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REVIEW PAPER

Burning Water: A Comparative Analysis of the Energy Return on Water Invested

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Abstract While various energy-producing technologies have been analyzed to assess the amount of energy returned per unit of energy invested, this type of comprehensive and comparative approach has rarely been applied to other potentially limiting inputs such as water, land, and time. We assess the connection between water and energy production and conduct a comparative analysis for estimating the energy return on water invested (EROWI) for several renewable and non-renewable energy technologies using various Life Cycle Analyses. Our results suggest that the most water-efficient, fossil-based technologies have an EROWI one to two orders of magnitude greater than the most water-efficient biomass technologies, implying that the development of biomass energy technologies in scale sufficient to be a significant source of energy may produce or exacerbate water shortages around the globe and be limited by the availability of fresh water.

Keywords Biofuels · EROEI · Water · Energy production · Ethanol · Energy crops

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Some scientists now proudly claim that the food problem is on the verge of being completely solved by the imminent conversion on an industrial scale of mineral oil into food protein—an inept thought in the view of what we know about the entropic problem. The logic of this problem justifies instead the prediction that, under the pressure of necessity, man will ultimately turn to the contrary conversion, of vegetable products into gasoline (if he will still have any use for it).

Nicholas Georgescu-Roegen (1973)

Introduction

With recent volatility in oil prices and the mounting evidence of upcoming peaks in global oil and gas production, much attention has been given to the search for alternative energy sources and technologies. Similar effort has been devoted to research focused on measuring the desirability of different energy technologies (Giampietro et al. 1997; Farrell et al. 2006). Much of this research has been concerned with estimating the energy return on energy investment (EROEI) of different technologies, defined as the ratio of the energy produced by a technology to the energy, both direct and indirect, consumed by the production process (Hall et al. 1986). EROEI is known variously as net energy, energy yield, and the fossil energy ratio (Hall et al. 1986; Odum 1973). Net energy is central to an energy theory of value, which asserts that energy, not money, is what we have to spend (Hall et al. 1986; Spreng 1988). Variations of net energy analysis have been widely applied since the 1970s as a first order filter of the viability of energy harvesting technologies (Spreng 1988). While its utility is currently the subject of heated debate, much of the disagreement centers around appropriate boundaries applied to inputs and outputs, not only on *what* to include but *how* they are methodologically included (Mulder and Hagens 2008). One significant application of net energy analysis is the comparison of the EROEI of an alternative fuel to what it is replacing. If a large portion of societies' high 'net' energy fuel mix were replaced by a much lower net energy source, the energy sector itself would begin to require a majority of the energy produced, leaving less available for the non-energy sectors.

However, implicit in the attention to EROEI as a policy criterion is the assumption that energy is the sole limiting resource of importance, with the determining factor generally being whether and by how much EROEI exceeds unity. All other potentially limiting factors are implicitly assumed proportional to the energy needed to drive a process (Cleveland et al. 1984). Even studies that seek to move the focus away from EROEI, such as the analysis of ethanol by Farrell et al., restrict their focus to energy inputs. A partial exception to this is the fact that some studies examining the EROEI of a technology also estimate its potential impact upon the production of greenhouse gases (Sheehan et al. 1998).

Certainly, the energy derived from finite and renewable resources is a function of multiple inputs including land, labor, water, and raw materials. A technology might have a high EROEI and yet require sufficient levels of scarce, non-energy inputs as to be extremely restricted in potential scale. For example, the amount of land required for biofuels is between two and three orders of magnitude more than the land area required for conventional fossil fuels (Smil 2006). Another example is the recent curtailing of planned solar voltaic projects caused by a shortage of polysilicon (Flynn and Bradford 2006).

In addition to non-energy inputs, energy technologies vary on their waste outputs and impact on environment. Within the biofuels class itself, there is a large disparity of pesticide and fertilizer requirements. Per unit of energy gained, soybean biodiesel requires just 2% of the nitrogen, 8% of the phosphorous, and 10% of the pesticides that are needed for corn ethanol (Hill et al. 2006). Ultimately, if net energy analysis is to be a useful decision criterion for energy projects, it must be complemented by other measures that estimate the energy return from the investment of non-energy resources (Mulder and Hagens 2008).

