The Oil Drum: Net Energy

Discussions about Energy and Our Future

What is the Minimum EROI that a Sustainable Society Must Have? Part 3: Calculating the minimum EROI to support the U.S. transportation system

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The following multi-part series is taken from a paper we published last year in the free, on-line journal ***Energies****. You may access the entire PDF here. All references can be found in the pdf. Part 1 can be found here. Part 2 can be found here.*

In this final installment of the Minimum EROI series we calculate the minimum EROI required from our energy sources to support the current transportation infrastructure of the U.S.

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5. Toward a more Comprehensive EROI: A first Estimate of the Downstream Costs associated with Refining, Transporting and Using Oil in the U.S.

If we extend the energy cost of obtaining a fuel from the wellhead towards the final consumer the energy delivered goes down and the energy cost of getting it to that point goes up, both reducing the EROI. This begins the analysis of what might be the minimum EROI required in society. We do this by taking the standard EROI (i.e. EROI_{mm}; about 10:1) for oil and then include in the denominator the energy requirements to get fuel to the point of use (i.e. EROI_{pou}) and the energy required to use it, generating an EROI_{ext}, i.e. extended EROI. In this analysis we assume the energy costs are paid for in oil.

5.1. Calculating EROI at the point of use

Refinery losses and costs: Oil refineries use roughly 10 percent of the energy in fuel to refine it to the form that we use [28]. In addition about 17 percent of the material in a barrel of crude oil ends up as other petroleum products, not fuel [1]. So for every 100 barrels coming into a refinery only about 73 barrels leaves as usable fuel. Natural gas does not need such extensive refining although an unknown amount needs to be used to separate the gas into its various components and a great deal, perhaps as much as 25 percent, is lost through pipeline leaks and to maintain pipeline pressure. Coal is usually burned to make electricity at an average efficiency of 35 - 40 percent. However the product, electricity, has at least a factor of three higher quality so that we do not count as costs the inefficiency of that process. What this means, however, is that oil resources that have an EROI of 1.1 MJ returned per MJ invested at the wellhead cannot provide energy profits for a society because at least 1.27 MJ of crude oil is required to deliver that one MJ to society as a fuel.

Transportation costs: Oil weighs roughly 0.136 tons per barrel. Transportation by truck uses about 3400 BTU/ton-mile or 3.58 MJ per ton-mile [29]. Transportation by fuel pipeline requires 500 BTU/ton-mile or 0.52 MJ per ton-mile. We assume that the average distance that oil moves from port or oil field to market is about 600 miles. Thus a barrel of oil, with about 6.2 GJ of contained chemical energy, requires on average about 600 miles of travel x 0.136 tons per barrel x 3.58 MJ per ton-mile = 292 MJ per barrel spent on transport, or about 5% of the total energy content of a barrel of oil to move it to where it is used (Table 1). If the oil is moved by pipeline (the more usual case), this percentage becomes about 1%. We assume that coal moves an average of 1500 miles, mostly by train at roughly 1720 BTU per ton mile or about 1.81 MJ per ton-mile [29], so that the energy cost to move a ton of bituminous coal with about 32 GJ/Ton to its average destination is 1500 miles x 1.81 MJ per ton-mile = 2715 MJ per ton, or 2.715 GJ per ton of coal, which is about 8 percent of it's energy content (Table 1). Line losses, if shipped as electricity, are roughly similar. So adding between 1 and 8 percent of the energy value of fuels for delivery costs does not seem unreasonable. We assume that these costs would decrease all EROIs by a conservative 5 percent (or 3 percent of crude oil in the ground) to get it to the user, in other words the fuel must have an EROI of at least 1.05: 1 to account for delivery of that fuel.

Thus we find that our $EROI_{pou}$ is about 40 percent (17 percent non fuel loss, plus 10 percent to run the refinery, plus 10 percent extraction, plus about 3 percent transportation loss) less than the $EROI_{mm}$ indicating that at least for oil one needs an EROI at the mine mouth of roughly 1.4 to get that energy to the point of final use.

