An Assessment of the Energy Return on Investment (EROI) of Oil Shale

FINAL REPORT

Prepared for

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June 2010

Executive Summary

Concern over limited oil resources and record energy prices has rekindled interest in the development of the vast oil shale resources of the Western United States. We reviewed the existing literature on the energy return on investment (EROI) for oil shale. EROI is the ratio of energy delivered to energy costs. The most reliable studies suggest that the EROI for oil shale falls between 1:1 and 2:1 when self-energy is counted as a cost. Self-energy is energy released by the oil shale conversion process that is used to power that operation.

This places the EROI for oil shale considerably below the EROI of about 20:1 for conventional crude oil at the wellhead. This conclusion holds for both the crude product and refined fuel stages of processing. Even in its depleted state—smaller and deeper fields, depleted natural drive mechanisms, etc.—conventional crude oil generates a significantly larger energy surplus than oil shale. This is not a surprising result considering the natural resource exploited in each process. The kerogen in oil shale is solid organic material that has not been subject to the temperature, pressure, and other geologic conditions required to convert it to liquid form. In effect, humans must supply the additional energy required to "upgrade" the oil shale resource to the functional equivalent of conventional crude oil. The extra effort carries a large energy penalty, producing a much lower EROI for oil shale.

Firm conclusions regarding the EROI are difficult to establish for a variety of reasons. There are very few reliable studies of current oil shale operations; many studies use a poor or undocumented methodology, and report what could be best described as "ballpark" estimates. Some studies exclude important categories of energy inputs that generate inflated estimates of the EROI for oil shale. This is what is known as the system boundary problem in EROI assessments, namely, deciding what inputs and outputs to include. In addition, much of the discussion regarding the EROI for oil shale should be regarded as preliminary or speculative because of the very small number of operating facilities that can be assessed. We do not have a large "sample size" of operations from which to draw robust conclusions.

The considerable uncertainty surrounding the technological characterization, resource characterization, and choice of the system boundary for oil shale operations suggests that oil shale cannot yet be "certified" as a clear net energy producer if one includes internal energy as an energy cost. Alternatively, one could exclude internal energy and count only purchased energy as input. The EROI calculated using this perspective is in the range of 2 to 16.

The low EROI for oil shale is closely connected to a significant release of greenhouse gases. The large quantities of energy needed to process oil shale, combined with the thermochemistry of the retorting process, produce considerable carbon dioxide and other greenhouse gas emissions. Oil shale unambiguously emits more greenhouse gases than conventional liquid fuels from crude oil feedstocks by a factor of 1.2 to 1.75

For every barrel of oil produced in an oil shale operation, between 1 and 3 barrels of water are required, confirming the conventional wisdom that this technology places significant demand on freshwater supplies. Pumping the large volumes of water required for industrial-scale oil shale

operations would be yet another energy investment negatively affecting oil shale's already thin EROI.

Introduction

The shale deposits in the western United States have long been known to contain kerogen, a combination of chemical compounds that can be converted into synthetic petroleum. A large portion of these resources reside on Federal lands, and in the early 20th century were set aside as the Naval Petroleum and Oil Shale Reserves. The federal government divested itself of some oil shale resources in the 1980s and 1990s, transferring ownership to the Northern Ute Indian Tribe or private ownership, while other shale-bearing lands were reassigned to the jurisdiction of the Department of the Interior

Converting kerogen from its solid form into synthetic petroleum is accomplished through one of two primary processes: (1) surface retorting ("conventional"), where the shale is mined, crushed, and then heated to a high temperature in oven-like retorts to extract the kerogen, and (2) *in situ* extraction, where energy is used to heat the shale while it is still underground, converting kerogen into liquid form so it can be pumped out, and refined into petroleum products. Both processes require a considerable amount of direct energy inputs, as well as water, capital and material inputs.

World production of oil from shale was about 684,000 tons in 2005 (WEC 2007), equivalent to about 5 million barrels, or 13,700 barrels per day. By way of comparison, global crude oil production in 2005 averaged 15.2 million barrels per day. A considerable amount of oil shale is also used as a fuel rather than as a feedstock. Estonia, which has for decades led the world in the production of oil shale, mined 14.6 million tons in 2005. Of this, 10.9 million tons of shale rock was burned directly like coal for electricity generation.

Interest in oil shale has waxed and waned. During the oil crises of the 1970s, the U.S. Government funded efforts to develop liquid fuels from oil shale. When oil prices dropped in the 1980s, projects were abandoned and companies saw their investments become worthless. Oil prices remained low most of the 1990s. As oil prices began to rise again in the 2000s, some energy companies expressed a modest level of renewed interest in the resource. Two barometers of interest in oil shale—the number of patents filed and the number of publications on the subject—illustrate this history (Figure 1).
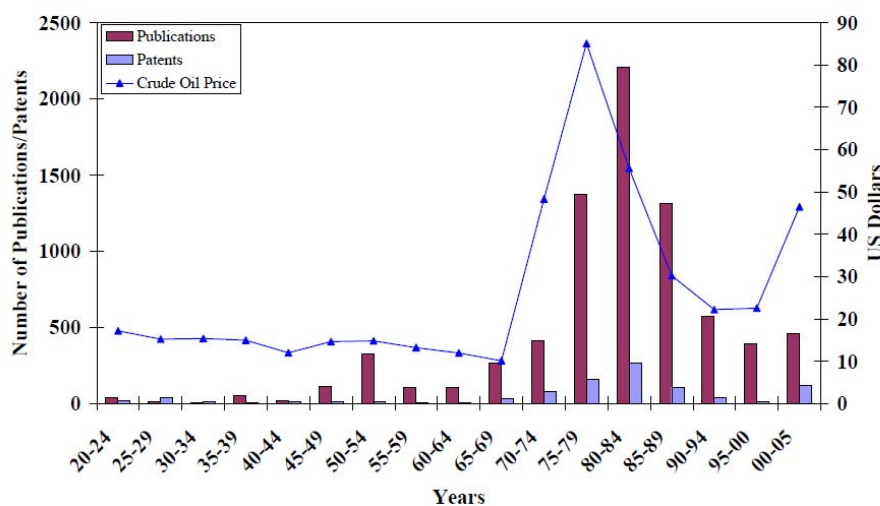
Figure 1. Oil Shale R&D (Source: Smith *et al.*, 2006)