Water is similar to oil in that it is embedded in all human systems, even if it is not directly recognized as such. Water withdrawals are ubiquitous in most energy production technologies. Indeed, by sector, the two largest consumers of saltwater and freshwater in the United States are agriculture and electrical power plants, both prominent players in the future energy landscape (Fig. 1) (Berndes 2002). If only fresh water is considered, fully 81% of the US use is for irrigation (Hutson et al. 2004).

Internationally, several assessments suggest that up to 2/3 of the global population could experience water scarcity by 2050 (Vorosmarty et al. 2000; Rijsberman 2006). These projections demonstrate that human demand for water will

Fig. 1 Estimated water usage by sector in the United States in 2000 (Berndes 2002)

greatly outstrip any climate-induced quantity gains in freshwater availability (Vorosmarty et al. 2000; Alcamo et al. 2005). This will be driven by the agricultural demand for water which is currently responsible for 90% of global freshwater consumption (Renault and Wallender 2006). Water shortages could become much more acute if there is wide-spread adoption of energy production technologies that require water as a significant input (Giampietro et al. 1997; Berndes et al. 2001). The need to leverage our declining fossil fuel supplies and efficiently allocate fresh water resources in the face of increasing demand and a changing hydrologic cycle are intimately linked and must be investigated as interdependent issues.

In order to explore the role of water in energy production, we apply the EROEI methodology to calculate the energy return on water invested (EROWI) for several energy production technologies. We combine this parameter with EROEI to account for the energy costs and thereby calculate what we term 'net EROWI', a preliminary measure of the desirability of an energy technology in contexts where water is, or may become, a limiting factor. Our estimates for gross EROWI and EROEI are taken from Life Cycle Analyses and other studies of energy and water usage taken from the literature. We did not use studies where we suspected significant water costs had been neglected.

Fresh water is unique in its potential for reusability. Globally, the current water stock in rivers is 2,000 km^3; the anthropogenic water withdrawals from these rivers is 3,800 km^3/year; and the global river discharge is 45,500 km^3/year (Oki and Kanae 2006). Unlike other resources, water is continually recycling. While this does not mean there are no limits on water withdrawals, it does imply that water that is withdrawn is not necessarily lost. For example, cooling water withdrawn for use by a nuclear power plant may be returned and withdrawn farther downstream to irrigate biofuels crops. However, some water does get consumed, either by being lost as steam or by being contaminated.

In this study, we attempted to parse water usage into two categories—water withdrawals and water consumed. We define water withdrawals as the diversion of freshwater from its natural hydrologic cycle, either at the surface or from below the ground, for anthropogenic purposes. Water consumed is defined as water used in the energy production process that is either lost to a given watershed as steam or contaminated beyond cost-effective remediation.

Methods

In order to calculate a gross EROWI we attempted to estimate the total water requirements per unit of energy produced. Where data allowed, we estimated separate EROWI measures for both water withdrawals and water consumed. Water consumed is likely to be much smaller than that which is actually withdrawn, and for this reason the data available generally only indicate water withdrawals. Ideally, EROWI is estimated for a given technology by applying the Life Cycle Analysis (LCA) methodology (Georgescu-Roegen 1973) to calculate freshwater usage per unit energy produced (l/MJ) for a given technology. Variations of the LCA methodology are generally used to calculate the EROEI for a technology (Hill et al. 2006) and the application to water is analogous. In particular, for each technology assessed, we sought to do the following:

1. define the technology precisely including the context of production and all assumptions regarding inputs;
2. find data in the literature for direct water inputs into the technology as well as indirect inputs defined as the water required to produce non-water inputs;
3. set the system boundaries clearly and sufficiently wide so that remaining water requirements are negligible.

Where co-products are produced at a stage in the production process (e.g. soybean meal in the production of soy biodiesel) and data allowed, price allocation was chosen to apportion the water inputs (Georgescu-Roegen 1973; Giampietro et al. 1997). Where data were available, we calculated the energy produced per unit of water consumed in addition to the EROWI for water withdrawals. Sample calculations for soy biodiesel are given in Table 1 as are details for each technology.

