2S) that is in the gas. Even though OSRG only has trace amounts of H_2S, it is still advantageous to have it removed, especially if it happens to occur in larger amounts.

4.4.3. Dehydration

Like CO_2, water can have a deleterious effect on various gas processing steps. It is important to remove water before OSRG is delivered to a process. This can easily be accomplished by using a glycol tower. Water dissolves in ethylene glycol and is driven off in a side boiler after which ethylene glycol is recycled to the absorption column. Triethylene glycol (TEG) is the most common absorbent for such systems.

4.4.4. Solvent absorption

New research into novel solvents offers still other possibilities for separating the individual components in OSRG. A mixture of ethane/ethylene could be separated by a solvent tested by Reine and Eldridge [8]. The CuCl/aniline/n-methyl pyrrolidone solvent was able to handle more gas than had been expected from solubility values and the selectivity between ethane and ethylene was sufficient to consider this solvent for an absorption separation system.

4.5. Distillation

As noted in the Compression section above, some of the components in OSRG will become liquids if placed under enough pressure. That would allow for separation of the components in a liquid phase by distillation. A good example of such a separation is described by Mauhar et al. [9]. It is

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[1] MEA – monoethanolamine, DEA – diethanolamine, DGA – diglycolamine, MDEA – methyldiethanolamine.

quite a suitable example since the feed stream for their system is not too dissimilar from OSRG. Their gas stream consisted of a "…mixture of propylene, propane, methane, ethylene, the C-4 fraction, hexane, water, hydrogen, N_2, and some other components from a petrochemical plant." Their desired product was a high-purity (99.2%) propylene stream. Even minor amounts of other gases could poison the catalyst that was being used to produce polypropylene from the propylene feed stream. They undertook both experimental and computer-simulations of the separation. They reported on the distillation tower design requirements along with the operating parameters that would be required to produce the desired product.

Given the similarity between the feed stream in the Mauhar example and OSRG, it is evident that one can design distillation columns that can perform the separations that would be necessary to produce individual components, like butylene or propylene or ethylene or butane or propane, from the raw OSRG stream.

4.6. Expansion and refrigeration processes

There are numerous cold-temperature processes that can be used for separating gas mixtures. The simplest such process employs a Joule-Thompson (JT) valve to cool down the gas stream. The individual components in the cold gas can subsequently be separated in a fractionation column. The simplicity of the JT comes from the fact that there are no moving parts in the separation process and the JT valve can handle a broad range of flows. The negative aspect is that the JT valve is less energy efficient than other alternatives.

The more common systems for ethane recovery are now based on turbo-expanders (TE). This process uses the pressure of the feed gas to run a turbine (T) that drops the pressure quickly and generates the needed refrigeration of the feed gas. Some modifications of the TE process have been implemented in order to address various shortcomings, such as limited ethane recovery and operation near the critical point of the gas, which makes the operation unstable.

Regardless of the process, if there is enough cooling imparted to the feed gas stream, then the various components can be separated into individual products by the use of fractionation or distillation columns. It comes down to an economic analysis of whether the refrigeration processing can be justified.

Cryogenic distillation is the ultimate cold-gas approach, where the components are transformed into a liquid phase. This has been shown to be commercially viable at coal mine methane (CMM) and natural gas projects in the USA. The cryogenic system is used to separate methane from non-HC gases so as to produce a higher quality gas product.

The cryogenic approach allows one to consider the option of producing a liquefied natural gas (LNG) product. In that case, methane would be kept in a liquid form and not vaporized to a gas like the other products. LNG makes methane readily transportable and does not make marketing of that product reliant on pipelines or pressurized tank delivery systems.

