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Energy Return on Energy Investment for an LWR Fuel Cycle*

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ABSTRACT

This paper summarizes the methodology and requisite data to assess the potential Energy Return on (Energy) Investment (EROI) for nuclear fuel cycle alternatives as documented in Smith et al. 2012, sponsored by the U.S. Department of Energy-Office of Nuclear Energy (USDOE-NE) Fuel Cycle Technologies (FCT) Program. The results of applying that methodology are presented for an example "once-through" fuel cycle using low enrichment uranium (LEU) in conventional light water cooled reactors (LWRs) on a basis of 1 metric ton of uranium fuel.

The methodology developed in 2012 was an extension of a prior evaluation of EROI as a metric for fuel cycle facilities, processes and technologies. That prior study [1] addressed the energy return on the addition of fuel recycle to an existing nuclear energy system. Limited to just the addition of fuel recycle, that study did not include all the energy investments required to create, operate and decommission the underlying nuclear fuel cycle, such as uranium mining, fuel fabrication, reactor construction, and used fuel disposition. This extension of the prior work addresses these remaining pieces of the fuel cycle to provide a basic evaluation framework and initial data to enable evaluation of EROI for nuclear energy in general, for the representative fuel cycle. The combined tools from the two studies can be applied to evaluate alternative fuel cycle options in the future with the addition of pertinent details.

In this analysis, energy consumption for an entire nuclear energy enterprise is considered in three sections: the front-end, the reactor, and the back-end. The front-end of the fuel cycle includes mining, milling, conversion, enrichment, de-conversion, fuel fabrication, and transport between front-end facilities. The reactor includes both energy inputs for construction, operation, and decommissioning, as well as the energy product output. The back-end of the fuel cycle includes repository construction, operations, maintenance, and closure; waste package and storage cask embodied energy; and energy to transport the waste packages by rail.

The intent of this study is to develop the methodology and analysis tool for a complete fuel cycle. Representative numbers were used in this report to demonstrate the functionality of the tool. The methodology and tool provide a framework for future exploration of the key energy intensity values and for conducting sensitivity studies on specific values, either to assess improved understanding of the values, or to explore the potential for alternative technologies to impact EROI.

INTRODUCTION

This report provides a methodology and requisite data to assess the potential *Energy Return on (Energy) Investment* (EROI) for nuclear fuel cycle alternatives, and applies that methodology to an example 'once-through' fuel cycle using low enrichment uranium (LEU) in conventional light water cooled reactors (LWRs). The EROI is the output energy produced divided by the consumed energy invested.

This analysis is sponsored by the United States Department of Energy - Office of Nuclear Energy (USDOE-NE) Fuel Cycle Technologies (FCT) Research and Development Program. The FCT program is chartered in the *Nuclear Energy Research*

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and Development Roadmap [2] to develop technologies to "enable sustainable fuel cycles" (DOE-NE Objective #3). Within the FCT program, the Fuel Cycle Options Campaign "performs integrating analyses of nuclear energy and fuel cycle systems to inform fuel cycle R&D, programmatic decisions, strategy formulation, and policy development". Campaign objectives include development of relevant fuel cycle metrics and development of tools and associated data for analysis of fuel cycle systems.

This study represents an extension of a prior evaluation of EROI as a metric for fuel cycle facilities, processes, and technologies. The prior study [1] addressed the energy return on energy invested for the addition of fuel recycle to an existing nuclear energy system. This extension of the prior work addresses energy investments required to create, operate and decommission the underlying nuclear fuel cycle, such as uranium mining, fuel fabrication, reactor construction, and used fuel disposition to provide a basic evaluation framework and initial data to enable evaluation of EROI for nuclear energy in general. It is intended as a basis for evaluation of alternative fuel cycle options in the future with the addition of pertinent details. It should be noted that the results of any energy return on energy investment analysis such as this depends on the assumptions made and data used during the preparation.