While the gross energy returned per unit of water invested is of interest, some technologies demand a relatively large energy investment as indicated by the EROEI. For this reason, following Giampietro et al. (1997), we used estimates of each technology's EROEI to calculate a 'net EROWI'. From both a policy and technology perspective it is the net EROWI that we are interested in because for the process to be sustainable, some of the energy yield must be reinvested as indicated by the EROEI. Thus:

$$\text{net EROWI} = \frac{\text{gross EROWI}}{\omega}$$

where ω is the EROEI/(EROEI − 1), which is the amount of energy production required to yield 1 unit of net energy (Farrell et al. 2006). Note that ω increases non-linearly

Table 1 Sample calculations for soy biodiesel

Production process	Water usage (l/MJ)	Energy usage (MJ/MJ)	Proportion of value for BD	Allocated water usage (l/MJ)	Allocated energy usage (MJ/MJ)
Soybean agriculture	76.82[a]	0.355	0.344 × 0.821[b]	21.70	0.100
Soybean transport	0[c]	0.019	0.344 × 0.821	0	0.005
Soybean crushing	0[c]	0.379	0.344 × 0.821	0	0.107
Oil transport	0[c]	0.007	0.821	0	0.006
Soy oil conversion	0.14	0.165	0.821	0.11	0.135
Biodiesel transport	0[c]	0.004	1.00	0	0.004
Total	76.96	0.929		21.81	0.357[d]

$\text{EROWI} = \frac{1}{21.81} \cdot 0.0461$

$\text{EROEI} = \frac{1}{0.357} \cdot 2.80$

$\text{Net EROEI} = \frac{2.80 \cdot 1}{2.80} * 0.0461 \cdot 0.030$

Water usage data is from Sheehan et al. (1998) and prices are 5 year averages from the US Department of Agriculture (1999–2003) (US Department of Agriculture 2005) and the US Department of Energy (2000–2004) (http://www.eere.energy.gov/afdc/)

[a] Includes irrigation according to production averages

[b] Assumes a yield of 0.111 kg of soybean meal at a value of \$0.212/kg, 0.028 kg of soy oil at a value of \$0.441/kg, 0.20 kg of biodiesel at a value of \$0.65/kg and 0.043 kg raw glycerin at a value of \$0.66/kg

[c] Less than 0.001 l/MJ

[d] Note that Sheehan et al. used mass allocation instead of price allocation and thereby calculated an allocated energy usage of 0.313 MJ/MJ of biodiesel produced

with declining EROEI, approaching infinity as EROEI approaches 1. Equivalently, net EROWI approaches 0.

Methodological Example: Calculation of Net EROWI: Soy Biodiesel

Table 1 provides a sample data table for the methodology used on each technology. First, all water inputs for each process stage were identified (see Table 2 for all data sources). In the production of soy biodiesel, two co-products—soybean meal and raw glycerin—are also produced. Water usage is allocated between the co-products based on their relative economic values as this gives the best estimate of the relative value to society of the co-products (Georgescu-Roegen 1973; Hill et al. 2006). EROWI is calculated as the inverse of total water requirements per unit of energy produced. EROEI is similarly calculated as the inverse of the total energy requirements. Since 2.80 MJ gross energy production only yields 1.80 MJ net energy, the net EROWI is given by $\frac{1.80}{2.80} * $ EROWI.

These methods and calculations were used for each of the 16 energy technologies assessed. While the methodology described above is the generally accepted procedure for LCA, it should be noted that there are many potential costs, both in terms of water and energy, that are still ignored. In particular, costs associated with environmental externalities are generally not accounted for by Giampietro et al. (1997).

Results

Using these formulae, our estimates of gross EROWI and net EROWI by technology are shown in Table 3. Gross EROWI ranged from 0.025 MJ/l for electricity production from biomass up to 285.3 MJ/l for petroleum diesel. Net EROWI for the same technologies was 0.02 and 228.4 MJ/l, respectively. However, amongst the renewable energy sources listed, the highest values, from a study by Mann and Spath (1997), were 3.86 and 3.61 MJ/l, gross EROWI and net EROWI, respectively, for biomass electricity from non-irrigated tree crops. However, these numbers appear anomalous, especially when compared to the data from a study by Berndes (2002). Mann and Spath (1997) used LCA software that did not necessarily incorporate comprehensive data on water inputs because water was not the focus of the paper (Mann, per. comm.). Setting this data aside, the best net EROWI for renewables is for sugar cane ethanol at 0.903, over two orders of magnitude lower than the most water efficient fossil energy sources (Fig. 2).