5. Utilization options

Considering the outline of CMM utilization options as a guideline for possible uses of OSRG, one can consider each of those alternatives for OSRG utilization along with some other possibilities that are tailored specifically for OSRG. The uses for CMM listed in Table 1 can be used as a guide for OSRG applications. A modified list, which includes applications specifically for OSRG, is as follows:

- Electricity generation
  - Central station power plant
  - Internal combustion engines
  - Gas turbines
  - Fuel cells
- Processing of OSRG to provide direct-use components
  - Gas dehydration and compression
  - Carbon dioxide removal with amine scrubbing systems
  - Pressure swing adsorption (PSA) for nitrogen rejection
  - Products – hydrogen, ethylene, propylene, others
- Combustion of OSRG in thermal energy applications
  - Residential/Commercial
    - District heating
    - Direct use in building(s)
  - Industrial
- Compression of OSRG to produce compressed natural gas (CNG)
- Conversion of OSRG to liquefied natural gas (LNG)
- Systematized use of OSRG

5.1. Electricity generation

5.1.1. Central station power plant

This is the easiest approach to OSRG utilization and is the one currently applied by EE. One can simply deliver the entire OSRG product stream to a central station power plant that is run with oil shale as the primary fuel. As noted above, the OSRG output from an Enerfit-280 unit would provide fuel for about 40 MW of generation at a central station. There are advantages to the central station plant for using such a fuel. Since it is a gas, there will be no boiler tube corrosion associated with this fuel. And there will be less environmental impact since there is no ash, and the NO_x emissions will be lower. The latter statement assumes that this gas will have the same impact as natural gas that is co-fired in a coal fired power plant.

5.1.2. Internal combustion engines

There are several sizes of internal combustion (IC) engines that are used for power generation. These range from industrial scale engines that have a

several MW output capacity to micro-combined heat and power (micro-CHP) units that might have capacities of only a few hundred Watts. There are intermediate size engines that have a nominal capacity of about 100 kW. All of these have their own specific market applications.

5.1.3. Gas turbines

Gas turbines (GT) are a common prime mover for electric power generators. The main disadvantage to using a GT in OSRG applications is the same as that experienced with GT in CMM projects. Both gaseous fuels, CMM and OSRG, are produced at nominally ambient pressures. Since fuel delivered to a GT must be supplied at pressures of 1000 kPa or greater, one would have to compress OSRG before it can be used as a fuel in the GT. Providing electricity to the compressors would be a parasitic load on the generator, or some of the OSRG would have to be used as fuel for compression if the compressors were gas-fired.

Fuels such as OSRG can be used in a wide range of gas turbine capacities, from several MW down to 20 kW. The latter are called micro-turbines. The only limitation is the amount of fuel available for the larger units.

5.1.4. Fuel cells

The principal author has had direct experience using CMM as the fuel for a fuel cell. The CMM was low quality and only had a heating value of about 15 MJ/m^3. A 200 kW fuel cell was successfully operated with this dilute fuel. As with IC engines and gas turbines, fuel cells are now available in a broad range of sizes. In addition to units that have several hundreds of kW in capacity, there are units that are micro-CHP and have a capacity as little as 1 kW. The micro-CHP units can also be up to 10 kW in size.

OSRG has a distinct advantage over CMM, or even natural gas, if one wanted to consider using it in fuel cells. All fuel cells currently available on a commercial basis can only use hydrogen as the direct fuel. In order to allow for the use of natural gas one must first convert it to hydrogen in a reforming unit. All fuel cells that use natural gas have to have a reforming system that chemically converts the methane and other HCs in the natural gas to hydrogen. Since OSRG has hydrogen in it already, one can consider extracting the hydrogen from OSRG and supplying that fuel directly to the fuel cell without the need for a reforming unit. As noted above, there are membranes that can be used to accomplish this separation.

5.2. Processing of OSRG to provide direct-use components

Since the raw OSRG consists of many constituents, there are numerous products that can be made from this mixed gas. These segregated gases can be used as fuels in various applications, or they might be used for other direct uses, such as chemical feedstocks.

5.2.1. Gas dehydration and compression

The first step in using OSRG is to remove the water vapor from OSRG (dehydration). As noted above, the typical dehydration system is based on TEG. Before the gas is processed in the TEG unit, it must be compressed so the gas-liquid equilibriums are within an effective range and the equipment sizes are reasonable. Depending on the pressure at which the TEG unit is operated, the compression step will already start removing some components from OSRG. An operating pressure of 700 kPa is a minimum for such units. At that pressure butane and butylene will be compressed to a liquid phase before OSRG is delivered to the TEG unit. One may choose to operate the dehydration unit at a higher pressure, in which case propane and propylene will also be compressed to a liquid. Given the proper design for the compression step(s), one can use this as a method for producing the heavier HCs from OSRG as separate products.