The Energy Policy Act of 2005 included a number of provisions related to the development of oil shale. Among these, the Department of the Interior's Bureau of Land Management (BLM) was to begin leasing its oil shale properties for research. BLM requested proposals in 2005. Winning applicants received leases to develop oil shale research and development projects on BLM properties in the Western United States; the initial leases were for 640 acres each, with options to expand if the sites and processes proved commercially viable. A 2007 report from the U.S. Department of Energy's (DOE) Office of Petroleum Reserves, Office of Naval Petroleum and Oil Shale Reserves, provides an overview of 27 companies that are major participants in the U.S. oil shale industry, including many of those who had submitted applications through this process. The 2007 report illustrates the fairly limited experience in actual development of oil from shale resources.

The Energy Policy Act also provided for the creation of a Strategic Unconventional Fuels Task Force. In 2007 this Task Force produced a report on the technological and economic aspects of oil shale production, but the report did not contain any specific information on the EROI for oil shale.

Energy Return on Investment (EROI) Methodology

One technique for evaluating energy systems is net energy analysis, which seeks to compare the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form. Figure 2 depicts a hypothetical energy system and the types of energy inputs (energy costs) and energy outputs (energy production) associated with that system. Figure 2 could refer to a single oil well or coal mine, a nuclear power plant, a wind farm, or an oil shale facility. The magnitude and timing of the energy production and energy costs are not intended to represent any particular energy system.

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Net energy analysis seeks to assess the direct and indirect energy required to produce a unit of energy. In reference to Figure 2, net energy analysis attempts to quantify all the energy produced and all the energy costs. Energy costs are the sum of direct and indirect energy costs. **Direct energy** is the fuel or electricity used directly in the extraction or generation of a unit of energy. An example is the natural gas burned in engines that pump oil to the surface. **Indirect energy** is the energy

Figure 2. The energy cost and energy outputs of a hypothetical energy facility.

used elsewhere in the economy to produce the goods and services used to extract or generate energy. An example is the energy used to manufacture the drilling rig used to find oil. The direct and indirect energy use is called **embodied energy**. Both the energy product and the embodied energy can be expressed in common physical units of measurement, such as British thermal units, or Btus.
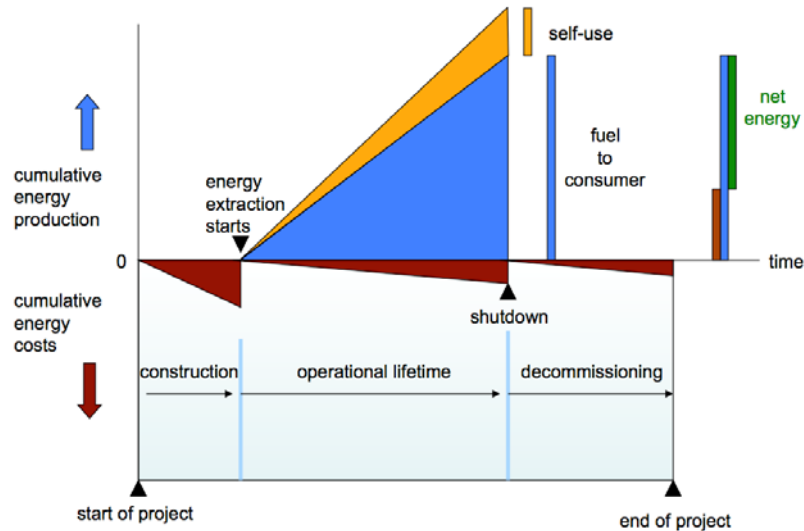
Energy return on investment (EROI) is the ratio of energy produced to energy costs. In the case of oil shale, the EROI entails the comparison of the energy content of the fuel produced to the amount of primary energy used in the manufacture, transport, construction, operation, decommissioning, and other stages of the oil shale facility's life cycle. Comparing cumulative energy requirements with the amount of energy the technology produces over its lifetime yields a simple ratio for energy return on investment (EROI):

EROI = (cumulative fuel produced) / (cumulative primary energy required)

EROI is a dimensionless number. An EROI = 10 means that 10 units of energy are produced for each unit of direct plus indirect energy used in the production process. This is sometimes expressed as "10:1." An EROI = 1 is an absolute cutoff point for an energy source, the point at which as much energy is used to deliver a unit of energy as that unit yields.

