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Net energy yield from production of conventional oil

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ABSTRACT

Historic profitability of bringing oil to market was profound, but most easy oil has been developed. Higher cost resources, such as tar sands and deep off-shore, are considered the best prospects for the future. Economic modelling is currently used to explore future price scenarios commensurate with delivering fuel to market. Energy policy requires modelling scenarios capturing the complexity of resource and extraction aspects as well as the economic profitability of different resources. Energy-return-on-investment (EROI) expresses the profitability of bringing energy products to the market. Net energy yield (NEY) is related to the EROI. NEY is the amount of energy less expenditures necessary to deliver a fuel to the market. This paper proposes a pattern for EROI of oil production, based on historic oil development trends. Methodology and data for EROI is not agreed upon. The proposed EROI function is explored in relation to the available data and used to attenuate the International Energy Agency (IEA) world oil production scenarios to understand the implications of future declining EROI on net energy yield. The results suggest that strategies for management and mitigation of deleterious effects of a peak in oil production are more urgent than might be suggested by analyses focussing only on gross production.

1. Background

Energy is fundamentally important to all of the processes that occur within our modern, (post)industrial society. Of all the energy resources in use, none is so vital as oil. It is an essential commodity that allows our transportation system to function, distributing much-needed food and resources among all corners of the globe.

The issue of the possibility, timing and mitigation strategies of the peak in global oil production has been discussed previously in this publication (Lloyd and Subbarao, 2009; Bentley et al., 2007; Greene et al., 2006; Alekett et al., 2010; Hirsch, 2008; Tsoskounoglou et al., 2008). Net energy analysis (NEA) and EROI have also been discussed (Chapman et al., 1974b; Leach, 1975; Bullard and Herendeen, 1975; Peet et al., 1987; Jefferson, 2008; Shaw et al., 2010; Lloyd and Forest, 2010; Sorrell et al., 2010).

Instead of focussing on total oil production, this paper looks at the net energy yield from oil production, i.e. the energy available to the economy from oil production, less the amount needed to deliver it. Consideration of this net energy perspective suggests that the implementation of peak oil mitigation and management strategies is more urgent than previously supposed.

1.1. Peak oil

Many of the oil resources currently in production were discovered decades ago. Discovery of new oil fields peaked in the sixties (Campbell and Laherrere, 1998). Production from an oil field has a very distinctive peaking shape with the peak in production, depending on the size of the field, occurring between 10% and 30% of the initial proved and probable (2P) reserves have been produced (IEA, 2008). The combined output of many such fields also has a peaking shape which could represent the production from a particular basin, country, region or even total global production. A number of major oil producing countries have already passed their peak in oil production. These include the USA (1972), Iran (1974), Russia (1987), the UK (1999) and Norway (2001) (BP, 2008). The issue of a peak in global oil production—peak oil—has been gaining greater attention in recent years since, thereafter, the availability of oil may become a serious constraint to economic opportunity and even continued well-being of countries currently dependent on such supplies.

A number of organisations, such as the International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC) and the UK Energy Research Council (UKERC), have made projections of future oil production. These are often based on economic

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models, such as MESSAGE (Messner and Strubegger, 1995), MARKAL (Seebregts et al., 2001) and the IEA's WEM (OECD/IEA, 2009). The IEA's projections for conventional oil production from the World Energy Outlook (WEO) 2008 and 2010 are plotted in Fig. 11. These predict a continued increase in production over the period to 2035, however the predicted increase is somewhat diminished between the WEO 2008 and WEO 2010 projections.

Hirsch (2008) distinguishes three scenarios for peak oil mitigation strategies:

1. Best case scenario: Maximum world oil production is followed by a period of relatively flat production (a plateau) before the onset of a decline rate of 2.5% per year.
2. Middling case scenario: World oil production grows to a relatively sharp break maximum, after which it goes into a monotonic decline (2.5% per year).
3. Worst case scenario: A sharp break worsened by oil exporter withholding, leading to rapid declining world oil production (potentially greater than 2.5% per year). The timing of withholding is not predictable, but it could easily occur before the peak in the middling case.

He goes on to say that, 'early mitigation will almost certainly be less expensive and less damaging than delayed mitigation,' since, 'it requires a very long time to build a substantial number of substitute liquid fuel production facilities and/or generators of alternate energy forms.'

1.2. Energy analysis

Energy analysis is the process of measuring the energy flows through the process or system under investigation. According to Boustead and Hancock (1979), 'Energy analysis is a technique for examining the way in which energy sources are harnessed to perform useful functions' Peet (1992) classifies energy analysis as, 'determination of the amount of primary energy, direct and indirect. That is dissipated in producing a good or service and delivering it to the market' reflecting the current focus of energy analyses on economic activities. Energy analysis is important for a number of reasons:

- firstly, because of the adverse environmental impacts linked with energy transformation processes, especially of concern recently being the emission of greenhouse gases associated with the combustion of fossil fuels;
- secondly, because of the finite availability of fuels and other energy resources and;
- thirdly, because of the strong link between net energy and the material standard of living and economic opportunity offered by a society (Hall et al., 1986).

There is an evidence that the quality (i.e. net energy returns) of the major energy sources used by modern, industrial society are declining (Cleveland, 2005).

1.3. Net energy and EROI

Energy production processes in particular and the energy sector in general serve society by producing surplus energy yields over and above the energy required to provide those services. An energy sector that requires all of the energy that it produces to fuel its own processes is of little use to society.

Whereas standard econometric energy models, such as MESSAGE, MARKAL and the IEA's WEM (OECD/IEA, 2009), account only for gross production by the energy sector, P, net energy analysis (NEA) considers all energy flows between the energy sector and the rest of the economy, as depicted in Fig. 1.