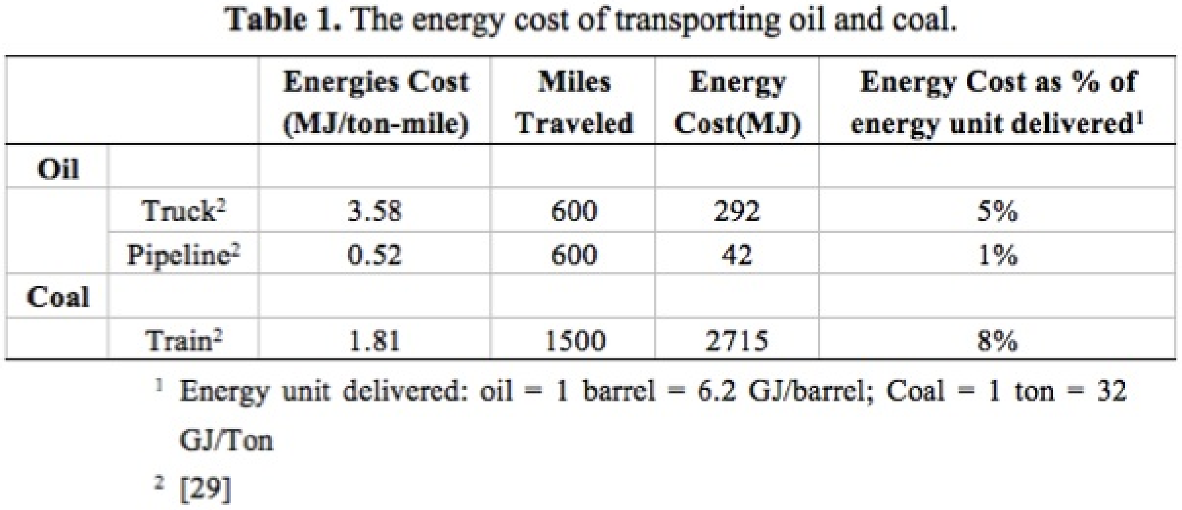


Table 1. The energy cost of transporting oil and coal.

		Energies Cost (MJ/ton-mile)	Miles Traveled	Energy Cost(MJ)	Energy Cost as % of energy unit delivered[1]
Oil					
	Truck[2]	3.58	600	292	5%
	Pipeline[2]	0.52	600	42	1%
Coal					
	Train[2]	1.81	1500	2715	8%

[1] Energy unit delivered: oil = 1 barrel = 6.2 GJ/barrel; Coal = 1 ton = 32 GJ/Ton

[2] [29]

5.2. Extended EROI: Calculating EROI at the point of use for oil correcting for the energy required for creating and maintaining infrastructure