Simple in concept, implementation of net energy analysis requires a number of assumptions regarding the treatment of co-products, the calculation of indirect energy inputs, and in boundary conditions (discussed below). A well-known example of a co-product is "distillers grain" from the fermentation of corn to manufacture ethanol fuel. Drymill ethanol production process uses only the starch portion of the corn, which is about 70% of the kernel. All the remaining nutrients - protein, fat, minerals, and vitamins - are concentrated into distillers grain, a valuable feed for

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livestock. Should the analysts credit the energy content of the distillers as an energy output, and thus include it in the numerator of the EROI for ethanol? Energy analysts debate this point.

These differences account for the well-publicized differences on ethanol EROI, with some studies finding an EROI above 1.0 (a positive net energy) and others finding an EROI below 1.0. Many studies pay little heed to these assumptions, producing a lot of confusion when trying to compare results across studies. We return to this issue below in the context of oil shale.

System Boundary

The choice about system boundaries is perhaps the most important decision made in most net energy analyses. This often boils down to what extent indirect energy costs are included in the analysis, and how "self energy use" or "internal energy" is accounted for. Some of the analyses in this survey assess only direct energy costs, such as the energy used to heat the shale or to pump fluids. Other studies also include indirect energy in the form of energy embodied in materials and capita equipment, although they vary in the extent and method with which they calculate such costs.

Self-use or internal energy is an important issue in the assessment of the EROI for oil shale. The Shell method of *in situ* retorting of kerogen produces significant quantities of hydrocarbon (HC) gas, which is burned to generate electricity, which, in turn, is used to provide heat for the oil shale extraction process (Brandt, 2008). Similarly, the Alberta Taciuk Processor (ATP) above-ground oil shale retort method produces HC gases and a solid char substance that are burned as fuels. One could argue that these internally generated fuels should not be counted as an energy costs because they do not have an opportunity cost—society did not give something up to create them, unlike the electricity an oil shale facility purchases from the grid. On the other hand, the char or gas generated by the process literally is used up to perform useful work, and thus is a necessary expenditure of energy to produce the desire liquid fuel. This argues for including the self or internal energy in the calculation of the EROI. As Brandt (2008) notes, the internal energy is essential to account for in the assessment of the greenhouse gas emissions from oil shale.

Energy systems have external costs as well, most notably environmental and human health costs, although these are sometimes more difficult to assess in energy terms. Energy systems also require inputs that are difficult to quantify in energy terms, such as the use of land and water. The oil shale system, for example, requires significant inputs of water and releases solid waste and greenhouse gases. Mulder and Hagens (2008) argue for the use of a multi-criteria EROI in which additional metrics are added to the analysis, such as energy yield per unit land or per unit water consumed.

Figure 3. Oil shale conversion processes.
Source: U.S. Dept. of Energy

Oil Shale Conversion Technology

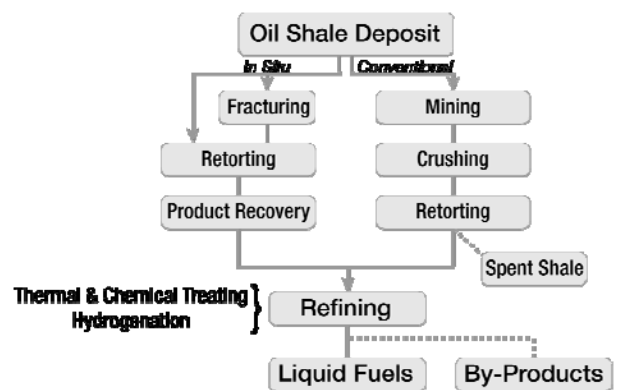The two main processing options for oil shale are surface retorting and *in situ* extraction. In surface

retorting, the shale is mined and brought to the surface, with the material then heated in a retort to extract the compounds that are processed into synthetic crude oil (Figure 3). *In situ* extraction involves heating the material underground and pumping liquids to the surface, where they then undergo further processing. Shell is conducting research on an *in situ* extraction at its Mahogany Research Project, in Rio Blanco County, Colorado. The small number and small scale of existing facilities limits the assessments that can be done. These and a few other projects form the basis of most recent analyses.

Review of Existing Studies

Table 1 summarizes the existing studies that report data on the EROI for oil shale. Note that these studies vary widely in their scope, method of assessment, and the degree to which the veracity of their conclusions can be objectively assessed. We exclude references to the EROI for oil shale that lacked sufficient explanation of assumptions and methods. We also exclude studies prior to 2000 because they reflect technologies and resource assessments that are outdated and/or inaccurate.

We present two estimates of the EROI. $EROI_{elec}$ accounts for the energy used to generate the electricity that is used in the oil shale operation. For the U.S. as a whole, about 3 Btus of fossil energy are used to generate 1 Btu of electricity at fossil fueled steam electric plants at electric utilities. $EROI_{therm}$ ignores the upstream energy costs of electricity generation and simply assigns the electricity used in the oil shale operation its thermal equivalent (1 kilowatt-hour = 3,413 Btu).

Brandt (2008) and (2009)

The most authoritative work on the energy and carbon balance of oil shale is by Brandt (2008, 2009) in which he models current technologies for *in situ* and surface oil shale operations. Brandt's analysis defines two different measures of EROI based on a distinction between what he calls "external energy" and "net energy." The external energy ratio (EER) compares the energy produced to the direct and indirect energy purchased by the oil shale facility. This method excludes the internal or self energy use as an "energy cost."