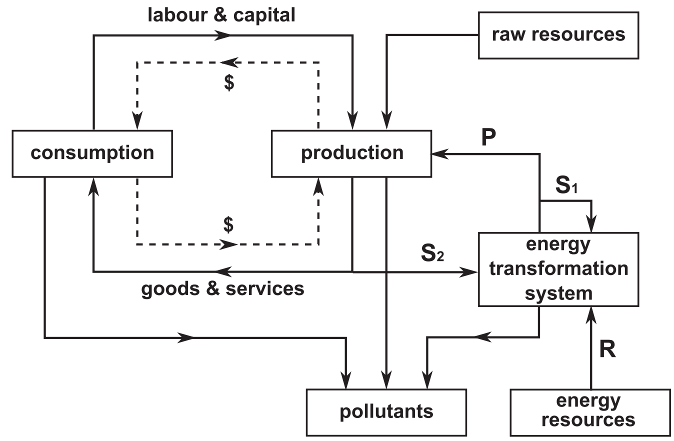

Fig. 1. Energy and material flows between the energy sector and the main economy based on diagram from Gilliland (1975).

The energy sector receives two 'inputs' from the rest of the economy in order to produce energy. Inputs in the form of energy, S_1 enable the energy sector to run its equipment, i.e. process energy. Inputs in the form of human-made-capital (HMC), S_2, are the physical plant that must be put in place in order to extract energy from the environment, e.g. oil wells, wind turbines, hydro dams, etc.

The net energy yield or benefit, the gross energy production less energy needs for extraction and processing, is $P-(S_1+S_2)$. The ratio of energy yield to the energy needed to obtain this yield, $P/(S_1+S_2)$, is known as the net energy ratio (NER) or energy-return-on-investment (EROI) (Baines and Peet, 1983; Hall et al., 1986).

A reduction in net energy yield may occur for one of three reasons:

1. the energy flow rate of the resource is declining, such as an increase in the water production of an oil field;
2. more energy is required to extract the resource, such as oil extraction by pumping down steam or gas during enhanced oil recovery (EOR) or;
3. both 1 and 2 are occurring simultaneously.

In all cases, the amount of energy required to produce a unit of energy output increases. This greater energy requirement will either be made up by utilising energy flows from within the same energy production process (internal), such as an oil producer using oil from the field to produce steam for EOR, or from energy flows originating outside of the process (external), such as an oil producer using coal or natural gas for the same purpose. In the latter case, the oil production process may be competing directly with other end-uses for the energy. Many authors have begun investigating the effects that declining EROI values will have on the economy (Hall et al., 1986; Gever et al., 1991; Peet, 1992; Cleveland, 1993, 2005; Hall et al., 2008).

Most estimates of EROI are made as static estimates of a resource at a particular moment in time. The authors have located over 500 such estimates for all of the energy resources currently under development, as well as some still under R&D. However some dynamic estimates have been made which track the EROI of a particular resource as it changes over time. A number of such studies track the EROI of oil production from various resources (Cleveland et al., 1984, 2000; Cleveland, 2005; Hall et al., 1986; Leach, 1976; Chapman et al. 1974a,b). These studies conclude that the EROI of most fossil fuel resources has been either (relatively) stable at an EROI of between 20 and 40 or decreasing over time,

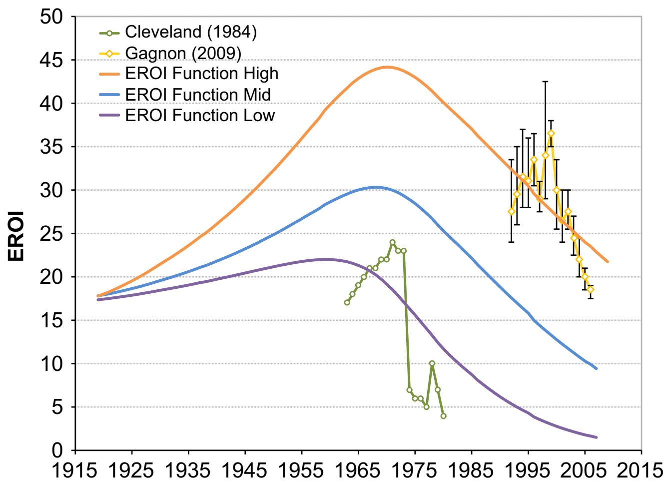

Fig. 2. EROI of global oil production [REFS—XXXX]. The smooth lines are high, mid and low cases of the EROI function described in the method section fitted to the EROI data (Cleveland et al., 1984; Gagnon et al., 2009).

some from an EROI of over 100. Such high values of EROI indicate a very quick payback on energy (and financial) investments to the oil production process, reflecting the large profitability of such investment.

One such study has been conducted by Costanza and Cleveland (1983) of oil and gas production in Louisiana. They identify a very characteristic shape for the EROI as a function of cumulative production, wherein the EROI first increases and then declines as production continues.

Two studies have analysed the EROI of global oil production (Cleveland et al., 1984; Gagnon et al., 2008). Cleveland et al. (1984) calculate the EROI of oil imported into the US by determining the energy intensity of exported goods equivalent in value to the imported oil. This will be taken as a proxy measure for the EROI of global oil production. Data from these studies is shown plotted in Fig. 2.

1.4. Implications of the net energy perspective

Society produces energy in order to accomplish a range of tasks from heating homes to transporting goods and people. It is the net, not gross, energy yield from the energy sector that enables these tasks to be carried out. An energy sector that produces no net energy yield is of no use to society. Accounting only for gross energy production disguises many fundamental changes that are occurring within the energy sector.

