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Petroleum Analysis Centre

THE OIL AGE

Understanding the Past, Exploring the Future

Editorial

Articles:

Background & Objectives

This journal addresses all aspects of the evolving Oil Age, including its physical, economic, social, political, financial and environmental characteristics.

Oil and gas are natural resources formed in the geological past and are subject to depletion. Increasing production during the *First Half* of the Oil Age fuelled rapid economic expansion, with human population rising seven-fold in parallel, with far-reaching economic and social consequences. The *Second Half* of the Oil Age now dawns.

This is seeing significant change in the type of hydrocarbon sources tapped, and will be marked at some point by declining overall supply. A debate rages as to the precise dates of peak oil and gas production by type of source, but what is more significant is the decline of these various hydrocarbons as their production peaks are passed.

In addition, demand for these fuels will be impacted by their price, by consumption trends, by technologies and societal adaptations that reduce or avoid their use, and by government-imposed taxes and other constraints directed at avoiding significant near-term climate change. The transition to the second half of the Oil Age thus threatens to be a time of significant tension, as societies adjust to the changing circumstances.

This journal presents the work of analysts, scientists and institutions addressing these topics. Content includes opinion pieces, peer-reviewed articles, summaries of data and data sources, relevant graphs and charts, book reviews, letters to the Editor, and corrigenda and errata.

If you wish to submit a manuscript, charts or a book review, in the first instance please send a short e-mail outlining the content to the Editor. Letters to the Editor, comments on articles, and corrections are welcome at any time.

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Editorial

Welcome to the first issue of the second year of this journal; we are very pleased to have made it this far, and thanks are due to the various authors who have provided such excellent papers

In this issue the ‘opinion piece’ is by Colin Campbell and myself on the present low price of oil, and in particular on the implications this might have for the general understanding of likely future oil supply.

In peer-reviewed articles, the oil forecast model in this issue is that by Vlasios Voudouris and colleagues. This is agent-based, and thus philosophically takes quite a different approach than the models covered to-date.

I am then very pleased to carry a paper on EROI data by Prof. Charles Hall, one of the leading experts on the topic. The paper is drawn from a chapter of a recently published book, and covers EROI ratios for a number of different energy sources. For information on how such ratios are calculated, and important caveats on their use, reference should be made to the original chapter.

Finally there is a paper that completes my three-part paper started two issues back on the estimates of the global ultimately recoverable resource (‘URR’) of conventional oil. A main conclusion here is that URR estimates significantly higher than that expected by extrapolation of the global oil discovery trend need to be treated with caution, especially if used to forecast oil production.

Finally, I am pleased to announce that the journal now has a website. This is: www.theoilage.org. Any comments on this website would be much appreciated.

- R.W. Bentley, March 2016.

Observations on the Present Low Price of Oil

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Abstract:

This paper makes a number of observations on the present low price of oil. First it contrasts the present price (below $40/bbl for Brent) with the higher (and often considerably higher) price expectations implicit in current forecasts for global oil supply. The preponderance of such forecasts foresee either global oil supply as increasing only slowly (and that by increases in the production of the relatively expensive non-conventional oils, with production of conventional oil as flat out to the end of the forecast time horizons), or foresee global production of conventional oil (or indeed of 'all-oil', including non-conventional) as reaching a peak in the relatively near or medium term, and then declining. On the basis of such forecasts the current low price of oil looks unlikely to continue for long. The paper then speculates on the reasons for the present low price, and suggests that none of the explanations proposed so far seems fully satisfactory, and that the truth is possibly not yet fully known. Finally, the paper looks at some of the important implications of the present low price in terms of society's understanding of future oil price risk.

1. Contrasting the Present Low Price of Oil with Current Oil Forecasts

Only a little over a decade ago, oil forecasts could be divided into two very distinct camps: those which saw global oil production as continuing to rise in a more-or-less business-as-usual manner, with consequently the oil price expected to remain low; and those which saw a near or medium-term peak in the global production of at least conventional oil, and hence which expected the price of oil to be high (on average), corresponding to the cost of producing the marginal barrels of non-conventional oil.