The net energy ratio (NER) includes purchased energy plus primary energy input from the feedstock resource itself (e.g., coproduced HC gas consumed for electricity generation). That is, the NER approach counts self or internal energy as an energy cost of producing liquid fuel.

Brandt (2008) models the Shell *in situ* conversion process that utilizes electricity to heat the underground shale over a period of 2 years. After heating, the liquefied kerogen can be pumped from the ground using conventional oil production techniques. The Shell process co-produces HC gas that powers a combined-cycle gas turbine, which in turn meets some of the project's electricity needs. External energy is needed for construction, drilling, refining, and product transport, and possibly as supplemental heating power.

The resulting EER ranges from 2.4 - 15.8:1, depending on assumptions. The NER, which takes into account the internal energy consumed is much lower, in the range of 1.2 - 1.6:1.

The resulting greenhouse gas emissions are projected to be about 20-50% higher than those of conventional oil (range of 30.6 to 37.1 grams C per megajoule (MJ) of fuel, compared to 25.3 for the average of gasoline and diesel). These values are comparable to oil sands (29-36) and lower than those of coal-derived liquids (42-49). This analysis does include fugitive greenhouse gas emissions.

Brandt (2009) assesses the surface retorting method for producing liquid fuel from Green River oil shale using the Alberta Taciuk Processor (ATP). The ATP is an above-ground oil shale retort method that combusts the coke or "char" deposited on the shale during retorting to fuel the retorting process. As with the *in situ* method, much of the energy input comes from the shale itself. Mining and refining account for about 1/3 of the overall energy demand; the energy used to operate the retort accounts for most of the remainder. Mining and refining are major external energy demands, and in some cases use external electric power for the retort. Systems that generate on-site using co-produced natural gas will count electricity as internal.

The EER ranges from 2.6 - 6.9:1. The lower range of uncertainty compared to the *in situ* method is probably due to the greater experience with actual systems. Variations in mining energy requirements and upgrading energy requirements account for more than half of the variation between the "low" and "high" cases. The NER ranges from 1.1 - 1.8:1. Energy requirements for materials such as steel and cement are included in this analysis, though the magnitude of this impact is relatively small according to the study's supporting materials.

Brandt (2009) estimates that the resulting greenhouse gas emissions are about 50-75% higher than those of conventional oil, and that is without considering fugitive emissions.

The RAND Study (Bartis et al. 2005)

RAND Corporation (2005) provides an overview of land use, conventional pollutants, greenhouse gas emissions, water quality, and water consumption associated with oil shale development. The RAND report is not a specialized EROI analysis *per se*, and it does not contain a full calculation of indirect energy inputs or a quantitative assessment of all externalities. However, it does provide data on certain direct energy inputs, as well as a qualitative description of externalities.

The report provides a detailed description of both surface retorting and *in situ* extraction technologies. Surface retorting involves crushing the oil shale and heating it to 900-1,000°F for over half an hour. The report also mentions the challenges encountered by the Unocal plant in the Piceance Basin, which closed in 1991 after producing at only half of its design output. Exxon's surface retorting Colony project was abandoned before completion. International experience in Estonia, China, Brazil, and Russia is seen as not illustrative for U.S. applications due to the plants' size and regulatory conditions.

The primary *in situ* process considered is the thermally conductive *in situ* extraction process demonstrated by Shell. This involves slowly heating the shale to a lower temperature (650-700°F) over a period of three years. Fluids (oil and gas) are then pumped out of the formation.

The principal direct energy inputs are the electricity used to heat the shale and the energy used to create the "freeze wall" that protects the local groundwater and prevents the valuable hydrocarbons from escaping the project boundaries.

The report states that "the heating energy required for this process equals about one-sixth the energy value of the extracted product." This by itself would suggest an $EROI_{therm}$ of 6:1, but as noted, there are additional energy demands for the freeze wall, and indirect energy inputs in materials and capital. More importantly, the heating energy is electricity that must be generated by burning a fuel. Specifically, the energy inputs are 250-300 kWh per barrel of extracted product. A value of 300 kWh equals about 1 GJ, and a barrel of oil contains about 6 GJ. However, if the electricity was produced from coal converted at an efficiency of 40%, then the actual primary energy inputs are 2.5 times as great as the nominal heating energy, or 2.5 GJ. Thus, the $EROI_{elec}$ would be 2.4:1. The size of a generating plant would be considerable, accounting for a significant share of the water demands. An *in situ* process capable of producing 100,000 barrels per day would require a generating capacity of 1.2 GW. Along with EROI impacts, the use of coal for generation would produce a significant greenhouse gas impact. Every 6 GJ of synthetic crude would produce, in addition to the emissions from its own combustion, the emissions from 2.5 GJ of coal. Another fuel source that might be utilized is the natural gas that is co-produced with oil shale; however, this would carry a higher cost.

Water consumption is specified as about three barrels of water per barrel of oil produced. RAND notes that earlier studies found water as a limiting factor for oil shale development.

Bunger et al. (2004)

Bunger *et al.* (2004) authored a report for the DOE entitled "Strategic Significance of America's Oil Shale Resource." Volume 2 of this report focused on the economic and technological aspects of oil shale development. This report characterizes the processing of oil shale through the Alberta Taciuk Processor (ATP), a surface retort, as "energy self-sufficient" for the purposes of heating. This means that the combustion of some of the compounds present in the shale provide the thermal energy required to extract the remaining compounds, and amount to about 12-15 kWh per metric ton of ore.