1.5. Effects of the peak in net energy yield from oil production

After a peak in the net energy yield from a resource has occurred, less and less of that resource is available for consumption within the economy, despite possible continued increases in gross production. This 'shortfall' in energy must be provided either by increasing self-consumption of that energy resource within the production chain, or by increasing inputs of other energy resources. In the latter case, the production process acts as an 'indirect' conversion of a more abundant resource, e.g. coal, for a more economically desirable resource, e.g. oil and may occur at cheaper cost than a 'direct' conversion such as coal to liquid processes. This peak may serve to increase the price of, not only the peaking resource, but other resources too. A clear understanding of such a scenario may only be provided by explicitly incorporating net energy analysis.

2. Method

2.1. A dynamic function for EROI

2.1.1. Theoretical considerations

Taking Costanza and Cleveland's model as a basis, the EROI of a resource initially increases before reaching some point of production, P_{max}, at which point the energy return is at its maximum value, before declining and eventually dropping below the break-even limit represented by an EROI value of one (Fig. 3). We now offer an explanation for the shape of this curve.

Assuming that this cycle corresponds with the *production cycle* identified by Hubbert (1956) for non-renewable resources, at what point in the production cycle will P_{max} occur? We conjecture that P_{max} should occur a quarter of the way through the production cycle. Hubbert's curve for annual production, $\dot{P}$, as shown in Fig. 4, initially increases exponentially before reaching a peak and thereafter declining. This curve passes through a point of inflection a quarter of the way through the cycle, corresponding to a maximum in the rate of change of annual production, i.e. the first derivative of annual production with respect to time, $\ddot{P}$.

The purpose of investment in increasing infrastructure is to buy an increase in annual production, therefore we may say that

$$\ddot{P}[\mathrm{EJ/yr}] \propto EROI[\mathrm{dmnl}] \times K[\mathrm{EJ/yr}] \tag{1}$$

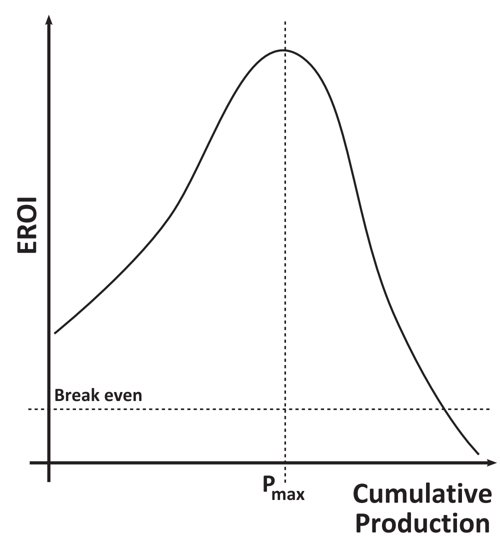

Fig. 3. EROI of oil and gas production in Louisiana as a function of cumulative production, from Costanza and Cleveland (1983).

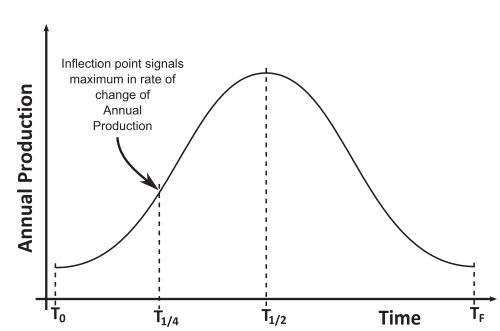

Fig. 4. Annual production over the entire *production cycle* of a non-renewable resource; the 'Hubbert curve'. If production is symmetric then the maximum change in the annual production occurs at the inflection point at $T_{1/4}$.

where K is capital investment in terms of embodied energy of infrastructure.

Presumably investment in infrastructure and operation increases exponentially (or at the very minimum linearly) between T_0 and $T_{1/2}$. If so, then annual production and investment are correlated between T_0 and $T_{1/4}$. Thereafter, each unit of investment earns less return in energy production, reflected in the decreasing rate of change of energy production, $\ddot{P}$. Since EROI is the correlating factor between investment and energy production, then EROI must be decreasing and, hence, must have peaked before $T_{1/4}$ in the production cycle. This would not be the case if investment were constant (in which case P_{max} would occur when $\dot{P}$ is a maximum) or if investment were decreasing over the period. However, both of these cases seem unlikely.

Within this work, we posit that this curve for the EROI is representative of, not only Louisiana oil and gas, but all non-renewable resources. The total EROI of the global resource should be an aggregation of the EROI, weighted by the amount of production, of many smaller fields or regions. We further assume that this EROI function is a product of two components: one technological, G, that serves to increase energy returns as a function of cumulative resource production (which serves as a proxy measure of experience, i.e. technological learning); and the other, H, diminishing energy returns due to declining physical resource quality. At the regional level, it may occur that some fields with lower returns (such as fields in the US during the early seventies) are developed before fields with higher returns (such as Middle Eastern oil in the eighties). However, the aggregation of many peaking functions will yield a global peaking function, which can be separated into these two components. The function $F(p)$ is depicted in Fig. 5 along with the two components:

$$F(p)[\text{dmnl}] = \varepsilon G(p)H(p) \tag{2}$$

where ε is a scaling factor that increases the EROI and p is cumulative production normalised to the size of the ultimately recoverable resource (URR),[1] such that