In recent times this dichotomy in forecasts has narrowed considerably, with today the first group now seeing global production of *conventional* oil not as increasing, but as remaining flat (out to the forecast horizon), with the extra oil needed to meet demand as coming from the expensive non-conventional oils. Forecasts in this group are mostly from the 'mainstream' forecasting organisations, including, for example, the IEA, BP and ExxonMobil (see Charts 4, 5 and 6 in *The Oil Age*, vol.1 no.2).

The second group of forecasts still maintain their earlier predictions of a peak in the global production of conventional oil (and indeed, often, also of 'all-oil') being expected in the near or medium-term. Forecasts in this second group are mainly from the 'independents', both consultancies and individuals; for example: Campbell (2015), Globalshift Ltd. (Smith, 2015), Laherrère (2015), Miller (2015) and Rystad Energy (Wold, 2015).

Note that these two groups of forecasts do not cover all views. Some analysts still have a more 'cornucopian' view of future oil supply: for example, BP's current Chief Economist, Spencer Dale (Dale, 2015), or Aguilera and Radetzki (2016). The latter authors, for example, point to the significant technological gains that have recently unlocked US shale ('light-tight') oil production; and speculatively predict that these gains will yield globally, in their reference case, up to perhaps 20 Mb/d of shale oil by 2035, and a similar additional amount from the application of the technology to more conventional oil reservoirs.

But on the basis of the forecasts from all three groups it is difficult to see the oil price as staying low for long. This is because if the global production of conventional oil (or, indeed, 'all-oil') peaks fairly soon, as many of the 'independents' predict (including one of us: Campbell), then simple competition for oil (*absent* extreme climate-change driven reductions in demand) will push up the price of oil, likely to very uncomfortable levels. (And see Wold, 2015, for a specific asset-based forecast of possible levels of future global oil production as a function of oil price.)

If instead the view of the more 'mainstream' forecasters is correct, and production of conventional oil stays flat, then necessarily the price of oil will rise as the more expensive non-conventional oils need to be produced, at costs up to over $150/bbl (see the IHS-CERA cost data in Figure 16 of Miller and Sorrell, 2014).

And finally even the ‘cornucopian’ views of Dale, or Aguilera and Radetzki, do not guarantee a low oil price. The later authors (and almost certainly Dale also) overlook the decline in conventional oil production that most ‘independents’ predict, such that the ‘extra’ oil suggested by Aguilera and Radetzki out to 2035 only roughly compensates for conventional oil’s expected decline over this period.

The upshot is that we should expect the price of oil to return fairly soon to at least that (on-average) of the non-conventional oil marginal barrel, perhaps $100/bbl or so; and potentially quite a bit higher if indeed the ‘all-oil’ peak is not too distant. (Note that in the latter case, the upper limit to price is probably largely set by demand-destruction resulting from the damage that a high oil price does to global economies.)

2. Explanations Proposed for the Present Low Price of Oil

Now we turn from what price trend to expect to asking the question: Why has the oil price fallen so low?

A wide variety of explanations has been offered for this by various pundits, often with the claim (or implication) of superior knowledge. In our view, none of the explanations offered so far seems, by itself, to be fully convincing. We are rather reluctant to enter into this area of speculation (even if as here, in an ‘opinion piece’) in what is intended as a fairly rigorous academic journal, but we do so as the underlying explanation for the present low oil price probably has fairly serious implications for the general understanding of the future price of oil.

First we note however, in agreement with analysts such as Paul Stevens of Chatham House, that oil has now become something of a commodity in its pricing, where - for commodities in general - a slight under-supply can send the price (at least in the short-term) very high; and correspondingly very low in the case of a small over-supply.

In oil’s case it seems currently that supply swings as small as perhaps 1% (equivalent to ~1 Mb/d) can bring about large changes in price. In this context we understand that much oil is now increasingly traded on short-term contracts, which exacerbates this trend. Note that this current situation, of 'oil as now a simple commodity', contrasts with the long period, of perhaps nearly a century, where oil producers tried (and generally succeeded) in controlling the price of oil, at least in terms of preventing it from dropping disastrously low (see Bentley and Bentley, 2015a, b).