Bunger *et al.* is not a specialized EROI analysis *per se*, and it does not contain a full calculation of indirect energy inputs or a quantitative assessment of all externalities. It also does not discuss the energy inputs required for *in situ* oil shale production. It provides a qualitative discussion of environmental impacts, with particular attention to how these compare to the impacts of production of petroleum from oil sands.

A subsequent DOE fact sheet on the EROI of various unconventional oil resources cited Bunger's work to provide a value of over 10:1 for surface retorting, roughly 7:1 for non-electric heating *in situ* extraction, and 2.5:1 for electric heating *in situ* extraction (DOE, unknown date). The fact sheet provides no methodological detail, so it is impossible to judge the veracity of its conclusions. It appears to consider only the external energy supplied to the process—the energy used for heating is excluded, as are indirect energy costs. Thus, the EROI reported in the DOE

study is certainly too high, although the margin of error is impossible to ascertain because of the lack of documentation in the study.

Legislative Peak Oil and Natural Gas Caucus (2007)

"Peak Oil Production and the Implications to the State of Connecticut" was submitted to Connecticut's legislative leaders and Governor in November 2007 by the Legislative Peak Oil and Natural Gas Caucus. The lead members were Representative Terry Backer and Senator Bob Duff, with support from Paul Sankowski and Steve Andrews. A December 2007 addendum on tar sands and oil shale also assessed the impacts of these resources. The report also cites EROI of 3:1 for surface retorting, though not specifying a source. There is no documentation for this result, so little confidence can be placed in its accuracy. Water demand is stated as 1 to 3 barrels of water per barrel of oil for industrial operations (such as cooling). The municipal and industrial growth required to support the production of 2.5 million barrels per day would require another 50 million gallons per day, in addition to the 100-300 million gallons of industrial water demand. The long timeframe for power plant construction is noted as a hurdle to development, and the water-related issues are given particular attention.

House Committee on Resources (2005)

The House of Representatives Committee on Natural Resources held hearings on the oil shale resource in June 2005. One of the speakers was Jack Savage, President and CEO of Oil-Tech, Inc. This company produced oil shale in a surface retorting process at a small facility in Utah. Mr. Savage discussed the operation, including the thermal energy self-sufficiency of the process. Mr. Savage also described his company's operations as requiring relatively low capital investment, which would argue for low indirect energy inputs in materials.

The representative from Shell, Mr. Terry O'Connor, discussed *in situ* production. Some specific practical challenges were identified, such as developing heaters that would last for the multi-year duration of the process.

Mark Maddox, Principal Deputy Assistant Secretary of Energy for Fossil Energy, answered a number of questions on oil shale. Citing Shell's work, he quoted an EROI value of 3:1 for *in situ* extraction, or 6:1 if the natural gas co-produced with the oil shale is used to provide the necessary heat. Mr. Maddox notes the connection between EROI and greenhouse gas emissions for oil shale development. Mr. Maddox also noted an additional source of CO_2 emissions: beyond that from the combustion of the oil shale and that of the energy used for heating, some process CO_2 emissions result when the carbonate compounds in the shale are heated in a retort. Finally, Maddox cites a figure of 1 to 2 barrels of water per barrel of oil produced.

The wording of Mr. Maddox's response to the energy balance question suggests that the answer refers to direct energy consumption. The values cited line up with the downhole heating energy demands in the RAND study, which are "one-sixth the energy value of the extracted product," or a 6:1 EROI if natural gas provides the heat. With 50% efficient generation, the EROI would be 3:1 for electric heating *in situ* production. Other indirect energy costs and indirect energy costs are excluded.

Cleveland (2005)

Cleveland's (2005) paper offers an extensive discussion of EROI methodology. The values reported for the EROI for oil shale are above and below the break-even point, with the median estimate around 5:1 or less. Most of the studies surveyed by Cleveland date from the 1970s and 1980s, and thus are not representative of the current state of technology and resource assessment.