5.2.2. Carbon dioxide removal with amine scrubbing systems

As with water, CO_2 needs to be removed before additional processing of the OSRG gas stream can be considered. CO_2 can be a particular problem if one processes the gas in a cryogenic system. It would become a solid at low temperatures and end up clogging the piping in a cryogenic plant. The advantage to the CO_2 removal is that the traces of H_2S that occur in the gas will also be removed so that the use of the remaining gas is more environmentally friendly.

5.2.3. Pressure swing adsorption (PSA) for nitrogen rejection

If heavier HCs are removed from OSRG, as suggested above, one is left with methane and ethane as the remaining HCs in the gas. If one is interested in concentrating these HCs, then pressure swing adsorption could be used to reject the nitrogen that is left with methane and ethane.

5.2.4. Products – hydrogen, ethylene, propylene, others

The objective of all of the gas processing and separations described above (and in the Component separation options section of this paper) is to provide products that have significantly more value as pure components rather than to use the mixed gas stream as a simple fuel. One can also consider supplying some specific gas mixtures to various markets. As an example, there is a healthy LPG market in the USA where a mixture of propane and butane is supplied in various sized cylinders for residential and commercial use. It is quite possible that this market could also handle a more complex mixture which adds butylene and propylene to the normal mix for LPG.

   The value of the products delivered to the LPG market provides a perfect example of the relative value between using the total OSRG gas stream for central station power generation as compared to individual product sales, where the product might be a simpler mixture than the total OSRG gas. The

US Energy Information Agency (EIA) tracks the prices of various forms of energy in the USA. Their data show that central station power plants fueled with coal paid an average of US$2.26/MMBtu (US$9/MM kCal or 0.21US$/MJ) for the coal delivered to the power plants during 2010. Less than a 3% increase is expected through 2012. In comparison, wholesale (sales for resale) prices for LPG were US$1.41/gal (0.37 US$/liter) in February 2011. That is equal to US$15.27/MMBtu (US$61/MMkCal or US$1.42/MJ), a value that is nearly seven (7) times the value that one would receive if the fuel were sold as an offset for coal. And, propane prices parallel prices for crude oil, so any spike in oil prices would correspondingly be seen in the wholesale propane price.

It is beyond the scope of this article to consider the costs associated with the recovering of propane and butane from the raw OSRG stream. That type of analysis will be performed in a subsequent paper covering the economics of OSRG processing, but it is hard to imagine that one could not make a significant rate of return for installing simple compressors and air coolers to extract C_3s and C_4s from OSRG when they have such an added value by themselves rather than leaving them mixed with other components.

Hydrogen can have a valuable use as a feed for fuel cells, which require hydrogen rather than HCs as the fuel. Hydrogen could have other uses as well. It could be applied to hydrotreating raw shale oil to raise it to a higher quality product. Enefit has even proposed reforming the entire OSRG gas stream to provide the necessary hydrogen for such hydrotreating [10]. That is a definite possible utilization for the total OSRG gas stream. However, depending on the amount of hydrogen that may be required, one might be able to avoid the requirement for building a partial oxidation unit to implement the reforming step and simply use hydrogen that could be extracted from the OSRG.

The butane/butylene, propane/propylene and ethane/ethylene pairs can all be separated into their individual components by distillation as described in the Component separation options section of this paper. Ethylene could then be sold to chemical plants that produce high density polyethylene (HDPE), linear low density polyethylene (LLDPE), low density polyethylene (LDPE) or other products that use ethylene as a feedstock, such as ethylene oxide, ethylene dichloride or ethyl benzene.

As an example of the enhanced value that these products have when used as chemical feedstocks, as opposed to fuel in a power plant, one can consider propylene (propene). Propene is the second largest chemical feedstock in the world, after ethylene [11].