The suite of technologies reviewed for Table 3 was chosen because of data availability. To augment this analysis, we also drew on a study by Berndes showing the range of evapotranspiration for various biofuels crops and then calculated the net EROWI again. These results (Table 4) are robust as they draw on a wide range of studies and the results are congruent with the data shown in Table 3. In particular, they confirm the significantly lower water efficiency of biomass-based technologies relative to non-renewable technologies.

Indeed, the study by Kannan et al. (2004) for a petroleum power plant in Singapore shows that even electricity production, generally one of the least water efficient forms of fossil energy production, can be made very water efficient when necessary. Singapore has perennial shortages of fresh water and the petroleum power plant studied there has a gross EROWI seven times higher than typical recirculating power plants. This is because direct water withdrawals are reduced to less than 0.02 l/MJ, a number dwarfed by the lower-bound water withdrawals of 13 l/MJ for biomass electricity production indicated by Berndes (2002). This implies that the most water-efficient fossil electricity source we discovered yields almost 600 times as much energy per unit of water invested as does the most water efficient biomass source of electricity reviewed by Berndes (2002).

Discussion

Few studies regarding the scalability of biofuels explicitly consider water requirements (Berndes 2002). Similarly, no assessments of future water needs incorporate increased irrigation demands related to biofuels production (Berndes 2002). For American corn production, an average of 7,950 l of irrigation water is required per bushel (National Academy of Science 2007). At 10.22 l of ethanol per bushel, this equates to 778 l of water needed per liter of ethanol prior to refining needs.

Evapotranspiration connected to feedstock cultivation dominates the consumptive water use of bioenergy systems. Corn and other biofuel crops can be grown without irrigation, though the yields are both lower and more volatile. From 1947 to 2006, irrigated corn acreage in Nebraska had a 43% higher yield than dryland corn. (United States Department of Agriculture—National Agriculture Statistics Service 2007). The proposed Renewable Fuel Standard in the recent US Energy Bill forecasts a domestic increase in ethanol and other biofuels to at least 13 billion gallons by 2012 and 36 billion gallons by 2022. Our study suggests that, due to the much higher return on water invested of fossil energy sources, an attempt to replace a significant portion of current fossil fuel consumption with biomass resources could lead to severe strains upon the world's water resources. However, changing feedstock to more drought tolerant varieties,

Table 2 Data sources and methodology for Table 3

Technology	Key specifications	Data sources
Nuclear electric	Once-through cooling National average	Kidd (2004), Stiegel et al. (2006)
Nuclear electric	Recirculating National average	Kidd (2004), Stiegel et al. (2006)
Coal electric[a]	Once-through, sub-critical National average	Stiegel et al. (2006)
Coal electric[a]	Recirculating, sub-critical National average	Stiegel et al. (2006)
Coal electric[a]	Cooling pond, sub-critical National average	Stiegel et al. (2006)
Tar sands[b]	Steam assisted gravity drainage (SAGD) In situ—Alberta, Canada	Griffiths et al. (2006), Deer Creek (2006), Alberta C.O.R. (2006)
Biomass electric[c]	113 MW Biomass IGCC—US Non-irrigated hybrid poplar	Mann and Spath (1997)
Biomass electric[d]	IGCC Irrigated hybrid poplar—Italy	Rafaschieri et al. (1999)
Biomass electric[e]	IGCC with various feedstocks Irrigated at a rate of 400 l/kg dry biomass	Berndes et al. (2001)
Petroleum electric[f]	250 MW plant—Singapore 25 years expected plant lifetime	Kannan et al. (2004)
Petroleum diesel	Average data for US refining	Tyson et al. (1993), Sheehan et al. (1998)
Soy biodiesel[g]	1990 average US soy production 18.4% oil content	Tyson et al. (1993), Sheehan et al. (1998)
Methanol from wood[e]	Prototype technology only Various feedstocks Irrigated at a rate of 400 l/kg dry biomass.	Berndes et al. (2001)
Hydrogen from wood[e]	Prototype technology only Various feedstocks Irrigated at a rate of 400 l/kg dry biomass	Berndes et al. (2001)
Corn ethanol[h]	Dry milling technology 8,700 kg/ha corn yield, 0.37 l/kg ethanol yield	Shapouri et al. (2003), Pimentel and Patzek (2005)
Sugar cane ethanol	From non-irrigated sugar cane production in Brazil Bagasse burned to process ethanol	De Oliveira (2005), Smeets etal. (2006)