The literature (much of it decades old) was used as the source of included energy content data. Detailed explanations are included in the full report [3]. Representative numbers were used in this demonstration. A more rigorous analysis could be completed with an effort to develop updated energy content data for the resources encompassed in this work.

Energy Return on (Energy) Investment is one of many figures of merit on which investment in a new energy facility or process may be judged. While EROI is not the only criterion used to make an investment decision, it has been shown that energy systems and supplies must exceed a minimum EROI to be integrated into technologically advanced societies. Furthermore, technological history shows a trend towards higher EROI energy supplies.

EROI calculations have been performed for many components of energy technology. The EROI or energy payback ratio of several technologies are reported in Gagnon [4] and listed here for comparison: 7 for coal fired power plants, 80 for wind turbines, 9 for photovoltaic modules, 5 for biofuels, and 16 for nuclear reactors. Such analyses for nuclear energy systems have not been conducted or updated for many years, and this report combined with the prior recycle study [1] provides the FCT Program with the ability to evaluate EROI for a wide range of fuel cycle alternatives.

DEFINITION OF EROI

Even within the sub-discipline of life cycle analysis (LCA) dedicated to energy analysis, multiple definitions for EROI exist. For valid comparisons among fuel cycles and for comparison to other types of energy production systems, it is important to state the EROI definition that is being used. Rotty [5] did an excellent job of explaining four of these definitions. In this study Final EROI is used to discuss the energy intensities involved in the nuclear fuel cycle. Both Primary EROI and Final EROI are calculated in the full report [3]; Final EROI is presented in this paper to demonstrate the results of this analysis.

Final EROI

Final energy is defined as the heating value of energy when it is delivered to the consumer. Examples of final energy carriers include electricity, distributed natural gas and purchased gasoline.

Final EROI ($EROI_f$) for a process such as a nuclear fuel cycle is the gross sum of the final energy delivered by the outputs of the process divided by the gross sum of the final energy equivalents of the inputs to the process. When an input or output is electrical, its electrical value is used directly in the EROI formula. Fuel inputs and outputs are tallied as the refined product energies (without the 10-15% additional primary energy required consumed in refinement).

$EROI_f$ treats both electricity and fuels on their intrinsic heating value basis. $EROI_f$ can be thought of as treating electrical energy as being equally desirable as the thermal energy available from refined fossil fuels. This measure of EROI is equivalent to Rotty's "R_3." Rotty explained that this ratio ($EROI_f$ or R_3) is particularly appropriate if electrical output is used to produce hydrogen or another synthetic energy carrier with about the same efficiency as the current thermal energy used for these purposes [5].

$$EROI_f = \frac{ELECTRICITY\ PRODUCED\ FROM\ NUCLEAR\ REACTOR}{SUM\ OF\ FINAL\ ENERGY\ INPUTS\ TO\ CONSTRUCTION, USE, AND\ DECOMMISSIONING}$$

FUEL CYCLE

The representative fuel cycle for this evaluation is *once-through* use of low enrichment uranium (LEU) in large (~1000 MWe) light-water cooled reactors. This is similar to what is currently deployed in the U.S., with a few additions or variations. Currently, in the U.S., there is very little domestic uranium production, and a significant fraction of the U.S. fuel supply comes from down-blending of excess high-enrichment weapons uranium. However, to represent the energy requirements of a complete once-through fuel cycle, the extraction and processing of uranium is needed; therefore, representative uranium supply processes are postulated. Similarly, the U.S. does not currently have a repository for disposal of used nuclear fuel. To represent the complete energy requirements for the once-through fuel cycle, such disposal is needed; therefore, a representative interim storage facility and a representative geologic repository are postulated.

For this example analysis, the fuel cycle is divided into three parts:

- Front-End – Production of nuclear fuel, including uranium mining and milling, conversion, enrichment, deconversion, and fuel fabrication,
- Reactor – The nuclear reactor that uses fuel to produce electricity, and
- Back-End – Aging of used fuel in interim storage and disposal in a geologic repository.