There are three commercial grades of propylene:
- 95–100% polymer grade
- 90–99.8% chemical grade
- 50–70% refinery grade

USA propylene contracts for May 2011 were as follows, based on ICIS Chemical Business (www.icis.com) data:

polymer-grade propylene (PGP) – 97.00 US¢/pound (lb) (US$2.13/kg)
chemical-grade propylene (CGP) – 95.50 US¢/pound (lb) (US$2.10/kg)
refinery-grade propylene (RGP) – 91.00–93.50 US¢/pound (lb) (US$2.06/kg)

The RGP had jumped dramatically from prices of 79.50 US¢/lb (US$1.75/kg) as recently as four weeks before the beginning of May.

Considering that an Enefit-280 retort will produce 75 MM m^3 of OSRG per year and that up to 9% of OSRG is propylene, one can calculate that each such retort will yield up to US$25 MM worth of propylene each year. This is the value if propylene is priced at US$0.90 per pound (lb) (US$1.98/kg). Based on information from EE they will produce about 57,000 barrels (Bbl) per day (6.7 million liters/day) of shale oil at their new project in Utah, USA. That will require about ten (10) of the Enefit-280 retorts, if that is the size units that will be installed. So the Enefit Utah project will produce up to US$250 MM worth of propylene per year. Not all of that can be recovered, even using good distillation design and operation, but this shows the order of magnitude of the value for the propylene that will be produced.

In comparison to the US$250 MM per year value for propylene as a chemical feedstock, it would only have a value of about US$12 MM if it were used as a fuel to offset coal delivered to a central station power plant in the USA. That is a difference in value of 20 times!

Based on data from EE, the project announced by Enefit for Jordan will call for the equivalent of nearly seven (7) Enefit-280 retorts to produce 36,000 BPD (4.2 million liters per day) of shale oil. The OSRG from that project would be worth about US$175 MM per year if propylene would have the same value in Jordan as it does in the USA.

The comparisons for ethylene and butylene are not quite as dramatic. But those products are still an order of magnitude more valuable if they are used as chemical feedstocks than as fuel in a central station power plant.

The plants in the USA and Jordan are still in planning phases. Considering only retorts that are already in existence, the value of propylene is already significant. EE reports that it is currently producing 40 MM m^3 of OSRG at its shale-oil plant in Estonia using two Enefit-140 retorts. And that all of the OSRG is currently delivered to the adjacent power plant and burned as fuel. Using the USA values for propylene it can be shown that burning the currently available propylene in the power plant makes it worth less than US$700,000 per year. If its value as a chemical feedstock is the same as in the USA, then the currently produced propylene would be worth about US$13 million per year. That is enough to justify an investment of nearly US$50 million to recover propylene and make a decent rate of return on the investment.

5.3. Combustion of OSRG in thermal energy applications

Even though the OSRG components have a higher value as chemical feed-stocks, it will still be desirable to consider the use of OSRG and some of its constituents in other applications. That applies especially to the lighter HCs like methane and ethane. Those will be left in the gas phase even if OSRG is compressed and processed for heavy HC removal. Either the total gas stream or the light ends of OSRG will have potential application in residential, commercial and industrial sectors.

5.3.1. Residential/commercial

One can use OSRG as a fuel in district heating applications, especially in countries like Estonia where such systems are prevalent. OSRG can be delivered to the boilers that supply the hot water for district heating. The authors will be writing a supplemental article to describe this option in more detail at a future time.

5.3.2. Direct use in building(s)

There are also ways to use OSRG, or its components, in individual buildings as well. There have been great strides in providing combined heat and power (CHP) units in Japan and Europe. In Denmark, CHP provides a significant amount of the electricity that is produced in that country. Many of those units are smaller than 10 kW, making them suitable for individual building application.

The light HCs from OSRG can also be used to fuel other types of micro-CHP units. The external combustion (Stirling) engine and internal combustion (Rankine) engine prime movers could be fueled directly with methane and other light HCs from OSRG.