[a] Assumes wet flue gas desulphurization which adds approximately 0.065 l/MJ to both withdrawals and consumption

[b] Assumes in situ bitumen production only, which is expected to account for approximately 50% of tar sands production over next 20–30 years. The *mining* of bitumen (the other 50%) lacked sufficient data for EROWI calculations. Water data from Griffiths et al. (2006)

[c] Water data taken from Table 22 in Mann and Spath (1997). Only water used in gasification plant was considered direct withdrawals

[d] Direct water inputs are not reported and so are taken from Mann and Spath (1997)

[e] All energy inputs are assumed derived from biomass with proportional water requirements

[f] Data did not include water usage in oil recovery. Water from dedicated desalination plants could be used at an energy cost of 0.006 MJ/MJ produced. This would reduce the EROEI to 3.65 but reduce freshwater withdrawals to zero

[g] Data was adjusted to account for price allocation instead of mass allocation of co-products which was used by Sheehan et al. (1998). This also adjusted the EROEI

[h] Water input data from Pimentel and Patzek (2005). EROEI and allocation data from Shapouri et al. (2003)

improved rainwater harvesting techniques, and utilizing biomass residues and process by-flows from food and forestry industries may lessen the water intensity of bioenergy production.

Water is already a limiting resource in many contexts (Gleick 2000), and increasing human withdrawals will have a dramatic effect on the earth's ecosystems and biodiversity (Alcamo et al. 2005). Furthermore, water

Table 3 EROWI, EROEI, and net EROWI by technology

Technology	Key specifications	Water use (l/MJ)[a]		EROWI (MJ/l)[b]	EROEI	Net EROWI[b]
		Direct[b]	Indirect[c]			
Nuclear electric	Once-through cooling National average	33.25 (0.145)	NA	0.030 (6.897)	10	0.027 (6.21)
Nuclear electric	Recirculating National average	1.162 (0.659)	NA	0.861 (1.517)	10	0.775 (1.37)
Coal electric	Once-through, sub-critical National average	28.62 (0.146)	NA	0.0349 (6.849)	NA	NA
Coal electric	Recirculating, sub-critical National average	0.560 (0.488)	NA	1.786 (2.049)	NA	NA
Coal electric	Cooling pond, sub-critical National average	18.922 (0.849)	NA	0.0528 (1.178)	NA	NA
Tar sands	Steam Assisted Gravity Drainage In situ—Alberta, Canada	(0.061–0.122)	NA	(16.39–8.19)	3.75	(12.02–6.01)
Biomass electric	113 MW Biomass IGCC—US Non-irrigated hybrid poplar	0.238	0.021	3.86	15.6	3.61
Biomass electric	IGCC Irrigated hybrid poplar—Italy	0.238	3.85	0.245	1.60	0.092
Biomass electric	IGCC with various feedstocks Irrigated at a rate of 400 l/kg dry biomass	40	NA	0.025	5.0	0.02
Petroleum electric	250 MW plant—Singapore 25 years expected plant lifetime	0.01943	0.00057	50.0	3.73	36.6
Petroleum diesel	Average data for US refining	0.0035	NA	285.3	5.01	228.4
Soy biodiesel	1990 average US soy production 18.4% oil content	0.011	21.7	0.0461	2.80	0.030
Methanol from wood	Prototype technology only Various feedstocks Irrigated at a rate of 400 l/kg dry biomass.	36.8	NA	0.0271	5.5	0.022
Hydrogen from wood	Prototype technology only Various feedstocks Irrigated at a rate of 400 l/kg dry biomass.	28.3	NA	0.0353	4.67	0.028
Corn ethanol	Dry milling technology 8700 kg/ha corn yield, 0.37 l/kg ethanol yield	1.86	9.60	0.0873	1.38	0.024
Sugar cane ethanol	From non-irrigated sugar cane production in Brazil Bagasse burned to process ethanol	0.973	NA	1.027	8.3	0.903