Comparison with Conventional Oil Production

Most of the world's liquid fuels come are derived from conventional extraction and processing of crude oil. How does the EROI for oil shale compare with that for conventional oil? Delucchi (1991, 1993, 2003) estimates the amount of energy used in various fuel cycles related to the use of alternative transportation fuels. This work is used in the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model sponsored by the Argonne National Laboratory. GREET evaluates the fuel cycle from well to wheel and for various fuel and vehicle technologies. Delucchi's (1991) data indicate an EROI of about 43:1 for crude oil at the wellhead that is destined to be refined into motor gasoline (Figure 4). Delucchi's (2003) revisions project an EROI of about 20:1 for crude oil at the wellhead by 2015. The decline from 43:1 to 20:1 from 1991 to 2015 is due in part to Delucchi's assumption that an increasing share of production will come from energy-intensive offshore drilling, heavy oil, and enhanced recovery.
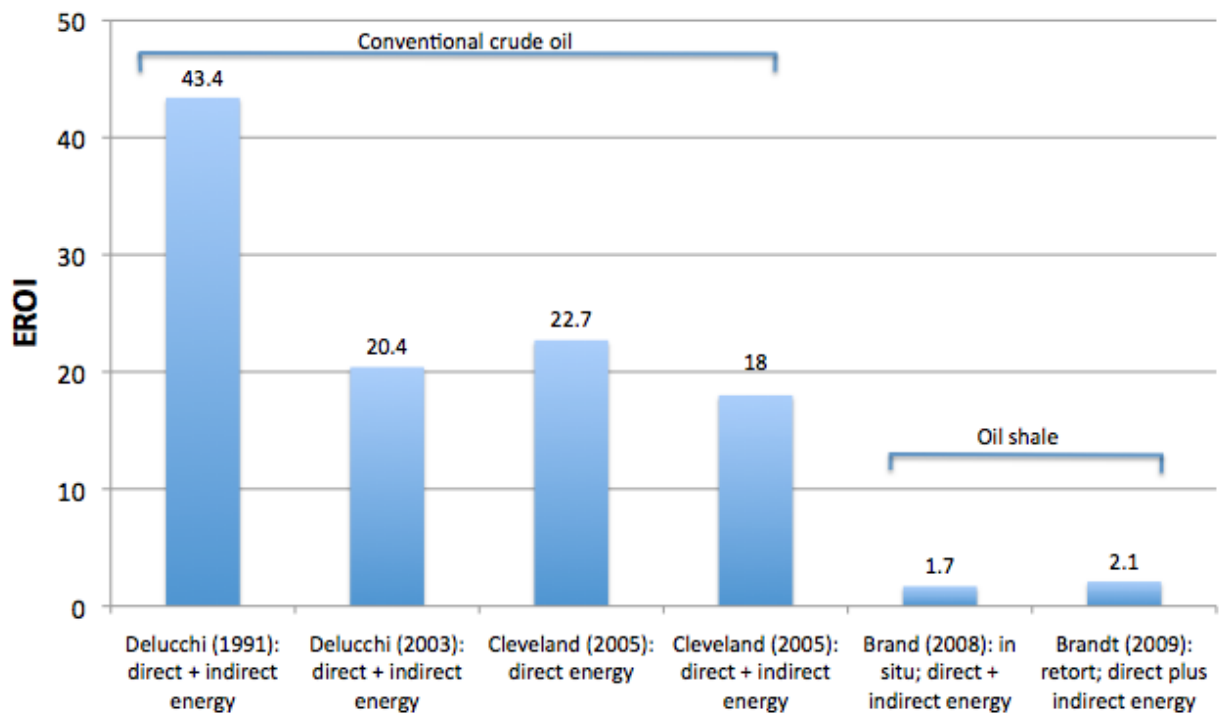

Figure 4. A comparison of estimates of the energy return on investment (EROI) at the wellhead for conventional crude oil, or for crude product prior to refining for oil shale.

Cleveland (2005) uses a different methodology to estimate an EROI for oil and gas production at the wellhead of about 23:1 in 1997. This figure is based on direct fuel and electricity costs only, and is the return to the sum of oil plus gas produced-no attempt is made to allocate joint energy costs separately to oil and gas. Cleveland estimates the EROI for oil and gas production to be about 18:1 in 1997 when direct plus indirect energy costs are included. Cleveland's estimates of EROI are lower than Delucchi's (1991) because his method uses a much more comprehensive definition of indirect energy use.

Brandt's work can be used as the basis for calculating the EROI for oil shale at a stage of processing similar to crude oil at the wellhead (See Appendix A for details). Both the *in situ* and surface retorting methods produce a "crude" product that must be refined into a useful fuel. Brandt's data indicate an EROI of around 2:1 for the extraction of the crude product from the shale (Figure 4). The estimates in Figure 4 are the average of Brandt's "high" and "low" scenarios.