5.3.3. Industrial

Any part, or all, of the OSRG gas stream can be used for providing a clean fuel for industrial applications. The only problem is that such uses would be as a fuel and would have the same financial limitations as using OSRG in central station power plants, i.e. the price for the delivered OSRG product(s) would be much lower than if the products were sold to more focused markets.

5.4. Compression of OSRG to produce compressed natural gas (CNG)

The objective for compressing OSRG into the form of a compressed natural gas (CNG) would be to make it available as a fuel for the transportation sector. This provides a definite opportunity to sell the product(s) into a market that yields a much higher price than selling OSRG into the power generation or thermal use markets. Recent wholesale prices for gasoline in

the USA have been about US$3.00 per gallon (US$ 0.79/liter)[2]. This is equivalent to about US$24/MMBtu (US$95/MMkCal or 2.27US$/MJ). As noted above, US coal fired power plants receive coal at an average cost of about US$2.26/MMBtu (US$9/MM kCal or 0.21US$/MJ) for the coal delivered to the power plants. Even in countries that import a lot of coal, like China, who face significant shipping charges, the price of the coal delivered to their ports is still less than US$5/MMBtu (US$20/MM kCal or 0.5US$/MJ). That provides a 5 to 10 time price advantage for selling a fuel into the transportation market as compared to the central station power generation sector. This comparison only considers the price of the gasoline as a commodity. It does not include the taxes since those taxes may also apply to CNG. If the taxes on CNG are lower, then the price differential between gasoline and CNG will be even greater.

The heavy HCs will leave the OSRG mixture, but ethylene will remain a gas even at CNG pressures as long as the temperature is above 10 $^{\circ}$C (the critical temperature for that gas). The critical temperature for ethane is 32 $^{\circ}$C, so it will remain a gas no matter what pressure is applied as long as the temperature is above that level. These temperatures will be exceeded during the compression phases so only after the gas cools will there be a chance that they drop out as liquids. There may be some value to strategic planning for filling the CNG cylinders, to keep ethane and ethylene in the gas phase.

There is no issue with ethane being in the gas mixture for CNG since it is a normal component in natural gas. The occurrence of ethylene in a motor fuel might have been questioned until it was discovered that research has been performed showing that ethylene is a totally acceptable fuel for automobile engines [12]. The report covering that research states that "From a series of laboratory work, conversion kit development work and on-road trials performed on the vehicle …

- Ethylene is noted to be comparable, if not better, to [sic] gasoline in terms of performance and emission (higher NO_x but lower CO).
- Its strong point is its fuel economy – This on-road vehicle trial program has indicated that one kg of ethylene is able to cover a distance of 26.3 km on the highway and 26.8 km on the federal road for one kg of the fuel used [sic]. In contrast, the vehicle running on similar route only managed to clock 17.0 km for one kg of the gasoline fuel consumed.
- Less engine vibration which indicates that combustion is smooth and free of sporadic engine knock".

It is not absolutely necessary to remove nitrogen from OSRG. It can be considered as a simple diluent that does not impart any negative character-

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[2] Gasoline is such a common worldwide commodity, and it is so easily transported at a cost that is low relative to the product price, that its wholesale price is virtually the same all around the globe. The only major difference in gasoline prices to the consumer in various countries is the tax added to the commodity price.

istics to the fuel for IC engine use. It may even have a slight benefit as its occurrence will slightly lower the combustion temperature in the engine, leading to slightly less NO_x emissions.

5.5. Conversion of OSRG to liquefied natural gas (LNG)

Converting OSRG to the equivalent of liquefied natural gas (LNG) is similar to the CNG option, but it takes the components to a liquid form rather than leaving it as a highly compressed gas. One uses cryogenics to produce the liquid. In the case of OSRG, there may be an advantage to considering the liquefaction of more than just the light HCs like methane and ethane. If some of the other components are made into liquids, the subsequent separations by distillation may be easier than other gas separation options such as lean oil absorption or pressure swing adsorption. Comparisons of such options are beyond the scope of this article, and will require local market price information in order to allow for comparison of the various options.

