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ENERGY RETURN ON ENERGY INVESTMENT, AN IMPORTANT FIGURE-OF-MERIT FOR ASSESSING ENERGY ALTERNATIVES

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ABSTRACT

Energy Return On Energy Investment (EROEI usually abbreviated as EROI and also referred as net energy analysis or energy payback ratio) is an important figure of merit for assessing the viability of energy alternatives. EROI analyses of geothermal energy are either out of date, of uncertain methodology, or presented online with little supporting documentation. Too often comparisons of energy systems are made ambiguous by inappropriately using a metric based on "efficiency" when EROI would be more appropriate. For geothermal electric power generation, EROI is determined by the energy delivered to the consumer compared to the energy consumed to build, operate, and decommission the facility. Thus, EROI compares high quality input energies, e.g. the diesel fuel used to run the drill rig to another high quality energy, the electricity produced.

The methodology (Input/Output Analysis) and results of past geothermal EROI are reviewed and issues or problems conducting and interpreting EROI analyses are discussed. The validity of past geothermal EROI estimates is investigated by spot checking come of the major energy inputs into constructing geothermal wells using process analysis rather than economic data. Preliminary updates of past geothermal power production EROI are estimated and applied to understanding the future of geothermal development.

GEOTHERMAL EROI

An explicit and proper analysis of energy balance is especially important for geothermal energy. A geothermal power plant involves four energy streams (Figure 1): 1) the heat extracted from the reservoir, i.e. the earth, 2) the heat rejected to the atmosphere, 3) the energy to construct, operate, and decommission the power plant, and 4) the electrical energy delivered to the customer. The heat flowing from the reservoir and the heat rejected to the atmosphere are significant in determining the efficiency of the system, but are not factors in EROI. For a geothermal electric power plant, EROI is determined by the energy delivered to the consumer compared to the energy consumed to build, operate, and decommission the facility.

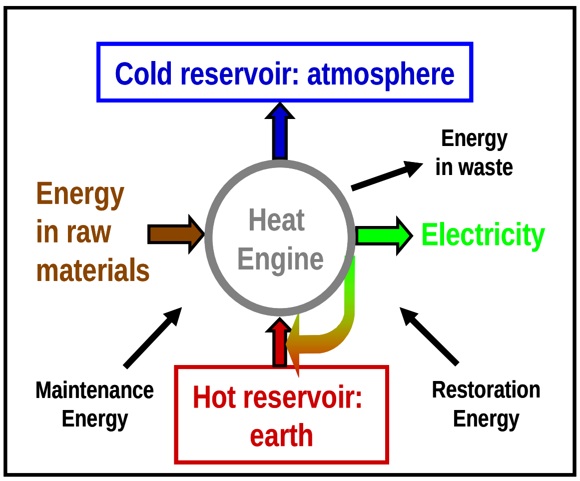

Figure 1: Geothermal heat engine converting raw materials and heat from the earth into electricity.

To be meaningful EROI must consider the value of the input and output energies. Not all energy is of equal value in its ability to do work. Thus, studies of energy alternatives need to consider the value of the inputs compared to the value of the output. As a heat engine, a geothermal power plant is excellent case study in energy inputs and outputs. Energy in a geothermal reservoir or the atmosphere is of no particular value unless it is incorporated into some process such as producing electricity. Energy embodied into the fuel and raw materials consumed

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to build, operate, and decommission the facility (steel, cement, fuel, chemicals, etc.) have inherent value. That is, it can be used for food production, shelter, transportation, etc. One way the value of energy can be accounted for formally using available free energy or exergy (Patzek, 2004). Portability and storability of the energy are other significant value metrics.

METHODOLOGY

Process Analysis

Process analysis of embodied energy is a detailed bookkeeping exercise tracing energy inputs from raw material mining through the chain of manufacturing to finished products. For example, this could include accounting the energy of mining raw materials (iron ore, coal, etc.), transporting raw materials to the foundry, forging the steel, machining the pipe, and shipping the resulting casing to the well construction location. The energy contained in the material as well as that consumed at each stage is "embodied" into the materials at the next stage. The second law of thermodynamics dictates that the embodied energy is always more than just the energy "contained" in the final product. As an example, for diesel fuel which is an energy dense and highly valued product, the embodied energy is ~20% more than the energy released by burning the fuel (Brinkman, 2005). The extra 20% accounts for the energy needed to produce, refine, and deliver the fuel.