Based on the prior EROI analysis [1] for the reactor portion of fuel cycles that incorporate fuel recycle, this analysis adds the front and back end of a once-through system and removes the recycle portions. The flow of material through the fuel cycle is shown in Figure 1.

METHODOLOGY

The purpose of LCA is to benchmark investments, processes and decisions with respect to their costs and benefits. Many LCA figures-of-merit exist, of which EROI is but one. In this study, a bounded Input/Output analysis is used to calculate $EROI_f$ for a nuclear energy system. The inputs are composed of the energy investments required in obtaining fuel materials; fabricating fuel; constructing, operating, and dismantling nuclear facilities; and disposing of the used fuel. The energy output is the energy delivered by the nuclear reactors.

A spreadsheet tool was constructed for the specific purpose of this input/output analysis. This tool allows the user to enter the parameters of the nuclear fuel cycle and assumptions about energy use in each process. The spreadsheet calculates Primary EROI and Final EROI, the Final EROI reported here. The basic EROI calculation is relatively simple. The complexity is in defining the energy production system to be evaluated, its *energy boundaries*, and in determining reasonable energy content values for the system components, described in the full report [3].

RESULTS

Front End

The final energy intensities of constructing, operating, and decommissioning and demolishing the processes on the front-end of the nuclear fuel cycle are summarized in Table 1. The processes in the front-end of the fuel cycle include mining of uranium ore, milling of the ore to produce yellowcake, conversion of yellowcake to UF_6, enrichment of U-

235, and de-conversion of depleted uranium (DU). Sources of information for this analysis include Rotty [5], Lenzen [6], and Schneider [7], in addition to the recent evaluation of environmental impacts, health and safety impacts, and financial costs of the front end of the fuel cycle by Carlson [8], which includes the evaluation of energy inputs.

In our fuel cycle representation, D&D energy for industrial type facilities without high-level radioactive material contamination is estimated as 20% of the construction energy. For facilities with high-level radioactive material contamination, such as reactors, D&D energy is estimated as 100% of the construction energy.

Table 1. Energy intensities for front-end processes, GJ(e+t)/MT enriched uranium fuel

Phase	Construction	Operation	D&D	Total
Mining	894	3,600	179	**4,674**
Milling	252	4,282	50.5	**4,585**
Conversion	86.8	2,794	3.03	**2,884**
Enrichment	2,945	7,001	120	**10,065**
Deconversion	78.4	-358	2.74	**-277**
Fabrication	44.1	3,747	1.93	**3,793**
Total Input	**4,301**	**21,066**	**357**	**25,724**

Reactor

The final energy intensities of constructing, operating, and decommissioning and demolishing the reactor are summarized in Table 2.

The typical LWR operates on a 12-18 month refueling cycle, with about 1/3 of the core replaced each cycle. The energy production from the fuel varies somewhat by reactor and fuel details, and even for individual fuel rods, and along a single rod - based on the local neutron fluence seen during irradiation. Energy production is typically referenced as a core-average burn-up in terms of Gigawatt days of thermal energy produced per ton of initial heavy metal. For the representative fuel cycle (Figure 1), we assume a burn-up of 50 GWd/tHM- larger than early reactors, smaller than anticipated in the future, and a reasonable value for current reactor practice.

On a unit of fuel basis, the pressurized water reactor (PWR) produces 4,320,000 GJ(th)/MTU which is equivalent to 1,425,600 GJ(e)/MTU.

Table 2. Energy intensities for the reactor, GJ(e+t)/MT enriched uranium fuel.