We can also compare these two technologies at the refining stage (Figure 5). Here the EROI is the energy content of the refined fuel compared to the energy required to extract, process, and refine the crude product into a finished fuel that is ready for end use. Delucchi's (1991, 2003) work suggests and EROI of about 4.7 for motor gasoline refined from conventional crude oil. Brandt's (2008, 2009) indicates and EROI of about 1.4 for liquid fuel refined from oil shale.
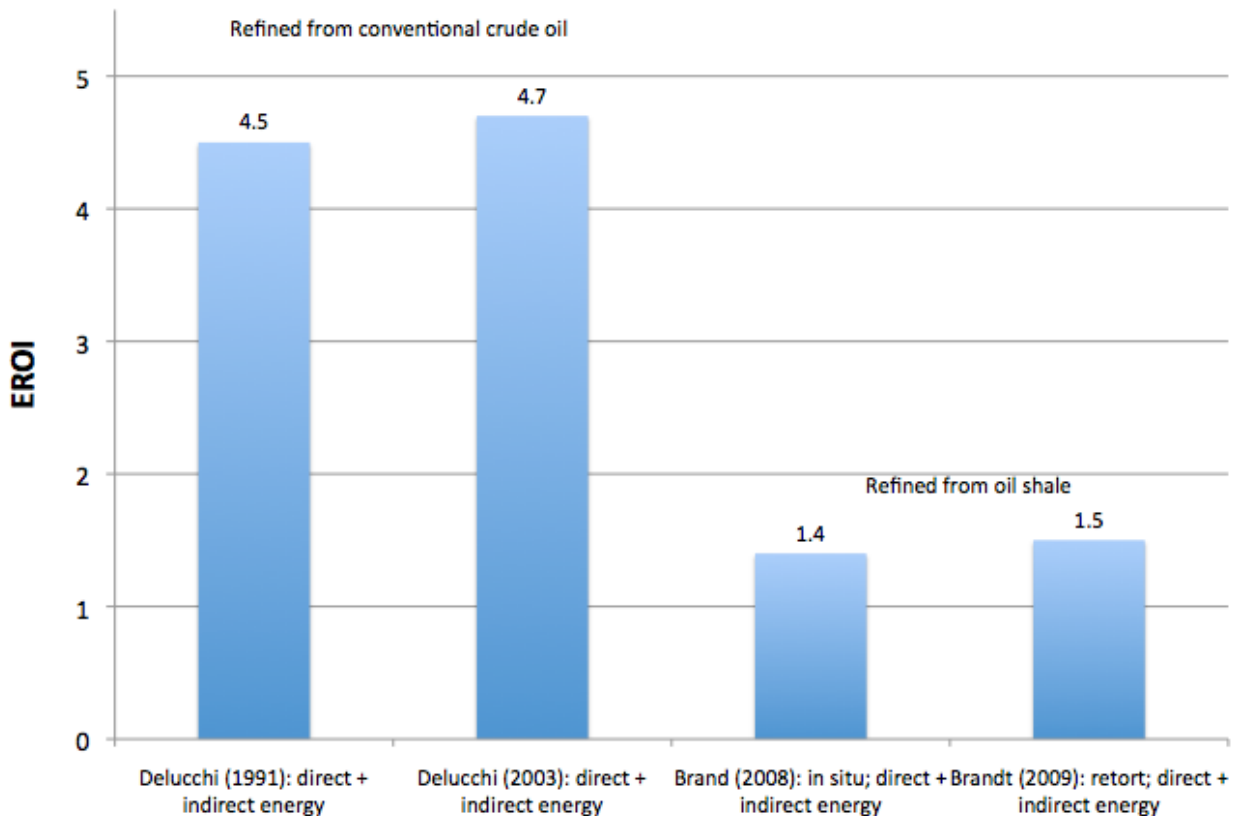

Figure 5. A comparison of estimates of the energy return on investment (EROI) for refined fuel produced from conventional crude oil and from oil shale.

Discussion

The discussion surrounding the net energy balance of oil shale is characterized by data and conclusions that lack rigorous analysis and review. Among those studies that apply some type of formal analysis, most focus on the assessment of a portion of direct energy use, ignoring other direct energy use and indirect energy use.

By a wide margin, Brandt's (2008, 2009) studies are the most credible. Brandt's work suggests that the EROI for oil shale falls between 1:1 and 2:1 when internal or self-use energy is included as an energy cost. This choice of system boundary is consistent with method used to calculate the EROI for conventional oil and coal extraction (Cleveland, 2005). In the case of conventional oil extraction, for example, considerable co-produced natural gas is burned as a fuel to power field operations. Cleveland (2005) includes so called "captive " fuel use as an energy cost of oil because it is energy that is literally used up to produce oil. The gaseous and char fuels generated and then burned in the oil shale production process should be viewed in the same way.

This places the EROI for oil shale considerably below the EROI for conventional crude oil. This conclusion holds for both the crude product and refined fuel stages of processing. Even in its depleted state—smaller and deeper fields, depleted natural drive mechanisms, etc.—conventional crude oil generates a significantly larger energy surplus than oil shale. This is not a surprising result considering the nature of the natural resource exploited in each process. The kerogen in oil shale is solid organic material that has not been subject to the temperature, pressure, and other geologic conditions required to convert it to liquid form. In effect, humans must supply the additional energy required to "upgrade" the oil shale resource to the functional equivalent of conventional crude oil. This extra effort carries a large energy penalty, producing a much lower EROI for oil shale.

There remains considerable uncertainty surrounding the technological characterization, resource characterization, and choice of the system boundary for oil shale operations. Even the most thorough analyses (Brandt, 2008, 2009) exclude some energy costs. These two observations lead to the conclusion that oil shale cannot yet be "certified" as a clear net energy producer. Put another way, we cannot yet say with certainty that the EROI for oil shale is unequivocally greater than 1.

An important caveat is in order here: the EROI of 1-2 reported by Brandt includes self energy use, i.e., energy released by the oil shale conversion process that is used to power that operation. For example, most of the retorting energy in the ATP process is provided by the combustion of char and produced gas, significantly reducing energy needs *from the point of view of the operator*. From a net energy perspective, how should this internal use of energy be treated? The answer depends on the question being asked. One could argue that the char and gas produced and consumed within the shale conversion process has zero opportunity cost—i.e., that energy would not, or could not, be used somewhere else in the economy, so it should not be treated as a "cost." The EROI calculated using this perspective is in the range of 2 to 16. On the other hand, the

internal energy is an essential expenditure of work necessary to produce the liquid fuel. The internal energy is absolutely necessary to accurately assess greenhouse gas emissions.

Another issue is energy quality. Society willingly sacrifices 3 Btus of coal to generate 1 Btu of electricity in thermal power plants. This makes economic sense because a Btu of electricity is more valuable than a Btu of coal. Oil shale operations consume large quantities of electricity to upgrade a low quality resource (oil shale) to a higher quality form (liquid fuel). But liquid fuel is still a lower quality form of energy than electricity, at least from a macroeconomic perspective. Accounting for these differences can dramatically alter the results of EROI analyses (Cleveland, 1992). The Shell *in situ* process is very electricity-intensive, and accounting for energy quality would, ceteris paribus, lower the reported EROI. Note, however, that one could argue against accounting for quality because if that electricity is self-generated, it may have zero opportunity cost. Future work should address these issues.