[a] These totals primarily include the processing water required and irrigation as noted. They do not include evapotranspiration which is treated later (see Table 4)

[b] Numbers in parentheses are for water consumption i.e. contaminated or evaporated

[c] Indirect water usage refers to the water required to produce the necessary feedstock. NA implies that the data used did not allow us to differentiate between direct and indirect water usage

shortages are already limiting energy production. Numerous power plants in Europe were shut down during recent summers due to water shortages, and drought remains a significant threat to biomass production as evidenced by the impact of water rationing upon Australian agriculture in 2007 (Drought threatens crop catastrophe 2007).

Stephen Chu, in his first interview as Secretary of Energy hinted at the importance of the water/energy nexus in California when he commented about climate change, "up to 90% of the Sierra snowpack could disappear, all but eliminating a natural storage system for water vital to agriculture".

In a resource-limited context, water could be diverted from current uses to be invested in energy production, especially if the market dictates society's priorities. This could have significant impacts upon food production and

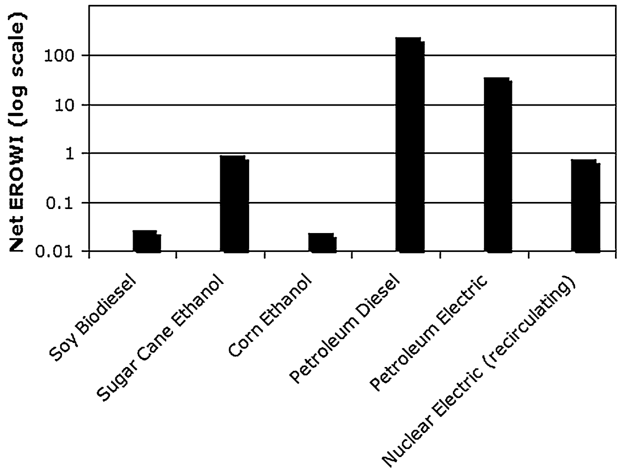

Fig. 2 Net energy returned on water invested (net EROWI) for selected energy technologies

human welfare (Pimentel et al. 1997). On the other hand, in many contexts, water may not be the most limiting input into bioenergy production—labor (Giampietro et al. 1997), land (Hill et al. 2006) and energy itself may become more limiting.

Study Limitations

Despite some early attempts at assessing water limitations on energy production which implied a clear potential for water to impact scalability (Giampietro et al. 1997), there are still very few studies that rigorously apply a methodology like LCA to determine water inputs into energy production. This is especially true in comparison to the wealth of studies that assess energy requirements and greenhouse gas emissions. Therefore, it was not always clear from the studies we drew on what boundaries were placed on the system, whether indirect water costs had been taken into consideration, or how costs were allocated for co-products. We discarded studies where significant water costs had been neglected. To do this, for each study under consideration we researched a given technology independently to be sure no major water costs had been left out. However, there is a need for more comprehensive data on water requirements of energy systems. Although this comparative analysis and methodology should be considered preliminary, we hypothesize that our results demonstrate significant variation in the water demands and thereby the scalability of different energy production technologies.

Related to the scarcity of available data is the difficulty of establishing a rigorous framework. At least three forms of water usage appear in the studies we cite—water withdrawals, water consumption, and plant evapotranspiration. Each of these represents a different type of cost, and they are not necessarily additive. Water that is used and then returned is available to downstream users. Evapotranspiration can only be interpreted as an opportunity cost since its capture or loss depends on what the alternative land-use would be. Even water consumption costs in the form of evaporation are not necessarily additive since they depend on where the water precipitates. Also, neither fossil nor renewable energy is spatially uniform around the world, which further complicates one uniform measure of net EROWI (Smil 2006). The tar sands have a moderate energy return, but are all located in one unique geologic region in Alberta, putting enormous pressure on local water resources would they be scaled fully.