Phase	Construction	Operation	D&D	Total
Reactor Input	10,889	16,679	1,999	**29,567**
Reactor Output	-	-1,425,600	-	**-1,425,600**
Net Input	**10,889**	**-1,408,921**	**1,999**	**-1,396,033**

Back-End

After the nuclear fuel assemblies have been used to generate power in a once-though fuel cycle at a nuclear power plant, the assemblies are temporarily stored in a spent fuel pool (for at least five years) until they cool down sufficiently to be transferred to on-site dry storage casks. In a complete fuel cycle, spent nuclear fuel is transported to a geologic repository for disposal in robust waste packages. Currently, most of the commercial spent nuclear fuel (SNF), on the order of 70,000 metric tons, is stored at utility power plant sites either in fuel pools (74%) or dry storage casks (26%) [9].

The energy requirements in the back-end of the fuel cycle shown in Figure 1 are assumed to include: the construction of storage casks, Transportation-Aging-Disposal (TAD) canisters, and waste packages; construction of the shallow land burial; construction, operation, and decommissioning of the interim facility; and construction, operation, and closure of the repository. The energy intensities for these processes are presented in Table 3 on the basis of 1 MT uranium fuel.

Table 3. Energy intensities for the reactor, GJ(e+t)/MT enriched uranium fuel.

Phase	Construction	Operation	D&D	Total
TAD Canisters	119	-	-	**119**
Waste Packages	225	-	-	**225**
Aging Casks	18.5	-	3.7	**22.2**
Shallow Land Burial	231	-	-	**231**
Interim Storage	48.2	74.3	9.6	**132**
Repository	168	3,809	54	**4,031**
Total Input	**810**	**3,883**	**67**	**4,761**

CONCLUSIONS

This study represents an extension of a prior evaluation of EROI as a metric for fuel cycle facilities, processes and technologies. A prior study [1] addressed the energy return on the addition of fuel recycle to an existing nuclear energy system.

This extension of the prior work quantifies the construction, operation and decommissioning of the underlying nuclear fuel cycle, such as uranium mining, fuel fabrication, reactor construction and used fuel disposition to provide a basic evaluation framework and initial data to enable evaluation of EROI for nuclear energy in general. It is intended as a basis for evaluation of alternative fuel cycle options in the future with the addition of pertinent details.

Based on data provided in the literature, the representative nuclear fuel cycle has a final EROI of 23.8. This includes a large range of assumptions including the construction of a geologic repository for the final storage of spent nuclear fuel that does not currently exist.

EROI is one of many metrics for decision makers to select optimal energy generators. The conclusions of this study must be taken into consideration along with the inherent environmental and financial costs.

FUTURE APPLICABILITY

The intent for this study was to develop the methodology and analysis tool for a complete fuel cycle. It is not the intent of the study to fully explore the wide range of potential energy intensities, or to reconcile the disparate values found in the literature. Representative numbers were used in this demonstration. The methodology and tool do provide a framework for future exploration of the key energy intensity values and for conducting sensitivity studies on specific values, either to assess improved understanding of the values, or to explore the potential for alternative technologies to impact EROI.

REFERENCES

1. SIMON 2011. "Energy Return on Investment – Fuel Recycle". A. J. Simon, M. Fratoni, C. Smith, and W. Halsey. Lawrence Livermore National Laboratory, LLNL-TR-497511, FCR&D-SYSA-2011-000317. August 2011.

2. DOE-NE 2010. "Nuclear Energy Research and Development Roadmap – Report to Congress". U.S. Department of Energy, Nuclear Energy. April 2010.

3. SMITH 2012. "Nuclear Energy Return on Energy Investment." C. Smith, J. Blink, M. Fratoni, H. Greenberg, W. Halsey, A.J. Simon, M. Sutton. Lawrence Livermore National Laboratory, LLNL-TR-577013, FCR&D-FCO-2012-000275. September 2012.

4. GAGNON 2002. "Life-cycle assessment of electricity generation options: The status of research in year 2001." L. Gagnon, et al. *Energy Policy*, 30(14), 2002.

5. ROTTY 1975. "Net Energy from Nuclear Power". R.M. Rotty, A.M. Perry and D.B. Reister. Institute for Energy Analysis, Oak Ridge Associated Universities, IEA-75-3. 1975.