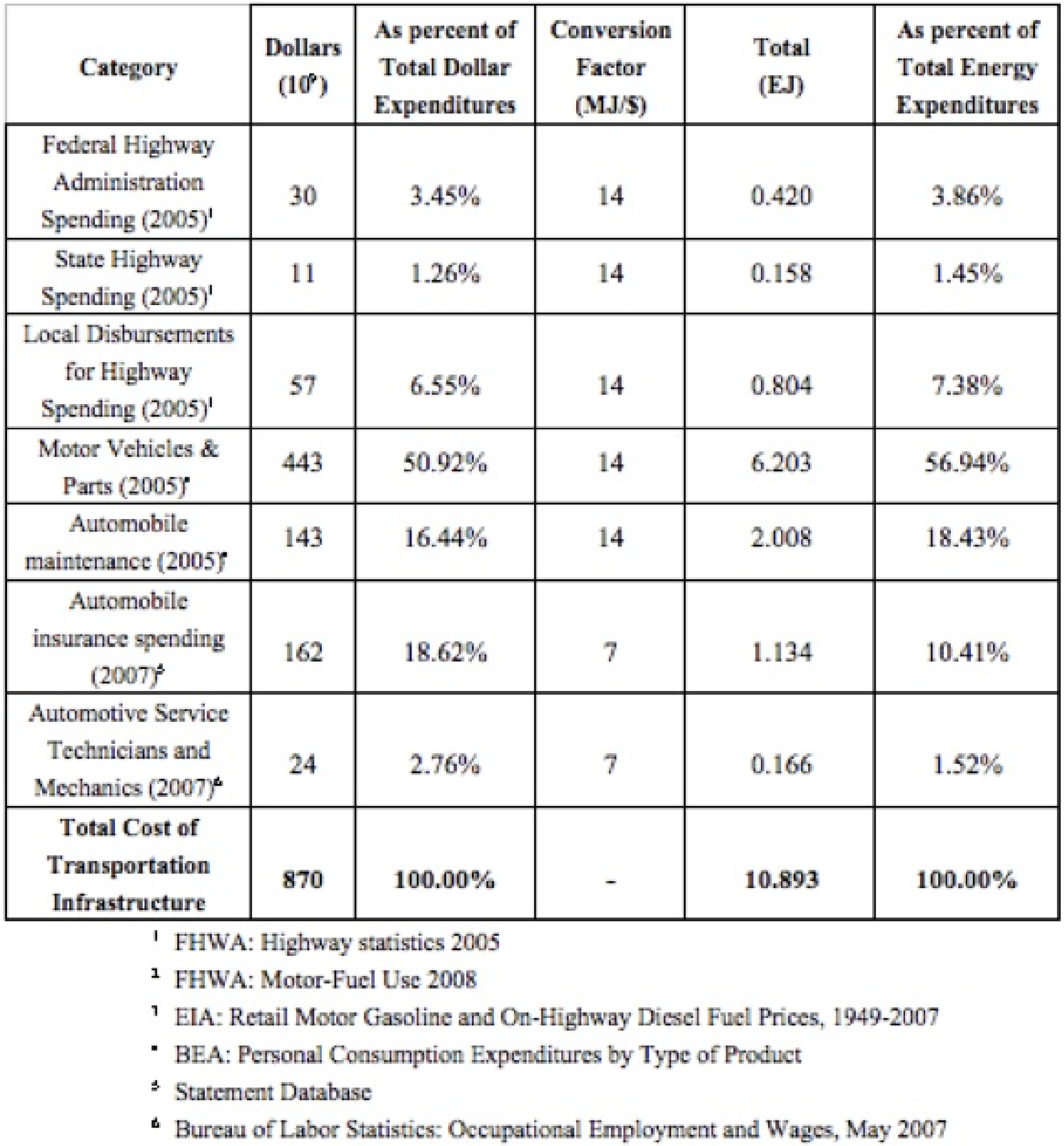
We must remember that usually what we want is energy services, not energy itself, which usually has little intrinsic economic utility, e.g. for most oil we want kilometers driven, not just the fuel that does that. That means that we need to count in our equation not just the "upstream" energy cost of finding and producing the fuels themselves but all of the "downstream" energy required to deliver the service (in this case transportation), i.e. 1) building and maintaining vehicles, 2) making and maintaining the roads used, 3) incorporating the depreciation of vehicles, 4) incorporating the cost of insurance, 5) etc. All of these things are as necessary to drive that mile as the gasoline itself, at least in modern society. For the same reason businesses pay some 45 or 50 cents per mile when a personal car is used for business, not just the 10 cents or so per mile that the gasoline costs. So in some sense the dollar required for delivering the service (a mile driven) is some 4 to 5 times the direct fuel costs, and this does not include the taxes used to maintain most of the roads and bridges. Now many of these costs, especially insurance, use less energy per dollar spent than fuel itself and also less than that for constructing or repairing automobiles or roads, although this is certainly not the case with the money used to deliver the fuel itself used in these operations.