$$p[\text{dmnl}] = \frac{P[\text{EJ}]}{URR[\text{EJ}]}$$

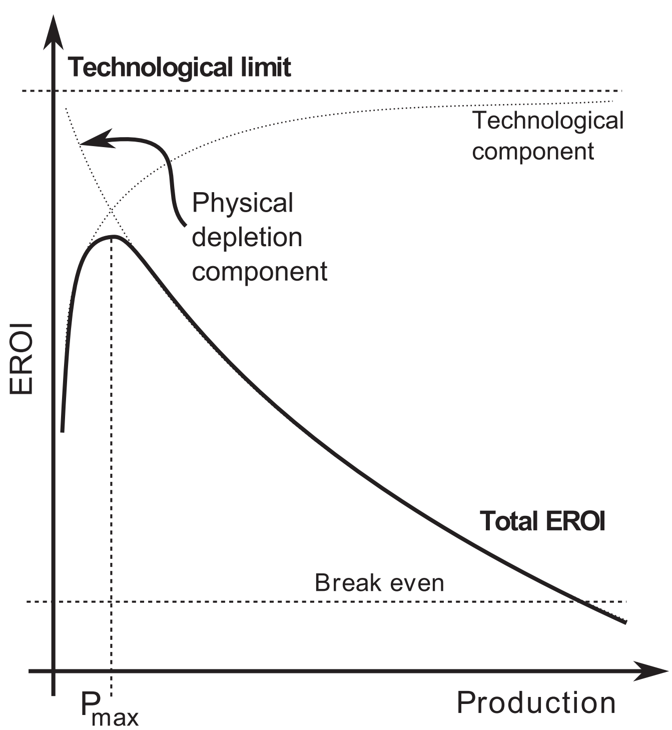

Fig. 5. EROI as a function of cumulative production. The (decreasing) physical depletion and (increasing) technological components are shown as dotted lines.

2.1.2. Technological component

We assume that the technological component of the EROI function asymptotically increases as a function of production as shown in Fig. 5. There are two factors that will influence this technological component of the EROI function: how much energy must be embodied within the equipment used to extract energy and how well that equipment performs the function of extracting energy from the environment. We assume that both of these factors are subject to strict physical limits. Firstly, that there is some minimum amount of energy that must be embodied in order to function as an energy extraction device, for instance the foundation of a wind turbine must successfully endure a large moment load. Secondly, there is a limit to how efficiently a device can extract energy. We further assume that, as a technology matures, i.e. as experience is gained, the processes involved become better equipped to use fewer resources: PV panels become more efficient and less energy intensive to produce; wind turbines become more efficient and increasing size allows exploitation of economies of scale. These factors serve to increase energy returns. However, it can be expected that these increases are subject to diminishing marginal returns as processes approach fundamental theoretical limits, such as the Lancaster–Betz limit in the case of wind turbines.

Technological learning curves (sometimes called cost or experience curves) track the costs of production as a function of production. These often follow an exponentially declining curve asymptotically approaching some lower limit. The progress ratio specifies the production taken for costs to halve. Between 1976 and 1992, the PV module price per watt of peak power, Wp, on the world market was 82% IEA (2000). This means that the price halved for an increase in cumulative production of 82%. Lower financial production costs should correlate with lower values of embodied energy (Hall et al., 1986; Costanza and Cleveland, 2004; Liu et al., 2008). The specific form of the function is

$$G(p)[\text{dmnl}] = 1 - X \exp^{-\chi p} \tag{3}$$

where $0 < X \leq 1$.

Here X represents the initial value of the immature technology and χ represents the rate of technological learning through experience, which will depend on a number of both social and physical factors. This rate is assumed to be constant.

2.1.3. Physical depletion component

The physical resource component of the EROI function is assumed to decrease to an asymptotic limit as a function of production, as shown in Fig. 5. In general, those resources that offer the best returns (whether financial or energetic) are exploited first. Attention then turns to resources offering lower returns as production continues. In general the returns offered by an energy resource will depend upon the type of source, formation and depth of the reserve, hostility of the environment, distance from demand centres and any necessary safety or environmental measures. The costs of production often increase exponentially with increases in these factors Cook (1976). The result is that the physical component of the EROI of the resource declines as a function of production. We assume that this decline in EROI, H will follow an exponential decay:

$$H(p)[\text{dmnl}] = \Phi \exp^{-\phi p} \tag{4}$$

where $0 < \Phi \leq 1$.

[1] Within this work URR is assumed to be the total resource that may be recovered at positive net energy yield.

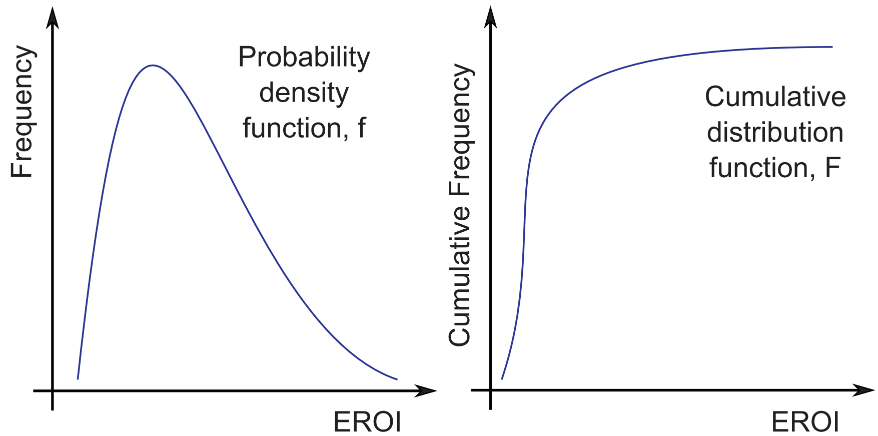

Fig. 6. Probability density function and cumulative distribution function for EROI of an energy resource.