6. LENZEN, 2008. "Life Cycle Energy and Greenhouse Gas Emissions of Nuclear Energy: A Review". M. Lenzen. Energy Conversion and Management 49 (2008) 2178–2199. Available at http://www.isa.org.usyd.edu.au/publications/documents/ISA_Nuclear_Report.pdf Accessed August, 2011.

7. SCHNEIDER 2010. "Measures of the Environmental Footprint of the Front End of the Nuclear Fuel Cycle". E. Schneider, B. Carlsen, and E. Tavrides. INL Technical Report FCRD-SYSA-2010-000104. 2010.

8. CARLSON 2012. "Environmental Impacts, Health and Safety Impacts, and Financial Costs of the Front-End of the Nuclear Fuel Cycle". B. Carlson, et al. FCRD-FCO-2012-000124, draft in review. September 2012.

9. GAO 2012 "Accumulating Quantities at Commercial Reactors Present Storage and Other Challenges". GAO-12-797. August 2012.

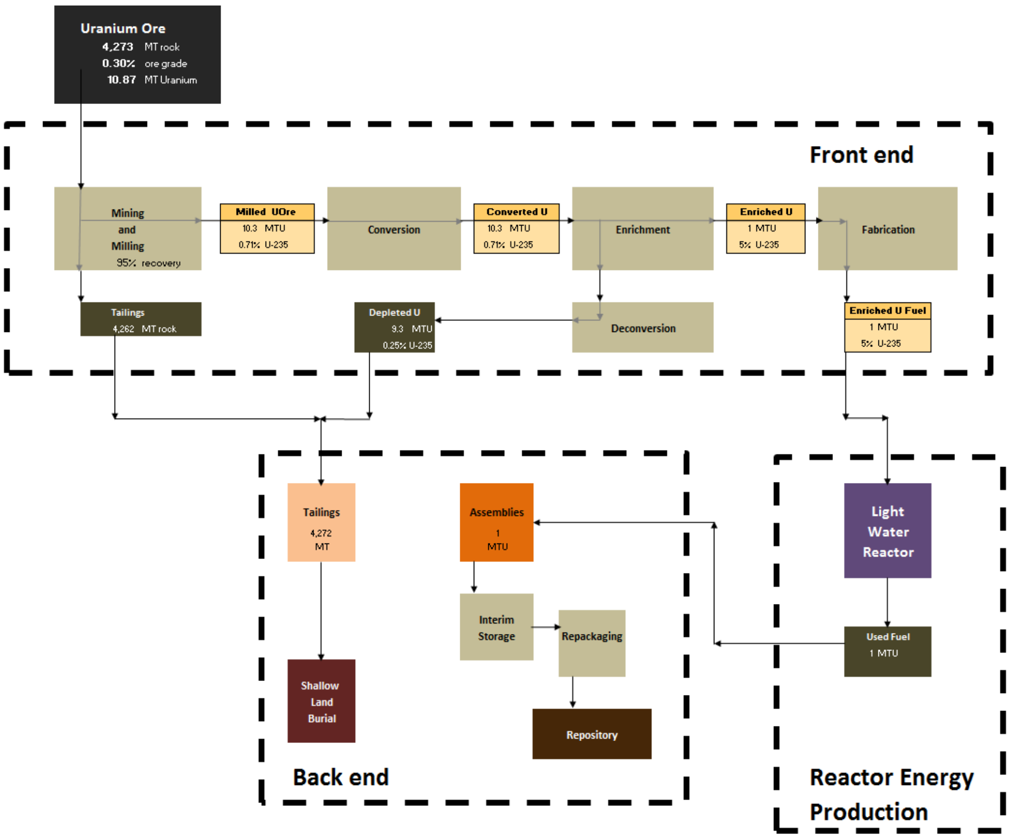

Figure 1. Material flows associated with one ton of uranium fuel moving through a representative once-through fuel cycle.