Since methane and other components have a much higher energy density when they are liquid, as compared to a highly compressed gas, the geographic boundaries of the potential markets for LNG are considerably larger than for CNG. Defining the exact geographic dimension of these relative markets will again require knowledge regarding the site-specific prices for various commodities.

5.6. Systematized use of OSRG

Many options have been described above for utilization of OSRG and its various components. Since there are so many constituents in OSRG, there are almost too many combinations and permutations of products that can be produced from OSRG. The challenge is to develop an "optimal" system for using OSRG so that there is a maximum revenue and/or maximum rate of return on investments that are generated as the various individual and mixed products are produced. Developing a systematized utilization strategy requires that one make economic assessments of the various use options and then compare a matrix of markets, products, costs and revenues. Rather than undertaking such a daunting task, one can take a more plausible approach. A reasonable processing scheme can be developed by considering the physical characteristics of the individual components and apply the various processing and utilization options described above in a logical manner.

One possible scheme is presented in Fig. 1. Even in this scheme, some of the products have more than one market into which they can be supplied. The general goal is to extract most of the components as individual compounds so that they can assume their greatest market value and not be de-valued by remaining in mixtures with other components that have less value. The first step is to compress OSRG so the heavier HCs (C_3s and C_4s) drop out as liquids. The simplest product from this compression would a "LPG-equivalent" fuel. That is already a higher value product than having the total
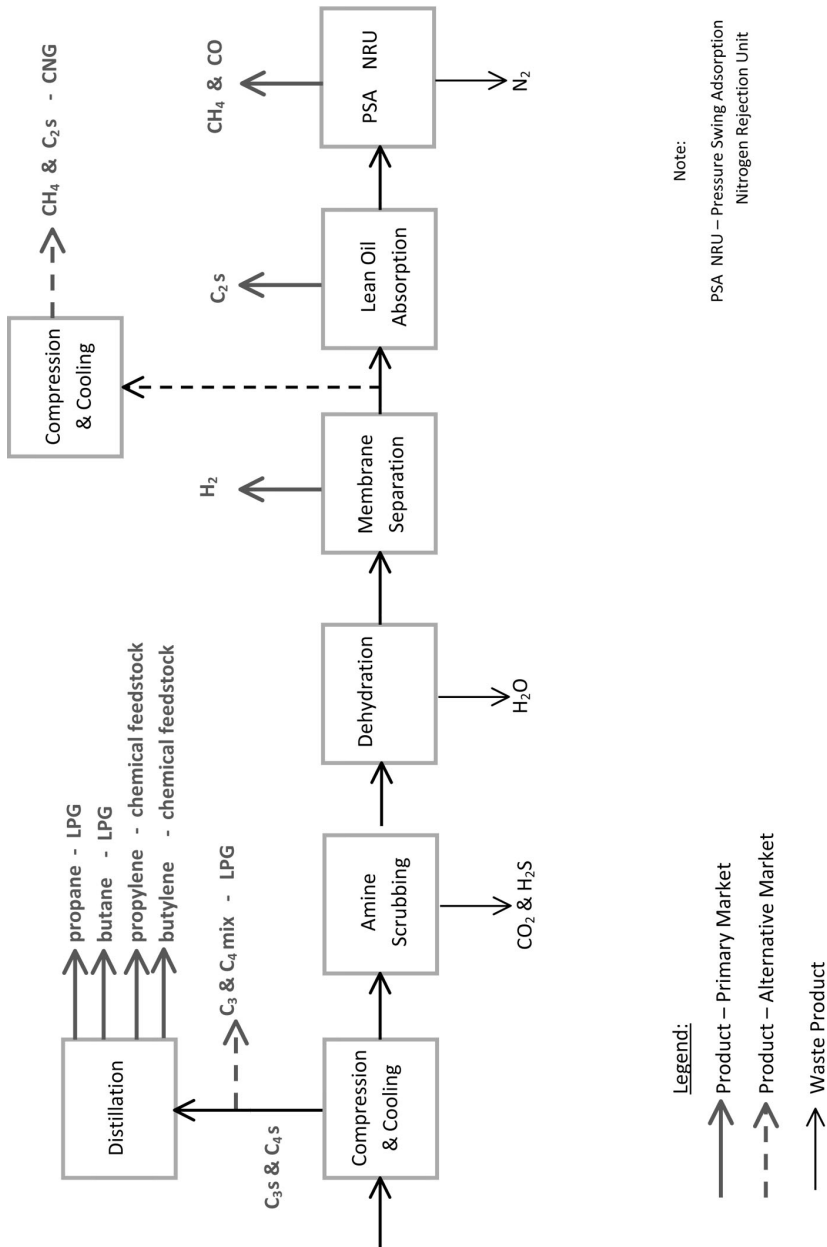
Fig. 1. Systematized OSRG utilization scheme.