Process analysis of the energy burden of a product requires considerable detailed work. Thus in the 1970's only a few process analyses of embodied energy were performed. Rather input/output analysis was used to estimate embodied energy.

Input/Output Analysis of Embodied Energy

The input/output approach to calculating embodied energy starts with life-cycle cost analyses and multiplies cost categories by standard energy intensities (kJ/$) to get the energy investment. Economic data is used to calculate energy intensities for each aggregated commodity of the economy. Monetary flows between economic sectors are assumed surrogates for material and burdened energy flows. That is, where energy or material flows are not know, monetary flow are put into the equations and it is assumed that the energy or material flows are positional to the monetary flows. The entire countries' economy is represented by the following simultaneous equations:

$$\sum_{i=1}^{N} e_i X_{i,j} + I_j = e_j O_j , \qquad (1)$$

where

$X_{i,j}$ is the transaction from sector *i* to sector *j*,

I_j is the energy input from the earth or sun and is non-zero only for primary energy sectors of the economy,

O_j is the total output of sector *j*, and

e_j is the embodied energy intensity per unit of X_{ij}

Expressed in matrix form the solution to equation 1 for the energy intensities is

$$e = I\left(X - O\right)^{-1} \qquad (2)$$

The Appendix provides an example of the application of this system of equations approach.

There several are disadvantages to using input/output analysis energy intensities. Even dividing the economy into 398 segments (Bullard and Herendeen, 1975), there is significant grouping of commodities; the resulting energy intensities are gross averages. The validity of monetary flows as surrogates for energy flows may vary from commodity to commodity and can only be assessed by detailed process analysis.

ISSUES AND PROBLEMS WITH EROI

EROI or net energy analysis is used to supplement economic analysis to identify technologies that are potentially net energy consumers rather than producers. Standard economic analysis does not necessarily make this distinction especially when there are subsidies. Concern that some energy technologies may not be net energy producers resulted in legislation requiring net energy analysis on federally supported facilities (Public Law 93-577, Sec. 5(a) (5)).

The existence of a legislative requirement to conduct net energy analysis or EROI does not mean that such analyses can or have been done adequately. In 1982 the U.S. General Accounting Office (GAO) criticized the U.S. Department of Energy (DOE) for not following Public Law 93-557 (GAO 1982). DOE's response (included as an appendix to the GAO document) states the benefits of net energy analysis or EROI is not worth the time and effort involved. The GAO, in the same document, asserts the feasibility meaningful EROI analysis.

Fundamental difficulties in performing EROI include specifying the system boundary and comparing input and output energies at different times and of different thermodynamic quality. As a result critics have said that EROI has seldom been used to make decisions. However, this objection overlooks the point that EROI should not be used to overrule other factors; instead it complements and guides how one thinks especially where there is concern regarding management of resources and the issue of subsidies creating unsustainable economic systems.

The issue that EROI analyses may not have been adequately performed in the past does not mean they should not be performed and will not be useful in the future. If an energy technology is a clear EROI looser, there needs to be compelling reasons for pursuing it. On the other hand, if a technology is a clear EROI winner, problems with the analysis may not be substantial enough to warrant further investigation. If a technology is EROI marginal, further analysis is most likely merited.

PAST GEOTHERMAL EROI ANALYSES

EROI analyses of geothermal energy are either old enough (Herendeen and Plant, 1979) that they need to be reviewed in light of current information, of uncertain methodology (Gilliland, 1975), or present results online with little supporting documentation. Herendeen and Plant analyses of geothermal power production EROI used what they described as the "standard" approach (IFIAS, 1974). Their approach used life-cycle cost analyses of geothermal power production and energy intensities (kJ/$) from input/output analyses to get the energy investment. The energy intensities used by Herendeen and Plant are from input/output analyses data published previously (Herendeen and Bullard, 1974, and Bullard et al., 1978). Criticisms of this "standard" approach include that over time, as the development of an energy resource becomes more cost effective, the EROI changes. However, according to Herendeen and Plant this should only make the EROI increase; that is, make the system more energy effective. Another issue is that, when prices change radically as fuel prices and rig rates have in the last few years or when costs are artificially depressed (see discussion of rig day rates in Mansure and Blankenship, 2008), energy intensities do not represent real energy costs. Without careful review of the energy intensities and how they are derived, one is left with questions similar to the following; 'Is the kJ/$ for cementing representative of raw materials, mixing, haulage, and pumping for cementing a well or is it representative of cement used in the building construction industry?'