Here Φ represents the potential EROI value of the virgin resource assuming an optimal production technology and ϕ represents the rate of degradation of the resource due to exploitation. Again this rate is assumed constant.

We justify this exponential curve by considering the distribution of energy resources. Some of these resources will offer large energy returns due to such factors as their energy density (e.g. grades of crude or coal), their ease of accessibility (e.g. depth of oil resources, on-shore vs. off-shore), their proximity to demand centres (e.g. Texan vs. Polar oil) and possible other factors. The EROI of one particular source should be, if not normal, then most likely displays a positive skew, i.e. the median is less than the mean, as depicted in Fig. 6. For example, there are more sites with lower average wind speeds than with higher wind speeds.

If we now assume that sites will be exploited as a function of their EROI, i.e. that those sites offering the best energy returns are exploited first, then we may now re-plot the cumulative distribution function as EROI depletion as a function of exploitation, i.e. production by rotating the axes and ranking the sites by EROI from highest to lowest (Fig. 7).

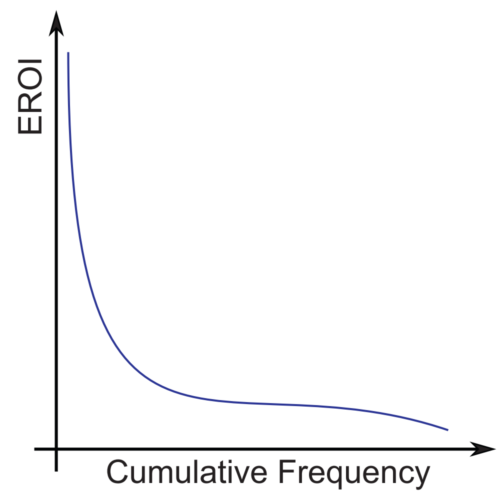

Fig. 7. Decline of EROI of energy resource due to exploitation of best resources.

2.1.4. Finding P_{max}

Since the EROI function for non-renewable resources is assumed to be a well-behaved function, the point P_{max} may be found via differentiation. P_{max} occurs at the value of p at which $(d/dp)(EROI(P_{max}))=0$. Using the product rule finds that

$$\frac{d}{dp}EROI=\frac{d}{dp}[F(p)]=\frac{d}{dp}[\varepsilon G(p)H(p)]$$

$$\Rightarrow \varepsilon\left[G\frac{dH}{dP}+H\frac{dG}{dP}\right] \quad (5)$$

Differentiating G and H, gives

$$\frac{dG}{dp}=X\chi \exp^{-\chi p} \quad (6)$$

$$\frac{dH}{dp}=-\Phi\phi \exp^{-\phi p} \quad (7)$$

Substituting Eqs. (6) and (7) into Eq. (5) obtains

$$(1-X\exp^{-\chi P_{max}})(-\Phi\phi \exp^{-\phi P_{max}})+(\Phi \exp^{-\phi P_{max}})(X\chi \exp^{-\chi P_{max}})=0$$
$$\Rightarrow X\Phi(\phi+\chi)\exp^{-\chi P_{max}}\exp^{-\phi P_{max}}=\Phi\phi \exp^{-\phi P_{max}}$$
$$\Rightarrow X(\phi+\chi)\exp^{-\chi P_{max}}=\phi \quad (8)$$

Taking the natural logarithm of Eq. (8) obtains

$$\ln(X(\phi+\chi))-\chi P_{max}=\ln(\phi)$$

$$\to P_{max}=\frac{\ln(X)+\ln(\phi+\chi)-\ln(\phi)}{\chi} \quad (9)$$

2.1.5. The EROI function for renewable resources

Unlike non-renewable sources, for which the EROI is solely a function of cumulative production, in the case of renewable energy sources the physical component of EROI is a function of annual production.[2] In this case a reduction in production means that the EROI may 'move back up the slope' of this physical component. In the interim, technology, which is a function of cumulative production, will have increased, further pushing up energy returns. This entails that the EROI of a renewable energy source is a path dependent function of production.

Decline in the physical component of EROI for renewable energy sources represents the likelihood of the most optimal sites being used earliest. For example, deployment of wind turbines presently occurs only in sites where the average wind speed is above some lower threshold and that are close to large demand centres to avoid the construction of large distribution networks. Over time, the availability of such optimal sites will decrease, pushing deployment into sites offering lower energy

[2] The technological component will still be a function of cumulative production, which serves as a proxy measure of experience.

returns, which should be reflected in declining capacity factors over time.

2.1.6. Supporting evidence

We provide supporting evidence for the EROI function presented by considering wind and solar resources for the US as a case study. The technological component of the EROI may be increased by the production of wind turbines that are able to better extract energy from the passage of air. This increase is subject to an absolute physical limit represented by the Lancaster–Betz limit Rauh and Seelert (1984) which defines the maximum proportion of energy that may be extracted from a moving column of air as $16/27 \simeq 60\%$. Experience curves for wind farms show that long-term costs of energy production from wind have fallen exponentially as a function of cumulative energy production (a proxy for 'experience') (Junginger et al., 2005).

The resource base for wind has been extensively (and intensively) mapped in several regions of the world. The National Renewable Energy Laboratory (NREL) Western Wind Dataset (NREL, 2010b) was used to produce a depletion curve of the US wind resource, ranked by power density (W/m^2) shown in Fig. 8. The power density of the wind resource initially declines exponentially as a function of land area, before dropping sharply below 500 W/m^2.