On the other hand the energy intensity of one dollar's worth of fuel is some 8 times greater than that for one dollar's worth of infrastructural costs. Table 2 gives our estimates of the energy cost of creating and maintaining the entire infrastructure necessary to use all of the transportation fuel consumed in the US. The energy intensities are rough estimates of the energy used to undertake any economic activity derived from the national mean ratio of GDP to energy (about 8.7 MJ/dollar), the Carnegie-Mellon energy calculator web site and from Robert Herendeen (personal communication). Specifically Herendeen estimates for 2005 that heavy construction uses about 14 MJ per dollar. In the 1970s insurance and other financial services had about half (7) the energy intensities as heavy industry [29].

Our calculation, then, of adding in the energy costs of getting the oil in the ground to the consumer in a usable from (40 percent) plus the pro-rated energy cost of the infrastructure necessary to use the fuel (24 percent) is 64 percent of the initial oil in the ground (Table 3). Thus the energy necessary to provide the services of 1 unit of crude oil (i.e. at the gas station) is roughly 3 units of crude oil, and probably similar proportions for other types of fuels. This cuts our 10:1 $\mathrm{EROI}_{\mathrm{mm}}$ to about 3:1 for a gallon at final use, since about two thirds of the energy extracted is necessary to do the other things required to get the service from burning that one gallon. It also means that we need a minimum EROI of 3:1 at the well head to deliver one unit from that oil to final demand.

Future research might further "extend" our "$\mathrm{EROI}_{\mathrm{ext}}$" by including the energy of all of the people and economic activity included directly and indirectly to deliver the energy. Since, as we have indicated, roughly 10 percent of the economy is associated with getting energy (this includes even those farmers who grow the grain or laborers who build the airplanes) that we as a nation might say that part of the denominator for the $\mathrm{EROI}_{\mathrm{ext}}$ would be ten percent of all of the energy used in the country.

Table 2. Estimates of energy and dollar expenditures within the total U.S. transportation sector.



Category	Dollars (10^9)	As percent of Total Dollar Expenditures	Conversion Factor (MJ/$)	Total (EJ)	As percent of Total Energy Expenditures
Federal Highway Administration Spending (2005)[1]	30	3.45%	14	0.420	3.86%
State Highway Spending (2005)[1]	11	1.26%	14	0.158	1.45%
Local Disbursements for Highway Spending (2005)[1]	57	6.55%	14	0.804	7.38%
Motor Vehicles & Parts (2005)[4]	443	50.92%	14	6.203	56.94%
Automobile maintenance (2005)[4]	143	16.44%	14	2.008	18.43%
Automobile insurance spending (2007)[5]	162	18.62%	7	1.134	10.41%
Automotive Service Technicians and Mechanics (2007)[6]	24	2.76%	7	0.166	1.52%
Total Cost of Transportation Infrastructure	**870**	**100.00%**	-	**10.893**	**100.00%**