Herendeen and Plant (1979a) results are summarized in Table 1. HDR refers to Hot Dry Rock, an early manifestation of what are now Engineered Geothermal Systems (EGS). They also provide power-in and power-out curves that can be used to determine energy payback time (time after startup the facility must operate in order to pay back the energy invested). This payback is equally important as EROI in assessing energy alternatives. Figure 2 shows the percentages of energy investment according to Herendeen and Plant for their 35 C°/km HDR case. The figure shows that fuel (energy in the diesel fuel used by the drilling rigs) is the largest energy component followed next by rig time. (The meaning of energy associated with rig time is not understood by the authors but is calculated as rig costs multiplied by kJ's/$ and applies presumably to drilling contractors. This is one example of the details of previous work that needs to be investigated).

ASSESSMENT OF PAST GEOTHERMAL EROI

As a preliminary check on the well construction side of Herendeen and Plant's work, we have estimated the input energy needed for casing, cementing, and diesel fuel for a 5.4 km EGS well (Table 2). For casing we used an actual casing design (5 stings plus conductor pipe) including weight per foot by grade and lengths including overlap. Our cementing estimate uses actual volumes and slurry densities. Our cementing and casing energy inputs agree reasonably well with Herendeen and Plant, especially considering that Herendeen and Plant's work is presumably based on smaller diameter wells, consistent with drilling practice in the 1970's. Detailed comparison with their work is difficult because we have not been able to locate the report by Republic Geothermal (1979) on which their cost inputs are based.

Table 1: EROI's calculated by Herendeen and Plant.

	EROI	Depth (km)
Liquid Dominated		
High turbine cost	4.3 ±1	
Low turbine cost	4.4 ±1	
HDR		
35°C/km	2.7 ±0.9	5.4[2]
45°C/km	3.4 ±1.0	4.2[2]
55°C/km	3.9 ±1.1	3.5[2]
Low Temp.	1.9 ±0.6	
"Best" case	13 ±3	
Geopressured	2.9 ±0.9	
Vapor Dominated	13 ±4	

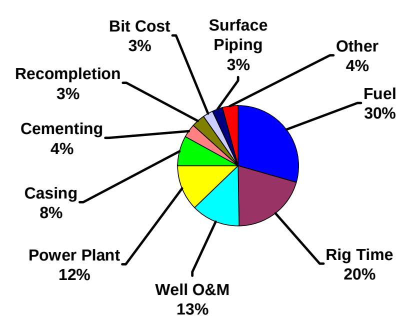

Figure 2: Herendeen and Plant's breakdown of the energy investment for their 35 C°/km HDR case.

[2] Estimated from the gradient. The depths are not recorded in Herendeen and Plant 1979b.

The factor of 5.7 times more fuel in Herendeen and Plant's calculation than in ours is substantially more than expected. Improved ROP, bit life, and diesel generator efficiency would reduce the fuel estimate in Herendeen and Plant's work significantly. We have attempted to estimate such reduction based on a report by Cummings et al. (1979) which contains a table "Range of values used for HDR drilling time estimates" of data taken from the Republic Geothermal work. Based on that information, the Herendeen and Plant's fuel calculation needs to be reduced by almost 60%, but even after such a reduction their estimate is 2.3 times ours. Differences in the horsepower on location can be significant, but in general, one would expect more horsepower (larger rigs, iron roughnecks, top drives, etc.) on location today, so the discrepancy remains unexplained. Herendeen and Plant's EROI was revisited using current bit and diesel engine performance information. This recalculation of EORI resulted in an increase of EORI from 2.7 to 3.8 for the 35°C/km .well described in Table 1.