A related issue is that at least some freshwater inputs into energy production (e.g. water injections for enhanced

Table 4 EROWI, EROEI, and net EROWI for biomass energy technologies

Biofuel/feedstock	Water usage (l/MJ)	EROWI (MJ/l)	EROEI estimate	Net EROWI
Biodiesel				
Rapeseed	100–175	0.010–0.0057	2.33	0.0057–0.0033
Ethanol				
Sugarcane	38–156	0.026–0.0065	8.3	0.023–0.0057
Sugar beet	71–188	0.014–0.0053	2.25	0.0078–0.0029
Corn	73–346	0.014–0.0029	1.38	0.0039–0.00081
Wheat	40–351	0.025–0.0029	2.40	0.015–0.0017
Lignocellulosic crops				
Ethanol	11–171	0.091–0.0058	4.55	0.071–0.0045
Methanol	11–138	0.091–0.0072	5.5	0.075–0.0059
Hydrogen	15–129	0.067–0.0078	4.67	0.053–0.0062
Electricity	13–195	0.077–0.0051	5.0	0.062–0.0041

Table adapted from Berndes (2002). The first column shows the range of water consumption (evapotranspiration) in feedstock production. The low water usage numbers for lignocellulosic crops are based on non-irrigated *Miscanthus* production. EROEI estimates not used in Table 3 are from Mortimer et al. (2003) and Lynd and Wang (2004) petroleum recovery) can be replaced by saltwater where available. Both of these issues argue for assessing the scalability of energy production in a spatial context. Incorporating temporal variation in precipitation patterns and predicted changes related to climate change also seems prudent.

Energy can also be invested in the desalinization of seawater. According to Kannan et al. (2004), the energy requirements to desalinize sufficient quantities of water to operate the petroleum power plant they studied in Singapore would only reduce the EROEI of the technology by 0.02. If waste heat from the plant is used for desalinization, the reduction in EROEI is only 0.01. In particular, from their data we calculate an energy cost for dedicated desalinization of 0.11 MJ/l. However, this is higher than any EROWI for all bioenergy technologies we review with the exception of sugar cane ethanol and the study by Mann and Spath (1997).

Regarding our methodology for calculating net EROWI, there are several aspects that would benefit from further analysis of more intricate tradeoffs between these two vital commodities. First, although much literature describes discrete levels of Energy return on investment (EROEI), a large component of the net EROWI will depend on the boundaries used in the net energy analysis itself. For example, Fig. 3 illustrates numerous EROEI calculations from the same wheat-to-ethanol process, using different boundaries and formulas (Börjesson 2008). A framework for parsing these differences into commensurate EROEIs is an important step toward more meaningful net EROWI figures.

Furthermore, the mixing of the energy quality of both inputs and outputs highlights an ongoing problem with net energy studies. Not only are all BTUs unequal in their value to society, but the markets pricing hierarchy of energy 'types' by cost, may not correlate with long-term scarcity. The quality issue is further complicated by cost/benefit tradeoffs within different energy/water technologies that could increase EROWI while decreasing EROEI just by altering how an input is procured. For example, nitrogen fertilizers (the dominant energy cost of fertilizers) are mostly produced using natural gas, but future electricity could be generated from a different subset of primary energy sources, lowering the energy input for biofuels. As energy is also an input for irrigation and water delivery systems, an interesting and relevant follow-up to this article might be an analysis of the Water Return on Energy Invested.

Finally, demand side policy changes may have water implications just as will the supply side. The current move toward electric vehicles, without a major change in the sources of electricity would create major new water demand. If hybrid/electric cars would fully replace gasoline vehicles, approximately three times more water is consumed and 17 times more water is withdrawn, primarily due to increased water cooling of increased thermoelectric