Now we turn to some of the explanations variously offered for the current price of oil (and there are indeed others). These have included:

1. Saudi Arabia (perhaps in coordination with Kuwait) has maintained production to hold market share against competition from rapidly rising US shale (light-tight') oil production.
2. Change of regime of the Saudi royal household. Whereas King Abdullah said he wished to restrict production from the kingdom '*to hold as much oil as possible in the ground for his grandsons*', maybe now the new king, or possibly his son, have taken a more commercial attitude.
3. Some Middle East suppliers (perhaps led by Saudi Arabia) have sought to use a low oil price to damage the economies of political rivals, such as Iran, or perhaps Russia; or those of cash-strapped OPEC rivals, perhaps Venezuela. (A more extreme view sees the hand of the US in this; willing to take pain at home with its shale producers in order to collaborate with Saudi Arabia and others in leaning on Iran or Russia.)
4. Others have suggested that the big producers are now financially well informed, and can trade to make significant gains on both a falling as well as a rising market.
5. More benign explanations exist: One is that some Middle East suppliers (again perhaps led by Saudi Arabia) have realised the damage that the high oil price was doing to political friends, such as the US, Europe and Japan, so decided to maintain production to lower the price.
6. A more self-centred view, but along similar lines, is that the producer countries realised that a high oil price was harming the economies of countries in which they in turn now have large investments, and were thus hurting themselves.
7. Another explanation is that there is a realisation among all oil exporters that their oil is at risk of becoming a 'stranded asset' due to impending action on climate change, and that they would

be wise to pump as fast as is reasonable now while there is still a market.

Which of these very different explanations is correct?

The explanation we understand that Saudi Arabia has most generally given is that of maintaining market share; and this we are inclined to judge - on admittedly relatively little data - as possibly the most likely. The potential flaws in this explanation are: (a) at a low price (under perhaps $80/bbl) the kingdom's finances are difficult, see below; and (b), once US shale producers are knocked out, the price will go back up and encourage them back in (albeit with a delay, as funders are likely to be more cautious the second time around).

In terms of adopting such a 'not lose market share' strategy, it may be that officials within the country remember all too well the production cuts of the 1980s. These were intended to hold the price up near 1978 levels, but where Saudi Arabia took the bulk of such cuts compared to most other OPEC members, and as a result saw a very significant falls in its income.

(In this context, it is perhaps worth mentioning the OPEC 'quota wars' reserves manoeuvring at that time, as this still has important repercussions to this day. OPEC quotas were based in part on reserves, and Kuwait had reported reserves of 67 Gb in 1970, which had fallen to 64 Gb by 1984 in the absence of any major new finds. Then, in 1985, the country massively increased its reported reserves, to 90 Gb, although nothing significant had changed in its oilfields. Then in 1987 it announced a further small increase, this time possibly genuine, to 92 Gb. But it seems that this last increase may have proved too much for the other OPEC members, and in 1988 Abu Dhabi matched Kuwait's reserves, at 92 Gb (up from 31 Gb); Iran went one better at 93 Gb (up from 49 Gb); Iraq went to 100 Gb (up from 47 Gb) and Venezuela increased its reserves from 25 to 56 Gb (by including its heavy oil that it had not previously counted for the OPEC quota). The level of Kuwait's new declared reserves may suggest that the country was now reporting *original*, rather than *remaining*, reserves, by not deducting past production - as indeed is industry practice when determining the shares of a field which crosses a lease boundary, as was effectively the case with the disputed Iraq/Kuwait Rumaila field. This uncertainty on OPEC's true reserves has been a difficulty for many analysts ever since.)

Returning to today and the low oil price, the question is: How long can this remain low?

Some have speculated that Saudi Arabia could maintain oil prices in the ~$30/bbl region for perhaps up to five years, by more aggressively doing what the country is currently doing: drawing down sovereign wealth funds; borrowing on the local, and in time international, markets; reducing government expenditure; decreasing energy subsidies; and considering an initial public offering (IPO) of parts of its oil infrastructure. But such a long period of financial pain seems extremely unlikely to us, even if geopolitics (vs. Iran and others) is in play; and almost certainly an oil price rise up to the $50 to $60/bbl region by later this year (2016) - as many experts closer to the market than us suggest - looks the more realistic.

3. Implications of the Present Low Oil price in Terms of Society's Understanding of Future Oil Price Risk

To conclude this short paper, we turn to an important topic: the implications of the present low oil price in terms of society's understanding of future oil price risk.