Table 2: Calculations of actual embedded energy in a 5.4 km EGS well compared to Herendeen and Plant's estimates.

	Our estimate			Herendeen and Plant		
	m^3	GJ/m^3	TJ	m^3	GJ/m^3	TJ
fuel	436	42.3[3]	18.4	2240	46.8	105

	tons[4]	GJ/ton[4]	TJ	k$	GJ/k$	TJ
casing	1420	28.5[5]	40.6	280	103	28.9
cement[6]	860	17.4[7]	15.0	48.3	270	13.0

The energy embedded in the other steel products such as the rig, drill pipe, drill collars used during well construction was estimated to be on the order of that in the casing. However, when amortized over wells that can be drilled during the useful life of this equipment, this energy is less than 1% of the total energy input even before recycling of the steel is considered.

A significant factor in determining EGS EROI is the well productivity. Herendeen and Plant used 20 well pairs for a 50 MWe power plant; that is, 2.5 MWe per production well. They assumed that after 5 years the temperature will decline sufficiently that the wells would need to be recompleted (restimulated). Figure 3 shows the effect of well productivity on the EROI for Herendeen and Plant's 35°C/km case. The low end of the curve corresponds to the 2.5 MWe per well assumed by Herendeen and Plant. The high end, 6 MWe per well, was calculated using GETEM (Mines, 2008) assuming a 215°C reservoir and 80 kg/sec well flow rate. (A 215°C reservoir temperature is that used by Herendeen and Plant. 80 kg/sec is the high base case well flow rate in *The Future of Geothermal Energy* (MIT, 2006)).

Obviously, EORI is very sensitive to the assumptions made during the analyses. As an example, if we increase the well productivity from 2.5 MWe to 5 MWe, increase the capacity factor from 85% to 95%[8], reduce fuel consumption, rig time, and number of bits 60%, and delete silica removal costs, Herendeen and Plant's EROI for the 35°C/km case increases from 2.7 to 7.8. Thus the clear need to update geothermal power production EROI estimates. Further increases in EROI are likely available due to increases in efficiency in the construction and operation of geothermal power production since the 1970's. Silica removal costs are in Herendeen and Plant's analysis because they used as their power plant cost basis work on the Heber resource (EPRI 1978). Heber has a total dissolved solids content of 13,000 ppm. While any long term geochemistry issues of EGS yet to be determined, Heber (a hydrothermal resource) is probably not representative of EGS.

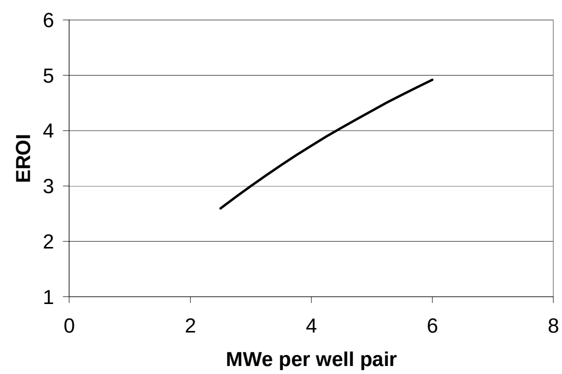

Figure 3: Herendeen and Plant 35 C°/km EROI as a function of well productivity.

Having pointed out the need to update Herendeen and Plant's work and recognizing the limitations of input/output analysis vs. process analysis, we plot Herendeen and Plant's EGS EROI's in Table 1 as a function of depth, Figure 4. While there are substantial uncertainties with projections beyond the range of actual data, note the figure shows that according to Herendeen and Plant's calculations somewhere about 8 km the energy needed to construct and operate the system exceeds the electric energy that can be produced. While we expect the actual point will be deeper than 8 km as better

[3] Brinkman, 2005.
[4] Metric tons.
[5] Burnham, 2006.
[6] Portland cement component.
[7] Marceau et al., 2007

[8] MIT (2006) used 95% as a baseline capacity factor.

estimates of EROI are obtained, the curve leads to several significant conclusions. First, in estimating the EGS resource base, depth below which the EROI is 1 should not be considered. As we seek new technologies to drill deep EGS wells, in addition to cost, consideration needs to be given to the energy needed to drill the well.