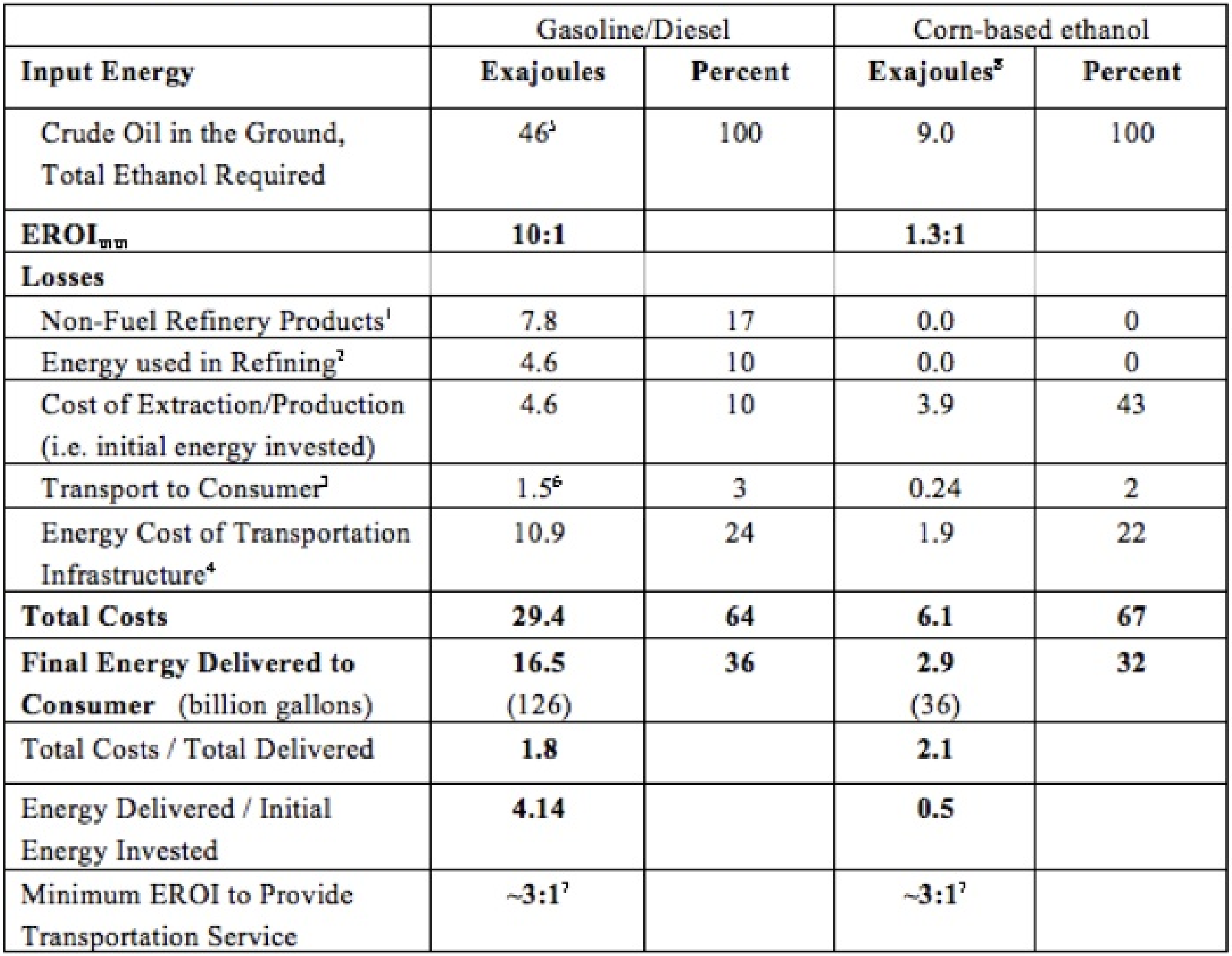
[1] FHWA: Highway statistics 2005
[2] FHWA: Motor-Fuel Use 2008
[3] EIA: Retail Motor Gasoline and On-Highway Diesel Fuel Prices, 1949-2007
[4] BEA: Personal Consumption Expenditures by Type of Product
[5] Statement Database
[6] Bureau of Labor Statistics: Occupational Employment and Wages, May 2007

An important issue here is EROI vs. conversion efficiency. The EROI technically measures just the energy used in getting the rest of the energy to some point in society, usually the well-head. But if we then say “to the consumer” we have to include the refinery losses and energy costs, and also the costs to deliver the fuel to the final consumer. It may also include the energy costs of maintaining the infrastructure to use that fuel. These are in reality a bleeding off of the energy delivered, or a conversion efficiency of moving one barrel of oil into transportation services. So whether we should say “The minimum EROI is 3:1” or, somewhat more accurately, that to deliver one barrel of fuel to the final consumer and to use it requires about three barrels to be extracted from the ground, with two being used indirectly, is somewhat arbitrary, although the second way is technically more correct.