Today, despite the various forecasts mentioned above, and in particular the recent evolution of the 'mainstream' forecasts towards a significantly more conservative position, few energy analysts, let alone people in the street, or in energy-using companies, in government, or in academia, are aware of these relatively near-term expectations of significant difficulties in oil supply.

And there is no question that the current year or more of oil prices at $50/bbl and below has pushed any concerns there might have been well into the distance. Two examples will suffice here: BP's recent *Technology Outlook* (November, 2015); and remarks by senior UK and EU people with responsibilities for energy that we have listened to at recent conferences, where the current zeitgeist is: 'We used to worry about peak oil, but now those fears are behind us.'

The oil price will go back up, whether this is by supply curtailment by Saudi Arabia and one or two others; by other OPEC producers agreeing cuts between themselves; by US producers reverting to Texas Railroad style pro-rationing (as one letter to *The Economist* suggested); or by proximity to the global production peak of conventional oil biting ever more deeply. But there is also little doubt that the price rise will be generally attributed to producers' decisions on supply, and also to lack of investment leading naturally to a commodity price cycle, with the expectation that sufficient new investment will bring the price down again.

We are thus concerned that the underlying supply constraints, long recognised in the forecasts from the 'independents', and increasingly recognised in forecasts from the 'mainstream' organisations, will remain unknown, and catch society out badly, as happened with the oil price rise post-2004. We need to understand the future.

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Advancing Oil (and Gas) Scenarios: The ACEGES Computational Laboratory

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Abstract:

This paper describes the computational model: Agent-based Computational Economics of the Global Energy System (ACEGES). This is agent-based in that it determines aspects of the global energy system by modelling interactions between individual agents (decision-making entities) that act within this system. The model contains a number of different classes of agents, and the behaviour of each agent within a given class follows user-defined rules. Multiple model runs allow statistical envelopes of behaviour ranges to be generated. Since considerable complexity can arise in a wide range of systems when even simple individual rules are being followed, it is suggested that the agent-based approach presents a realistic way to capture such overall system behaviour.

This paper illustrates the use of this agent-based approach for forecasting global oil and gas supply, and presents details both of the model and of indicative results. It is recognised that the model needs further expansion (for example, by incorporation of additional information on the difference between the supply of conventional and non-conventional hydrocarbons) if it is to provide a full picture of reality. This expansion is underway and will be reported in subsequent papers.

1. Introduction

In times of uncertainties, scenarios offer a particularly useful approach. Scenarios are intended to challenge a manager's personal microcosms, and to reflect both the present and the past, before structuring the uncertainties of the future. In this sense, scenarios can act as an 'early warning system', by focusing on the driving forces that make differences to a system as perceived by decision-makers.

Scenarios, as critical planning and decision-support tools, work well when the business world is best characterised by 'morphogenesis' rather than 'stasis' – this is when the business environment is populated by 'resting points' rather than 'fixed point attractors' that can be forecast. The acceptance of the world of morphogenesis requires acceptance and inclusion of uncertainty in the decision-making process, and a focus on how the constituent components of the world work and interact.

Conventionally, scenarios are built upon a dynamic sequence of events or changes. However in times of unprecedented uncertainties and increasingly complex interconnections scenarios should be built upon a dynamic network of *interacting* events or changes. To that end, we put forward the framework called Agent-based Computational Economics of the Global Energy System (ACEGES), which is based on the agent-based modelling paradigm.

The premise is that ACEGES-based scenarios are more robust and useful for planning by supporting policy makers and business executives to 1) think about where their organization may be out of alignment with the emerging business megatrends - incipient societal, political, technological and economic shifts; 2) understand how the business environment as a coherent whole evolves, growing organically from bottom-up; 3) become more adept about the ways to foster their organization and its decision-making. The key idea is that the future should not be regarded as 'complicated' but as 'complex', in that there are uncertainties about the driving forces that generate unanticipated futures, which are difficult to explore analytically.

As the forces of change become more inter-connected, scenarios cannot neatly decompose them into separate and isolated sub-processes of change, which can be analysed independently. Aggregation of individually analysed sub-processes by means of summation to provide narratives of a coherent whole fails when the correct process of aggregation is not a sum. This is because of the existence of interacting and heterogeneous forces and agents such as, in this case, individual oil/gas producing organisations and countries.