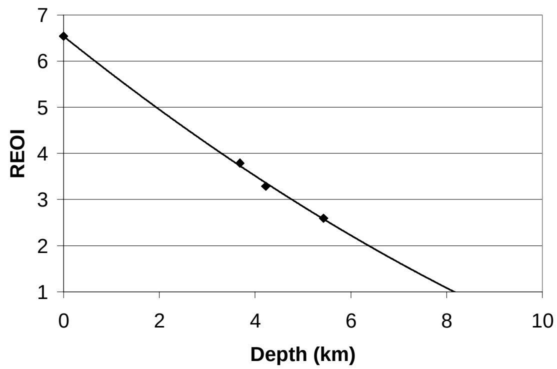

Figure 4: Herendeen and Plant EGS EROI as a function of well depth.

Other things that may change the EROI include the strategy for replacing production as temperature declines and the embodied energy attributed to labor and services. Herendeen and Plant assume that declining production will be replaced by recompleting the wells via additional stimulation. The viability of this approach is unproven. In fact from the *Future of Geothermal Energy* (MIT 2006) one would assume that after the temperature declines, wells are abandoned. Since well field construction accounts for most of the input energy, switching from recompletion to abandonment would result in a significant EROI penalty.

From Figure 2 we see that Rig Time and Well Field O&M account for 20% and 13% of the input energy respectively. Well Field O&M is not defined in Herendeen and Plant's work and thus, without the Republic Geothermal (1979) report we are not able of assess how much of this is materials and how much is services and labor, but the latter is probably substantial. Rig contractor costs are not primarily for materials and as noted above the amortized energy embedded in the rig and machinery is not substantial. We are left then with the conclusion that from 20% to 33% of the input energy is for labor and service like functions. Life Cycle Assessments (LCA) have typically not found labor and services to be a significant contributor to input energy (e.g., Wu et al., 2006). Thus, either major contributors to input energy have been overestimated by Herendeen and Plant or the energy embedded in geothermal power production has a different distribution than other systems.

CLOSING REMARKS

Geothermal resources are much simpler than many of the other energy alternatives (e.g., they don't have the complexity of soil depletion of bio-fuels, they integrate into the existing infrastructure without storage, they don't produce long term hazardous waste, etc.), so geothermal energy should be an example of where EROI has been done thoroughly. However, our understanding of the EROI of geothermal power production has substantial gaps and is frequently misunderstood outside the geothermal community. Clearly there is much work that should be done to provide a defensible EROI to guide geothermal development and compare geothermal resources to other energy alternatives.

REFERENCES

Brinkman, N, Wang, M., Weber, T., and Darlington, T., (2005), May Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems — A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions, Argonne National Laboratory, http://www.transportation.anl.gov/modeling_simulation/GREET/publications.html.

Burnham, A., Wang, M., and Wu, Y., (2006), "Development and Applications of GREET 2.7 – The Transportation Vehicle Cycle Model," Argonne National Laboratory Report ANL/ESD/06-5, Argonne, IL. http://www.transportation.anl.gov/modeling_simulation/GREET/publications.html

Bullard, C.W. III, and Herendeen, R.A. (1975), "The energy cost of goods and services," *Energy Policy*, December 1975.

Bullard, C. W. III, Penner, P. and Pilati D., (1978), "Net Energy Analysis, Handbook for Combining Process and Input-Output Analysis," *Resources and Energy*, **1**, p267- 313.

Cummings, R.G., Morris, G., Arundale, C.J., and Erickson, E.L., (1979), "Economic Factors Relevant for Electric Power Produced from Hot Dry Rock Geothermal Resources," University of New Mexico, DOE/ET/27017-T1.

EPRI, (1978), "Preliminary Design Manual for a Geothermal Demonstration Plant at Heber, California," EPRI ER-670, prepared by Holt/PROCON, Pasadena, CA.

GAO, (1982), "DOE Funds New Energy Technologies without Estimating Potential Net Energy Yields," GAO/IPE-82-1, U.S. General Accounting Office, Washington D.C.