The low EROI for oil shale is closely connected to a significant release of greenhouse gases. The large quantities of energy needed to process oil shale, combined with the thermochemistry of the retorting process, produce carbon dioxide and other greenhouse gas emissions. Oil shale unambiguously emits more greenhouse gases than conventional liquid fuels from crude oil feedstocks by a factor of 1.2 to 1.75 (Brandt, 2008, 2009).

A fuel with a modest EROI that emitted few greenhouse gases could at least be a candidate for an alternative source of energy. However, a very low EROI combined with a very high carbon intensity should remove an energy system from serious consideration as an alternative to conventional crude oil extraction and refining. Oil shale in the western United States appears to fall into this category.

Appendix A

Brandt (2008) examines *in situ* production of synthetic crude from shale. We use a method similar to Delucchi (1991) to calculate the EROI at separate stages of processing.

The refined fuel delivered is 2333-2475 MJ per tonne of shale. The energy inputs prior to crude transport are 1309-1638 MJ per tonne of shale. Thus, resource recovery consumes an amount of energy equal to 53-70% of the energy in the final product. Crude transport, refining, and fuel distribution consume an additional 231-342 MJ per tonne, or 9-15% of the energy in the final product. Overall, processing requires 62-85% of the energy in the final product; so production of 100 MJ of oil shale requires inputs of 62-85 MJ along the way. This gives the overall EROI of 1.2-1.6.

As per Brandt, the EROI for the feedstock recovery alone is 1.6-2.0. That is based on the energy in the fuel at the wellhead, not the energy in the final product. If we define the EROI based on the energy in the final product (similar to how Delucchi expresses energy demand at each stage), then the EROI of recovery is **1.4-1.9**, and the EROI of refining is 6.8-10.7, for an overall EROI of, again, 1.2-1.6. When using a stepwise EROI (each one based on energy in final product):

$$EROI_i = \frac{E_{final}}{\Delta E_{step}} \quad \text{and} \quad EROI_{tot} = 1/\left(\sum_i \frac{1}{EROI_i}\right)$$

Thus, $EROI_1 = \frac{2333}{1638} = 1.42$, $EROI_2 = \frac{2333}{342} = 6.82$, and $EROI_{tot} = \frac{1}{\frac{1}{1.42} + \frac{1}{6.82}} = 1.18$

That is for the "high" case (high energy use, low EROI)

Using the "low" case, EROI = 1.61.

For the retorting case (Brandt 2009), the analysis depends on whether you draw the line "at the wellhead" before or after the upgrading stage. The output of the retort is upgraded before being sent to the refinery. If you draw the line before the upgrading stage, the "Recovery EROI" is **1.7-2.5**, the "Refining EROI" is 3.4-7.0, and the overall EROI is 1.1-1.8. If you draw the line after the upgrading stage, the "Recovery EROI" is **1.4-2.3**, the "Refining EROI" is 5.9-8.2 (more energy is attributed to the feedstock recovery stage), and the overall EROI is still 1.1-1.8.

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Table 1. Summary results of the energy, carbon and water costs associated with oil shale.

Authors	Year	Process	EROI (electric)	EROI (thermal)	kg CO_2 per bbl	Water (bbl per bbl oil)	Scope	Notes
Bartis *et al.*	2005	*in situ* electric	2 to 4	6 to 7	"significantly higher" than conventional oil	3	Heating Energy	Electricity demand of 250-300 kWh per bbl of oil Regards down-hole gas burning as speculative
DOE	2006	*in situ* electric; *in situ* thermal; surface	2.5; --; >10	--; 6.9; --	"large quantities"; "may need to be captured"	-	Heating and Mechanical Energy	Fact Sheets (citing unspecified Bunger 2006 work for EROI)
Bunger *et al.*	2004	surface retorting (ATP)	"energy self-sufficient" for heating	--	"higher" than conventional petroleum	"may still be a constraining factor"	Heating and Mechanical Energy	
Brandt	2008	*In situ* electric, on-site CCGT from co-produced gas	2.4 – 15.8 (external) 1.2 – 1.6 (net)	--	30.6-37.1 g C per MJ of refined fuel delivered → ~600-730 kg CO_2 per bbl of refined fuel produced	-	Simplified process-model LCA; energy and material inputs	Fugitive emissions included; output is compared to average of diesel and gasoline
Brandt	2009	Surface retorting (ATP), shale char is principal energy source	2.6 – 6.9 (external) 1.1 – 1.8 (net)	--	129-153 g CO_2 per MJ of reformulated gasoline → ~660-780 kg CO_2 per bbl of gasoline	-	Process-model LCA; energy and material inputs	Fugitive emissions not included; output is compared to reformulated gasoline
Legislative Peak Oil and Natural Gas Caucus	2007	Surface retorting;	3	--	-	1 to 3	Unspecified	
House Committee on Resources	2005	*In situ* electric; *In situ* thermal	3 --	-- 6	"likely to be substantially higher" than conventional petroleum production.	1 to 2	Heating energy	Principal Deputy Assistant Secretary for Fossil Energy, based on Shell data