OSRG burned as a central station fuel. These heavier HCs have an even higher end value if they are segregated further. As noted above, the propylene delivered as a feedstock to a chemical plant will have 20 times the value than if it were burned for power plant fuel. Figure 1 shows that propylene and other heavy HCs can be separated from each other by using distillation after they are compressed to a liquid.

Amine scrubbing, to remove CO_2 and H_2S, and dehydration are the next steps after heavy HC segregation. After that, hydrogen can be removed from the remaining OSRG stream by using an appropriate membrane. Hydrogen can be used as a fuel for fuel cells, or in a hydrotreater to upgrade the produced shale oil, or it could be sold for industrial use.

The remaining methane and C_2s could be compressed to supply CNG for vehicle fuel. Since the local CNG market may not be large enough to absorb the amounts of CNG that can be produced from a commercial scale oil shale processing plant, one is more likely to continue separating even the light HCs, i.e. methane, ethane and ethylene. A lean oil absorption system can accomplish this. Then finally, methane can be purified with a pressure swing adsorption nitrogen rejection unit (PSA NRU).

There are certainly countless other systematized schemes for delivering a variety of products from a raw OSRG stream. Any scheme will need to be assessed in light of the local market sizes and prices.

6. Conclusions

Calculations show that OSRG constitutes a significant amount of the energy produced from oil shale retorts. In the case of the Galoter-based process that has been implemented by EE, OSRG represents about ¼ of the energy content of the shale that is delivered to a processing plant. A single Enefit-280 retort, which is the latest retort model that is currently under development by EE, would yield enough OSRG for about 40 MW of generating capacity. This assumes that all the OSRG is burned in a power generating facility. However, the main conclusion herein is that OSRG has much more value when used in applications other than power generation.

OSRG is comprised of many interesting and potentially valuable components. These range from simple fuel compounds like methane to more exotic compounds such as butylene, propylene, and ethylene. The latter compounds all have a significant value as chemical feedstocks. About half of the gas is comprised of hydrocarbons (HCs) with the remainder being hydrogen, carbon dioxide and monoxide, oxygen and nitrogen.

The compounds in OSRG can be segregated from each other with any number of gas separation technologies. The processes can be used to yield various products that individually, or in simpler mixtures, have much higher values than the OSRG raw gas.

Given the numerous options for processing and using OSRG, there are almost too many choices for delivering various products from OSRG. This article includes one possible scheme for the systematic processing of OSRG. This calls for the sequential removal and processing of OSRG to produce up to nine (9) different products. One needs to define the prices for the various products that can be produced from OSRG and then an assessment can be made of the economic viability of producing the various products. Establishing the prices for the various products is beyond the scope of this article. The current work describes a review of the technological options and describes the economic potential. Making an economic assessment of various processing options will require the identification of the location for a potential application since the relative economics of various energy forms vary from country to country, and even regionally within a given country.

The desirability of making economic analyses for disaggregating OSRG is confirmed. Even one single component – propylene – has been shown to have a potential market value of up to US$250 million (MM) per year if produced from oil shale retorts on the scale that EE is proposing to develop in Utah, USA. Even the current production of OSRG in Estonia could yield products that would generate revenues in the tens of millions of dollars per year if OSRG were to be sold as separate products rather than used as a fuel in the central station power plant.

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