Gilliland, M., (1975), "Energy Analysis and Public Policy," *Science*, **189** n4208, 1051-1056.

Herendeen, R.A., and Bullard III, C.W. (1974), "Energy Cost of Goods and Services, 1963/67," Document No. 140, Energy Research Group Office of Vice Chancellor for Research, University of Illinois, Urbana-Champaign.

Herendeen, R.A. and Plant, R.L. (1979a), "Energy Analysis of Four Geothermal Technologies," *Energy*, **6**, p73.

Herendeen, R.A. and Plant, R.L. (1979b), "Energy Analysis of Geothermal-Electric Systems." Energy Research Group Office of Vice Chancellor for Research, University of Illinois, Urbana-Champaign, http://www.osti.gov/geothermal/.

IFIAS (1974), "Energy Analysis Workshop Report S-10246," International Federation of Institutes for Advanced Study, Stockholm, Sweden.

Mansure, A.J., and Blankenship, D.A., (2008), "Geothermal Well Cost Analyses 2008," Geothermal Resources Council *Transactions*, **32** 43-48.

Marceau, M., Nisbet, M., and VanGeem, M., (2007), "Life Cycle Inventory of Portland Cement Concrete," Portland Cement Association, as recorded in NREL LCA database LCI database, http://www.nrel.gov/lci

Mines, G., (2008), "Geothermal Electricity Technologies Evaluation Model, DOE Tool For Assessing Impact Of Research On Cost Of Power," Proceedings, Thirty-Third Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, SGP-TR-185.

MIT, (2006), "The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century," INL/EXT-06-11746, ISBN: 0-615-13438-6, http://www1.eere.energy.gov/geothermal/future_geothermal.html

Patzek, T.W. (2004), "Thermodynamics of the Corn-Ethanol Biofuel Cycle," *Critical Reviews in Plant Sciences*, **23**(6), 519-567, http://petroleum.berkeley.edu/papers/patzek/CRPS416-Patzek-Web.pdf.

Republic Geothermal, (1979), "Industrial Assessment of Drilling Completion and Workover Costs of the Well and Fracture Subsystems of Hot Dry Rock Geothermal Systems."

Wu, M., Wang, M., and Huo, H., (2006), "Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States," ANL/ESD/06-7, Argonne National Laboratory, http://www.transportation.anl.gov/modeling_simulation/GREET/publications.html

APPENDIX

The following example of the use of solving simultaneous equations for the input/output relationships between a three sector economy is adapted from "The energy cost of goods and services" (Bullard and Herendeen, 1975). The first sector of the economy represents primary energy extraction from the environment (e.g., oil or a geothermal well field). The second sector is energy refinement/transformation (e.g., oil refining or a geothermal power plant). The third sector is the balance of the economy, that part of the economy where available data is dollar flows rather than energy flows.

Ideally all flows from sector to sector would be in energy or material units; however, this example shows how flows can be a mixture of energy, materials, and dollars, the latter two being surrogates for energy for segments of the economy where energy flows are not known. Since energy flows are knowable for the first two sectors it is natural to express the transactions of these sectors in energy units. Since energy transactions for the balance of the economy are not known (in essence that is what the input/output analysis is trying to estimate), it transactions are expressed in dollars.

The input from the earth into this example economy is assumed to be

$$I = \begin{bmatrix} 50kJ & 0 & 0 \end{bmatrix}. \qquad \text{(a1)}$$

That is, only sector 1 draws energy into the economy. The numeric values are simply chosen to demonstrate the nature of the mathematics rather represent our economy. The transfers between segments of the economy are assumed to be

$$X = \begin{bmatrix} 10kJ & 40kJ & 0 \\ 5kJ & 5kJ & 10kJ \\ 5\$ & 0 & 5\$ \end{bmatrix}. \qquad \text{(a2)}$$

where $X_{row,column}$ is the transaction from sector *row* to sector *column*, for example $X_{1,2}$ = 40 kJ is the transaction from sector 1 to sector 2. The outputs of each sector of the economy are assumed to be

$$O = \begin{bmatrix} 50kJ & 0 & 0 \\ 0 & 40kJ & 0 \\ 0 & 0 & 20\$ \end{bmatrix}. \qquad \text{(a3)}$$

Figure A1 shows the network of transactions corresponding to matrices *E*, *X*, and *O* as prescribed by equation 1.