Unlike conventional approaches that use computation, for example, for the empirical analysis of observational data and the calculation of the equilibria of systems of equations, agent-based models take us in a new direction that focuses on computer laboratories of complex dynamic systems, such as is the case with real-world energy systems. Agent-based computational laboratories add a new approach to the existing toolbox for understanding oil and gas markets. This new tool is fundamentally different because it accepts under a single umbrella:

- A higher degree of inter-connectedness between the building blocks of the business world: from hierarchical to network structures.
- A higher degree of heterogeneity: removal of "N-replication" of decisions made by representative agents/pool of agents such as oil producing countries/OPEC.
- Explicit representation of multi-layered space: physical, regulator, business and socio-economic.
- Development of data-free representations: important for business megatrends – incipient societal, political, technological and economic shifts.
- Handling of a far wider range of nonlinear dynamics than conventional approaches: the computer keeps track of the many interactions in order to see what happens over time.

Agent-based models need not be complex or complicated because simple micro-foundations (without the assumption that the business world will move towards a predetermined state) can generate complex macro-regularities.

2. Why and When to Use Agent-based Modelling?

Agent-based models (ABM) – a bottom–up simulation-based modelling approach – is a methodology that has the potential to overcome the shortcomings of traditional analytical methods to model complex markets (Tesfatsion (2006) and references therein). In a nutshell, ABM models are computational models of micro-agents (e.g., oil producing companies) operating in an environment (e.g., oil reserves, pipelines, tankers), in which they interact repeatedly with other agents over a period of time, thereby permitting the computational study of phenomena as complex adaptive systems (CASs). For Tesfatsion (2006), CAS is a complex system that includes planner units, i.e., units that are goal-directed and that attempt to exert some degree of control over their environment to facilitate achievements of these goals. Voudouris (2011) argues that the development of realistically rendered ABM models offers a better way for the representation and scientific investigation of complex, dynamic phenomena such as energy markets

Historically, modellers have addressed questions about how decisions (of oil and gas production or demand) are made with aggregated models by generally assuming perfect information and rational behaviour. The key distinction between ABM models and other types of economic modelling is that of agent autonomy and the interactions between them (see Fig. 1). Agents in ABM models are decision-making entities capable of reactivity, social communication, goal-directed learning, and, most important of all, self-determinism on the basis of private internal processes such as profit maximisation. Thus, the agent is modelled as an independent entity that makes decisions and takes actions using the limited share of influence and/or uncertain information (bounded rationality) available to it, similar to how organizations and individuals operate in the real world. A main feature of ABM models is the repetitive and competitive interactions between the agents – an agent makes publicly available to other interacting agents only a subset of their private information and actions (see Fig. 1).

The other important building block in the ABM paradigm is the representation of the physical and social environment (i.e., ‘space’) within which agents operate. Each agent may observe only a subset of the multilayer environment (representing bounded rationality). ABM models define the initial state of the market by specifying the attributes and methods of each agent and the characteristics of the environment using observational micro-data. The initial attributes of any particular agent might include type characteristics, structural

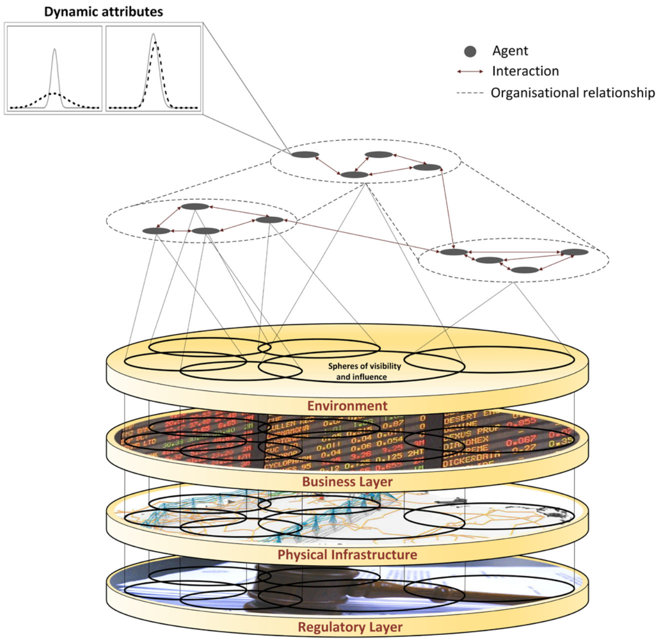


Figure 1: The architecture of an ABM model (adopted from Voudouris, 2011).

characteristics, and initial information about other agents. The initial methods might include market protocols, learning modes (e.g., reinforcement learning), trading rules (e.g., profit maximisation), and rules for changing rules (e.g., strategy updating of forecasting models based on past performance). The market then evolves over time without further intervention. All events that subsequently occur arise from the historical evolution of agents' inter- actions (Jennings, 2000; Tesfatsion, 2006).