NREL have also produced the National Solar Radiation Database (NSRDB), for the mainland US (NREL, 2010a). This data was used to produce a depletion curve of the US solar resource ranked by energy flux density (Wh/m^2/day) shown in Fig. 9. The energy flux density of the solar resource declines exponentially as a function of total land area from a maximum of just over 8000 Wh/m^2/day.

Brandt (in press) has made a long-term study of the EROI of oil production in California between 1955 and 2005. The EROI of this oil at the mine-mouth is shown in Fig. 10. An exponentially decreasing curve is shown for comparison. The initial decline is greater than exponential.

2.2. Application of the EROI function to oil production

Using the dynamic EROI function, the net energy production, N, can be calculated from historic energy production, P, via the formula:

$$N = P\left(\frac{EROI}{EROI+1}\right) \tag{10}$$

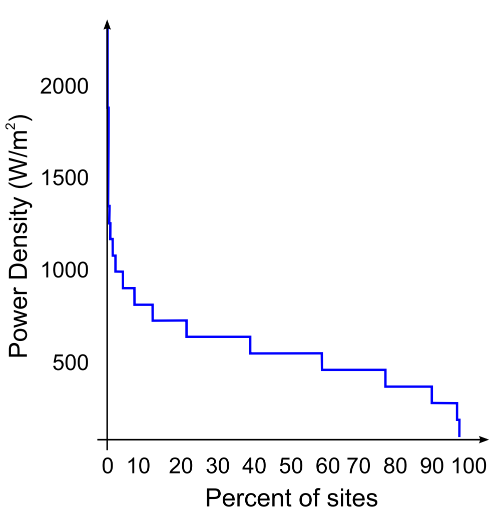

Fig. 8. Depletion curve for the wind resource in the United States ranked by power density (W/m^2) as a percentage of total land area. The quality of the wind resource decreases exponentially.

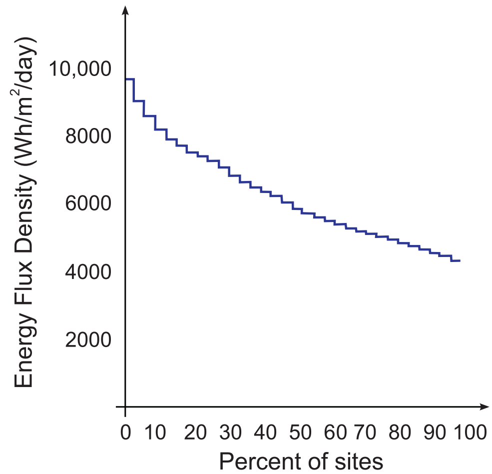

Fig. 9. Depletion curve for the solar resource in the United States ranked by energy flux density (Wh/m^2/day) as a percentage of total land area. The quality of the solar resource decreases exponentially.

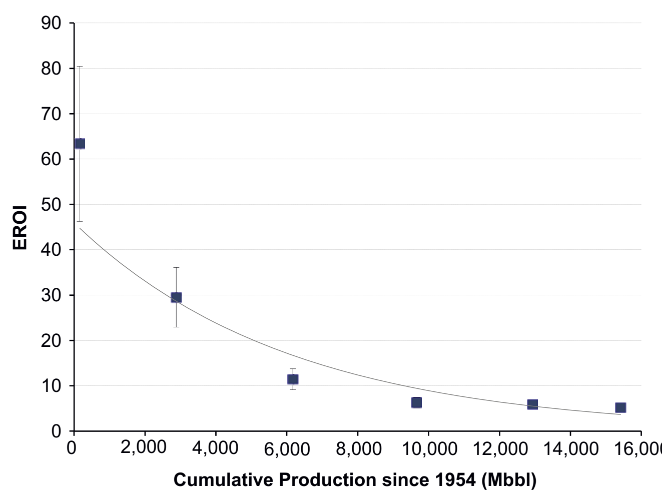

Fig. 10. EROI at the mine-mouth for California oil production between 1955 and 2005 plotted as a function of cumulative production with exponential curve plotted for comparison.

Table 1
Parameter values from curve-fitting procedure.

Case	Peak EROI, ε	URR [EJ]	X	χ	Φ	ϕ	P_{max} [% URR]
High	60	14,000	0.75	20	1	2	11
Mid	55	11,500	0.7	10	1	3	11
Low	55	15,000	0.7	11	1	8	5

2.2.1. Fitting parameters to historic EROI data

Firstly, best-fit values for the parameters, X, χ, Φ and ϕ and peak EROI, ε were found using a residual sum of squares minimisation procedure using weighting factors for the historical estimates of EROI (from Cleveland et al., 1984; Gagnon et al., 2009) for production of conventional oil. The parameter values are listed in Table 1.

The results of the curve-fitting procedures are shown in Fig. 2. The peak in EROI occurs in the early seventies at a value of just over 30.

3. Results and discussion

The data for historic production of conventional oil has a very distinctive shape, plotted in Fig. 11. Production proceeded exponentially between 1950 at a level of 21 EJ/yr up to a level of 122 EJ/yr in 1975, when the OPEC oil embargo caused a stall in production. Production continued to increase up to a level of 138 EJ/yr in 1980 when supply was interrupted by the Iran War and rising prices diminished demand. Oil production did not reach the 1980 level again for a decade until 1990 and has since increased more or less linearly. The International Energy Agency (IEA) publishes a yearly World Energy Outlook (WEO), in which projections are made for future production from conventional oil. Projections from the WEO 2010 are also plotted in Fig. 11. Using the estimates of EROI and the high, mid and low EROI functions found in the previous section to determine the net energy yield from conventional oil produces the results also plotted in Fig. 11.