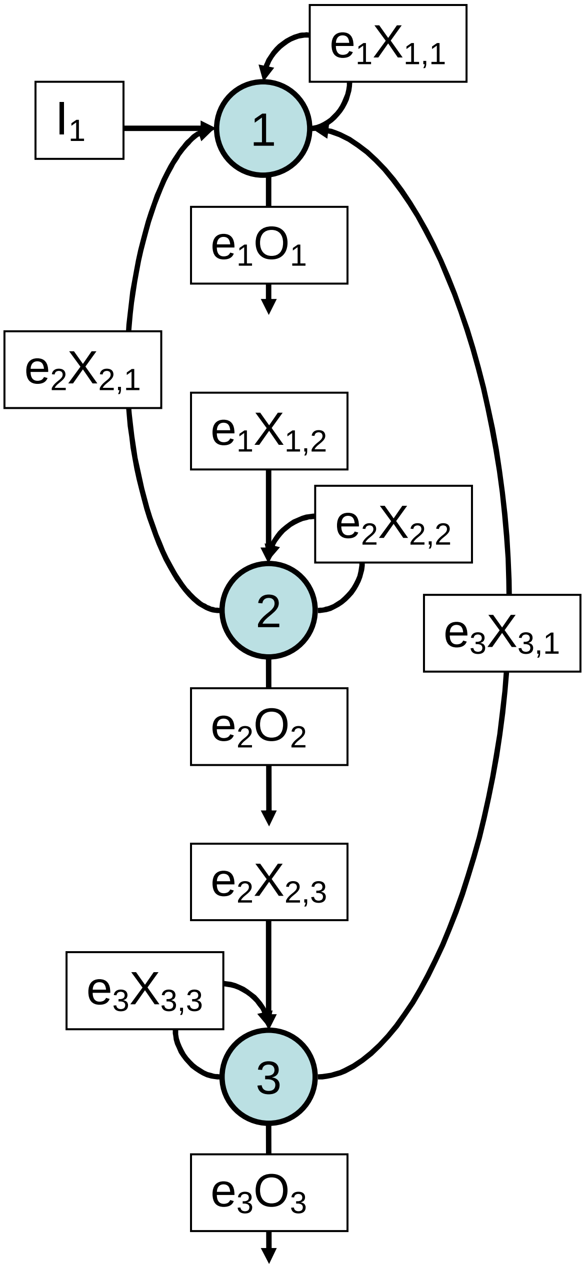

Figure A1: Transaction network of example economy.

According to equation 2, the energy intensities for this economy are

$$e = \begin{bmatrix} \frac{105}{64}\frac{kJ}{kJ} & \frac{15}{8}\frac{kJ}{kJ} & \frac{5}{4}\frac{kJ}{\$} \end{bmatrix}. \qquad \text{(a4)}$$

Thus every dollar transfer represents (5/4) kJ. Every kJ of transaction from segment two of the economy is burdened with an extra (7/8) kJ; that is it has an embodied energy of (15/8) kJ.

The demand for segment j of this economy is its output less the sum of its transactions

$$Y_j = O_j - \sum_{i=1}^{N} X_{i,j}\,, \qquad \text{(a5)}$$

$$Y = \begin{bmatrix} 0 \\ 20kJ \\ 10\$ \end{bmatrix}, \qquad \text{(a6)}$$

The energy demand for the whole economy is the demand for each economy segment times its energy intensity

$$\sum_{i=1}^{N} e_j Y_j =$$

$$\frac{15}{8}\frac{kJ}{kJ}20kJ + \frac{5}{4}\frac{kJ}{\$}10\$ = 50kJ\,, \qquad \text{(a7)}$$

the energy withdrawn from the earth. This demonstrates the internal consistency of the mathematics. How well the numbers input into these equations represent the economy is a whole separate issue.

Bullard and Herendeen (1975) example goes beyond what is presented here showing how to incorporate transactions in and out of the economy (imports and exports from the country).