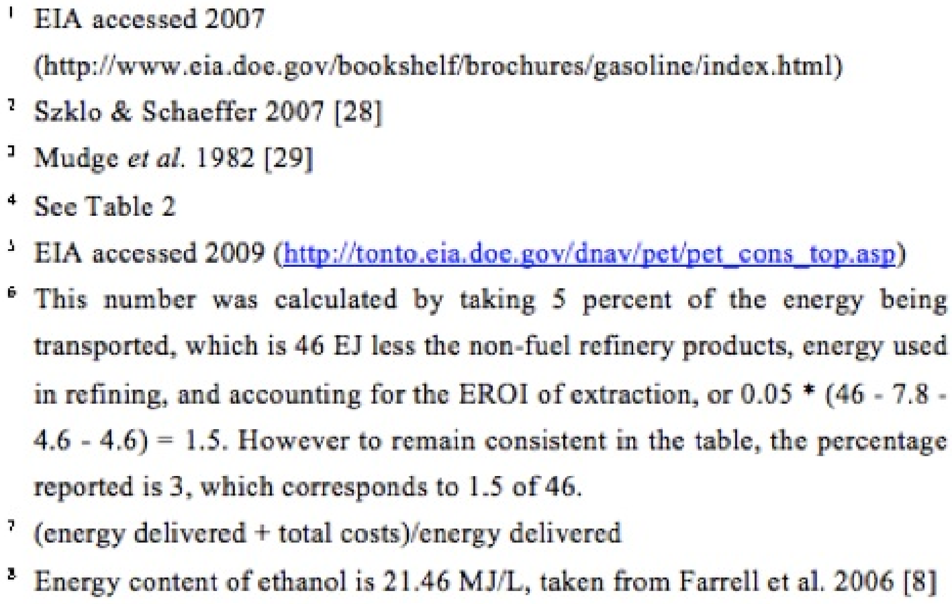
5.3. Extended EROI for Corn-based Ethanol

Given that our national goal is to deliver 36 billion gallons (2.9 EJ) of ethanol, then we can work backwards to calculate that something like 111 billion gallons of ethanol (or its equivalent of fossil fuels) would be required at the farm gate to generate and deliver the original 36 billion gallons of energy service to the end user with its attendant production, transportation and infrastructure costs. That number is the original 2.9 EJ delivered as fuel, plus 1.9 EJ for the infrastructure requirement (24/36 from oil x 2.9 EJ delivered), plus 0.24 EJ for the energy used in transportation (0.05 x (2.9 + 1.9)), plus 3.9 EJ for the energy to produce the required ethanol (0.76 x 5.1). Thus an additional 75 billion gallons (or 6.1 EJ) are required to deliver 36 billion gallons at the pump, so that an EROI of at least 3:1 is required for the fuel to not be subsidized by fossil fuels. EROIs above 3:1 are rarely reported for any liquid biofuels.

Table 3. Approximate values and percentages of costs (or losses) in delivering gasoline/diesel and corn-based ethanol to the end-user.



	Gasoline/Diesel		Corn-based ethanol	
Input Energy	**Exajoules**	**Percent**	**Exajoules[5]**	**Percent**
Crude Oil in the Ground, Total Ethanol Required	46[5]	100	9.0	100
EROI_{mm}	**10:1**		**1.3:1**	
Losses				
Non-Fuel Refinery Products[1]	7.8	17	0.0	0
Energy used in Refining[2]	4.6	10	0.0	0
Cost of Extraction/Production (i.e. initial energy invested)	4.6	10	3.9	43
Transport to Consumer[3]	1.5[6]	3	0.24	2
Energy Cost of Transportation Infrastructure[4]	10.9	24	1.9	22
Total Costs	**29.4**	**64**	**6.1**	**67**
Final Energy Delivered to Consumer (billion gallons)	**16.5** (126)	**36**	**2.9** (36)	**32**
Total Costs / Total Delivered	**1.8**		**2.1**	
Energy Delivered / Initial Energy Invested	**4.14**		**0.5**	
Minimum EROI to Provide Transportation Service	**~3:1[7]**		**~3:1[7]**	



[1] EIA accessed 2007 (http://www.eia.doe.gov/bookshelf/brochures/gasoline/index.html)

[2] Szklo & Schaeffer 2007 [28]

[3] Mudge *et al.* 1982 [29]

[4] See Table 2

[5] EIA accessed 2009 (http://tonto.eia.doe.gov/dnav/pet/pet_cons_top.asp)

[6] This number was calculated by taking 5 percent of the energy being transported, which is 46 EJ less the non-fuel refinery products, energy used in refining, and accounting for the EROI of extraction, or 0.05 * (46 - 7.8 - 4.6 - 4.6) = 1.5. However to remain consistent in the table, the percentage reported is 3, which corresponds to 1.5 of 46.