In the high EROI case, net energy production in 2007 is 170 EJ/yr, around 96% of gross production. Applying this high case to the IEA WEO 2010 projection, we see that the net energy yield increases to a value of 175 EJ/yr in 2018, around 94% of gross production, and thereafter plateaus, reaching a peak in 2033 at a value of 177 EJ/yr, some 92% of projected gross production for that year. Even this highest EROI scenario displays a distinct divergence between gross oil demand and net energy yield. This divergence accelerates after 2018. In order for net energy yield to be greater than that suggested by this scenario would require the discovery and subsequent production of a large amount of easily accessible oil. This occurrence seems unlikely. If instead, as seems more likely, market share of unconventional sources such as oil sands increases then the net energy yield is likely to be much lower than that suggested by this scenario.

Looking at the mid EROI case, in 2007, net energy from oil production was at 159 EJ/yr, around 89% of gross production. The IEA WEO 2010 projection results in a peak in net energy yield in 2018 at a level of 168 EJ/yr, around 90% of gross production in that year. In the final year of the analysis, the net energy yield is 161 EJ/yr, some 83% of gross production.

Looking lastly at the low EROI case, we see that net energy yield from oil production peaked in 1980, at a level of 128 EJ/yr. The net energy yield then drops to a value of 106 EJ/yr in 2006.

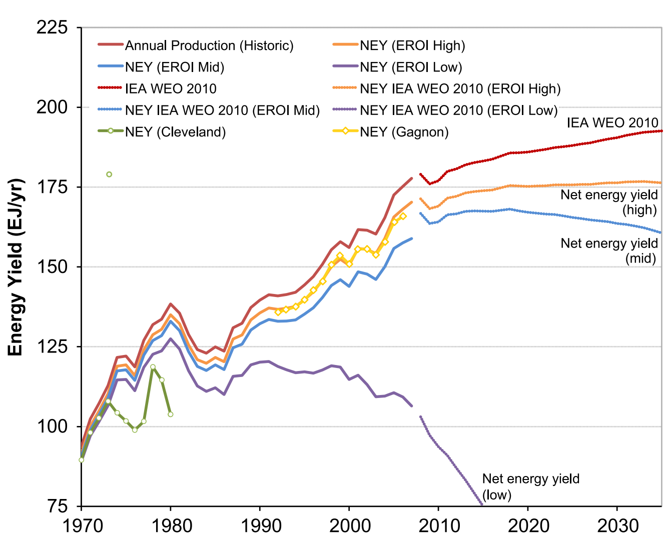

Fig. 11. Total and net energy yield from conventional oil production. Historic production is taken from a number of sources (BP, 2008; EIA, 2006, 2007, 2008; Etemad and Luciani, 1991; Grübler, 1998; IEA, 2008). Projection of oil demand to 2035 is taken from IEA WEO 2010. The net energy yield from this projection has been calculated based on the high, mid and low EROI scenarios.

Using the IEA WEO 2010 projections, we see that the net energy yield drops precipitously to a value of 16 EJ/yr in 2035, less than 10% of gross production. We must stress that this is a highly improbable scenario, but indicates how strongly the gross and net energy perspectives may diverge when the EROI is low. It is unclear if this pessimistic scenario is less probable than the optimistic high EROI scenario.

These results mean that strategies for management and mitigation of deleterious effects of a peak in oil production are more urgent than might be suggested by many analyses. The urgency with which these policies are to be implemented are much greater since the timing of the peak and subsequent decline rate of *net energy production* will certainly precede that of gross production. Since it is net energy yield that is important to the functioning of society, this distinction is of the utmost importance. With reference to Hirsch's (2008) scenarios, a 'best case' *gross production* scenario could in actuality be a 'worst case' scenario, in terms of *net energy yield*.

4. Conclusions

The work presented in this paper offers an approach by which the net energy production from a resource may be calculated easily over the entire production cycle of the resource. This encompasses the formulation of a dynamic function for EROI, which is assumed to be the product of both a technological (increasing) component and a physical (decreasing) component. Use of this function suggested that net energy yield from oil production may peak within the next decade, even despite continued increases in gross production. The implementation of peak oil management and mitigation strategies is thus of the utmost urgency.

Greater research emphasis on net energy analysis of oil production is needed to ensure a broader picture of the reality of the situation is presented. This will enable greater preparedness to deal with potentially deleterious effects of declining oil production when it occurs. A critical policy goal is to re-develop and re-build our built environment and economy such that energy and resource requirements are much reduced.

References

Alekett, K., Höök, M., Jakobsson, K., Lardelli, M., Snowden, S., Söderburgh, B., 2010. The peak of the oil age—analyzing the world oil production reference scenario in world energy outlook 2008. Energy Policy 38, 1398–1414.

Baines, J.T., Peet, J., 1983. The Dynamics of Energy Consumption: Changing Expectations for the Supply of Goods and Services. Department of Chemical Engineering.

Bentley, R., Mannan, S., Wheeler, S., 2007. Assessing the date of the global oil peak: the need to use 2p reserves. Energy Policy 35, 6364–6382.

Boustead, I., Hancock, G.F., 1979. Handbook of Industrial Energy AnalysisEllis Horwood.

BP, 2008. Statistical Review of World Energy. Technical Report. British Petroleum.

Brandt, A.R., in press. The effects of oil depletion on the energy efficiency of oil production: bottom-up estimates from the California oil industry. Sustainability.

Bullard III, C.W., Herendeen, R.A., 1975. The energy cost of goods and services. Energy Policy 3, 268–278.

Campbell, C.J., Laherrere, J.H., 1998. The end of cheap oil. Scientific American 278, 78.