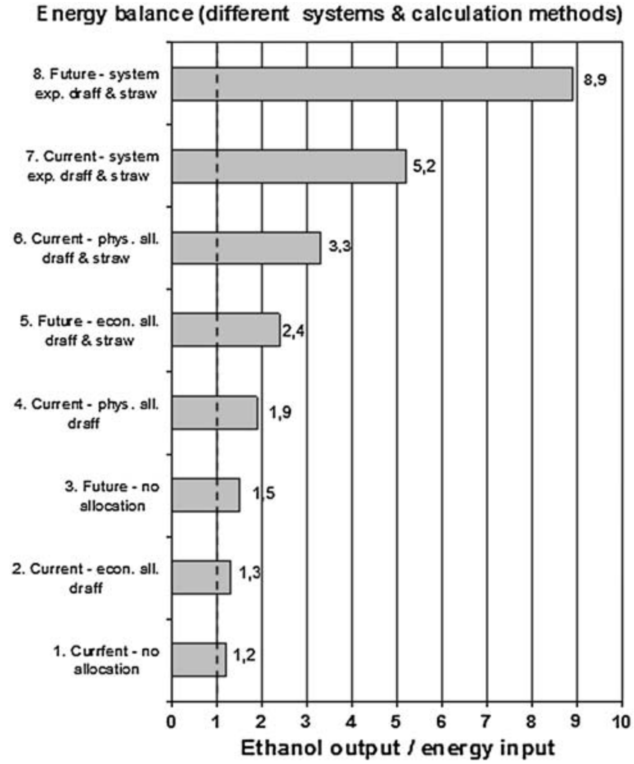

Fig. 3 Energy balance—different system boundaries (Börjesson 2008)

generation (Webber and King 2008). Furthermore, demand side moves away from meat consumption would allow more land to be used for bioenergy as the water/land intensity is much lower for vegetarian than meat intensive diets (Berndes 2008). As such, future refinements to an energy and water framework will likely have to extend beyond those two vital commodities.

Conclusion

There is increasing concern that conventional market mechanisms may not give correct or timely signals to a world dependent on the energy services obtained from fossil fuels. EROEI attempts to focus on limited natural resources as opposed to conventional financial analysis which, by relying on a potentially infinite metric (currency), can give a false impression of the wealth available to the world (Georgescu-Roegen 1973; Hall et al. 1986; Odum 1973; Spreng 1988; Soddy 1933). Energy (and other scarce resources including water) is what we have to spend—financial capital is just a marker for such real assets. However, despite the decades-old and ongoing debate over the energy balance of biofuels, we have demonstrated that the EROEI of an energy technology is only a partial indicator and will fail to correctly inform policy and investment if factors other than energy become limiting. Although it can be modified to account for issues such as energy quality (Cleveland 1992) or refined to express returns in terms of specific energy inputs (Farrell et al. 2006), it still suffers from a restrictive focus on energy alone—the one resource that we know an energy production technology can replace (Cleveland 2005).

Past study has demonstrated that a primary advantage of fossil energy resources is their large EROEI (Cleveland 2005; Tainter et al. 2006). In this study, we have demonstrated that they also have a strong advantage in many cases in terms of their return on water invested. Biofuels have been touted as a key development that will stem future fossil fuel emissions and associated climate change impacts (Tilman et al. 2006b; Goldemberg 2007; Ragauskas et al. 2006), and the development of biofuel production facilities and processing techniques has been supported by multinational oil corporations and federal governments alike (Sanderson 2007). However, research assessing the future of biofuel production rarely considers the wider effects such as impacts on ecological systems and the availability of land and water resources (Tilman et al. 2006a; Goldemberg 2007). It has been shown that these impacts are potentially very large (Hagens et al. 2006; Tilman et al. 2006b). Additionally, the demand for corn as a feedstock for biofuel production has had secondary consequences for corn prices and land demand (Kennedy 2007; Odling-Smee 2006) and hence human welfare. The ripple effects of demand increases will likely include increasing land conversion, habitat destruction, fertilizer use, and water withdrawals. All of these consequences should be considered in assessing how society should replace our reliance on fossil fuels.

Our study here, looking only at water demand, predicts:

- the development of bioenergy in scale sufficient to be a significant source of energy will likely have a strong, negative impact upon the availability of fresh water;
- assuming the water requirements for infrastructure development are minimal, technologies such as solar and wind which do not require on-going water inputs will be at an advantage in many contexts.

Above all, we believe our analysis demonstrates that energy technologies must be assessed in a multi-criteria framework and not just from the perspective of energy alone. Ultimately, we should strive to have a renewable resource portfolio aggregating the highest returns on our most limiting inputs (Mulder and Hagens 2008).

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