[7] (energy delivered + total costs)/energy delivered

[8] Energy content of ethanol is 21.46 MJ/L, taken from Farrell et al. 2006 [8]

Thus by both economic (Figure 1) and energetic (i.e. assuming an $EROI_{mm}$ of 10:1) measures calculated here it appears that at present roughly 10 percent of our economy is required to get the energy to run the other 90 percent, or 20 percent used to get 80 percent to the point of delivery, and even a larger percentage if the use infrastructure is included. This seems to be true if numerator and denominator are in either dollars or in energy. (Note: Our use of relatively cheap coal and hydroelectricity, both with a relatively high EROI, lifts the actual ratio “at the well-head” so that the $EROI_{mm}$ for all energy delivered to society, but not the consumer, is roughly 20:1). By the time the oil energy is delivered to the consumer, 40 percent has been used and the $EROI_{pou}$ has fallen to roughly 6:1 (including the entire refining, conversion and delivery chain). But it is energy services that are desired, not energy itself, and to create these energy services requires energy investments in infrastructure that carry, at a minimum, large entropic losses. If infrastructure costs are included, the $EROI_{ext}$ falls to about 3:1 because two-thirds of the energy has been used; implying that more energy is being spent on extraction, refining, delivering, and maintaining the transportation infrastructure than is found in the end product. Thus by the time a fuel with an $EROI_{mm}$ of 10:1 is delivered to the consumer – that is after the energy costs of refinement and blending, transport, and infrastructure are included, the $EROI_{ext}$ is 3:1. This means that twice as much oil is used to deliver the service than is used in the final-demand machine, and since most of our oil is used in transportation, including trucks and tractors, it is probably at present a reasonable number for the entire oil chain in our society.

6. Conclusions

Our educated guess is that the minimum $EROI_{mm}$ for an oil-based fuel that will deliver a given service (i.e. miles driven, house heated) to the consumer will be something more than 3:1 when all of the additional energy required to deliver and use that fuel are properly accounted for. This ratio would increase substantially if the energy cost of supporting labor (generally considered a consumption by economists although definitely part of production here) or compensating for environmental destruction was included. While it is possible to imagine that one might use a great deal of fuel with an $EROI_{mm}$ of 1.1 : 1 to pay for the use of one barrel by the consumption of many others, we believe it more appropriate to include the cost of using the fuel in the fuel itself. Thus we introduce the concept of “extended EROI” which includes not just the energy of getting the fuel, but also of transporting and using it. This process approximately triples the EROI required to use the fuel once obtained from the ground, since twice as much energy is consumed in the process of using the fuel than is in the fuel itself at its point of use. Any fuel with an $EROI_{mm}$ less than the mean for society (about 10 to one) may in fact be subsidized by the general petroleum economy. For instance, fuels such as corn-based ethanol that have marginally positive EROIs (1.3: 1) will be subsidized by a factor of about two times more than the energy value of the fuel itself by the agricultural, transportation and infrastructure support undertaken by the main economy, which is two thirds based on oil and gas. These may be more important points than the exact math for the fuel itself, although all are important.

Of course the 3:1 minimum “extended EROI” that we calculate here is only a bare minimum for civilization. It would allow only for energy to run transportation or related systems, but would leave little discretionary surplus for all the things we value about civilization: art, medicine, education and so on; i.e. things that use energy but do not contribute directly to getting more energy or other resources. Whether we can say that such “discretionary energy” can come out of an $EROI_{mm}$ of 3:1, or whether they require some kind of large surplus from that energy directed to more fundamental things such as transport and agriculture was something we thought we could answer in this paper but which has remained elusive for us thus far.

7. Acknowledgements

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