Chapman, P.F., Leach, G., Slesser, M., 1974a. 2. The energy cost of fuels. Energy Policy 2, 231–243.

Chapman, P.F., Leach, G., Slesser, M., 1974b. Energy budgets 2. Energy cost of fuels. Energy Policy 2, 231–243.

Cleveland, C.J., 1993. An exploration of alternative measures of natural resource scarcity: the case of petroleum resources in the U.S. Ecological Economics 7, 123–157.

Cleveland, C.J., 2005. Net energy from the extraction of oil and gas in the United States. Energy 30, 769–782.

Cleveland, C.J., Costanza, R., Hall, C.A.S., Kaufmann, R., 1984. Energy and the U.S. economy: a biophysical perspective. Science 225, 890–897.

Cleveland, C.J., Kaufmann, R.K., Stern, D.I., 2000. Aggregation and the role of energy in the economy. Ecological Economics 32, 301–317.

Cook, E., 1976. Limits to exploitation of nonrenewable resources. Science 191, 677–682.

Costanza, R., Cleveland, C.J., 1983. Ultimate Recoverable Hydrocarbons in Louisiana: A Net Energy ApproachLouisiana State University.

Costanza, R., Cleveland, C.J., 2004. Value theory and energy. In: Encyclopedia of EnergyElsevier, New York, pp. 337–346.

EIA, 2006. International Energy Annual 2006.

EIA, 2007. Annual Energy Review 2007.

EIA, 2008. International Energy Outlook.

Etemad, B., Luciani, J., 1991. In: World Energy Production, 1800–1985 = Production mondiale d'énergie, 1800–1985Librairie Droz, Genève.

Gagnon, N., Hall, C., Brinker, L., 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. Energies 2 (3), 490–503.

Gever, J., Kaufmann, R., Skole, D., Vorosmarty, C., 1991. Beyond Oil: The Threat to Food and Fuel in the Coming Decadesthird ed. University Press of Colorado, Niwot, Colorado.

Gilliland, M.W., 1975. Energy analysis and public policy. Science 189, 1051–1056.

Greene, D., Hobson, J., Li, J., 2006. Have we run out of oil yet? Oil peaking analysis from an optimist's perspective. Energy Policy 34, 515–531.

Grübler, A., 1998. Technology and Global ChangeCambridge University Press, Cambridge.

Hall, C.A., Cleveland, C.J., Kaufman, R., 1986. Energy and Resource Quality: The Ecology of the Economic Process. John Wiley and Sons.

Hall, C.A.S., Powers, R., Schoenberg, W., 2008. Peak oil EROI investments and the economy in an uncertain future. In: Pimentel, D. (Ed.), Biofuels Solar and Wind as Renewable Energy Systems: Benefits and RisksSpringer, Dordrecht, pp. xxi, 504 p.

Hirsch, R., 2008. Mitigation of maximum world oil production: Shortage scenarios. Energy Policy 36, 881–889.

Hubbert, M.K., 1956. Nuclear energy and the fossil fuels. Drilling and Production Practice, vol. 95. American Petroleum Institute, Shell Development Co.

IEA, 2000. Experience Curves for Energy Technology Policy. Technical Report. OECD/IEA.

IEA, 2008. World Energy Outlook 2008. Technical Report. International Energy Agency.

Jefferson, M., 2008. Accelerating the transition to sustainable energy systems. Energy Policy 36, 4116–4125.

Junginger, M., Faaij, A., Turkenburg, W.C., 2005. Global experience curves for wind farms. Energy Policy 33, 133–150.

Leach, G., 1975. Net energy analysis—is it any use? Energy Policy 3, 332–344.

Leach, G., 1976. Energy and Food ProductionIPC Science and Technology Press.

Liu, Z., Koerwer, J., Nemoto, J., Imura, H., 2008. Physical energy cost serves as the 'invisible hand' governing economic valuation: direct evidence from biogeochemical data and the us metal market. Ecological Economics 67, 104–108.

Lloyd, B., Forest, A.S., 2010. The transition to renewables: Can pv provide an answer to the peak oil and climate changes challenges? Energy Policy 38, 7378–7394.

Lloyd, B., Subbarao, S., 2009. Development challenges under the clean development mechanism (cdm)—can renewable energy initiatives be put in place before peak oil? Energy Policy 37, 237–245.

Messner, S., Strubegger, M., 1995. User's Guide for MESSAGE III. Technical Report. IIASA.

NREL, 2010. National Solar Radiation Database.

NREL, 2010. Western Wind Dataset.

OECD/IEA, 2009. World Energy Model—Methodology and Assumptions.

Peet, J., 1992. Energy and the Ecological Economics of SustainabilityIsland Press, Washington, DC.

Peet, N.J., Baines, J.T., Macdonald, M.G., Tohill, J.C., Bassett, R.M., 1987. Energy supply and net energy in New Zealand. Energy Policy 15, 239–248.

Rauh, A., Seelert, W., 1984. The Betz optimum efficiency for windmills. Applied Energy 17, 15–23.

Seebregts, A.J., Goldstein, G.A., Smekens, K., 2001. Energy/Environmental Modeling with the Markal Family of Models.

Shaw, D., Hung, M.F., Lin, Y.H., 2010. Using net energy output as the base to develop renewable energy. Energy Policy 38, 7504–7507.

Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R., 2010. Global oil depletion: a review of the evidence. Energy Policy 38, 5290–5295.

Tsoskounoglou, M., Ayerides, G., Tritopoulou, E., 2008. The end of cheap oil: current status and prospects. Energy Policy 36, 3797–3806.