ABM models offer three main benefits over other modelling techniques for the representation of wholesale power markets. They:

- Capture emergent phenomena, which result from the interaction of the individual entities.
- Provide a natural description of a complex adaptive system. If the system is composed of behavioural entities, agent-based models better capture the reality of these systems.

- Are flexible. The flexibility comes in different dimensions. More agents for instance can be added, and the complexity of their behaviour – in the form of their degree of rationality, ability to learn and evolve – can be fine-tuned. This is important when different market designs need to be integrated in the model.

ABM models are useful when:

- The interaction between the agents is complex (see Fig. 2).
- The agents exhibit complex behaviour, including learning.
- The representation of physical space is crucial. In the case of oil production, it might be important to represent the physical infrastructure that might limit the export capacity or crude oil storage.
- The aim is to reveal and explain the complex and aggregate market behaviours that emerge from the interactions of the heterogeneous agents (Koritarov, 2004).

However, ABM models are not appropriate when:

- The dynamics of the systems are linear.
- The representation of physical space is of limited importance.
- The interactions between the constituent components of the system is limited.
- Micro-data is not available. For example, if you want to develop a detailed agent-based model of global crude oil demand, limitation of survey data on consumer behaviour (of transport) limits the usefulness of a detailed agent-based model for demand dynamics.

3. The ACEGES model

Here, we detail the latest version of the ACEGES model [first proposed by Voudouris (2011) and demonstrated by Voudouris *et al.* (2011)] to estimate plausible trajectories of future country-specific crude oil (and natural gas) production and export capacities.

Since an agent's interactions take place at the knowledge level (Newell, 1982), decisions need to be made about which goals to follow, at what time, and by whom. This means that agents choose to interact with other agents directly, or with organisations or institutions (see Figure 1). They may also choose to be part of an organisation in searching to fulfil their designed goals. According to Jennings (2000, page 280), "*agents are flexible problem solvers, operating in an environment over which they have only partial control and observability*". This control and observability depend on their own state and behaviour, and on those of their organisations. The organisations (e.g. subsystems) may also interact directly.

In particular, the ACEGES model facilitates the exploration of plausible futures (long-term scenarios) by means of computational experiments that require setting up the key driving forces of the model, such as crude oil production capacity growth rates, crude oil demand growth rates, the peak/decline point (e.g., the proportion of EUR cumulatively produced after which the production decline phase starts) and estimated volumes of oil originally present before any extraction (oil EUR). The important point here is that the key uncertainties are not necessarily restricted to a limited set of values, but are defined by highly flexible country-specific probability distributions.

Using the simulation engine of the ACEGES model, these distributions are used to explore the full uncertainty space of the long-terms scenarios of crude oil production and demand. Therefore, the scenarios are published in the form of conditional probability distributions rather than as point forecasts to avoid suppressing the very wide degree of uncertainty surrounding the projections.

The ACEGES model is a hybrid economic and resource-constrained model by modelling both the demand and the supply side of the global oil market. Because of the high flexibility of the ACEGES model, long-term scenarios can be developed based upon the 'predict (demand) and provide (supply)' philosophy, or based upon dynamic adjustments of demand and supply.

3.1 Agent's demand function

Currently, the demand side of the ACEGES model is a probabilistic function defined by Equations 1.1 and 1.2. The specification of g^t_a (the country-specific demand growth rate) is used to capture a range of factors (e.g., prices, energy efficiency measures, technological innovation) that can affect the growth rate of the country-specific demand for crude oil. Therefore, g^t_a can be a (parametric or non-parametric) regression function with explanatory variables (including time).

Equation 1.1

$$demand_{a_t} = demand_{a_{t-1}} * \exp(g^t_a)$$

Equation 1.2

$$\begin{aligned} g^t_a | \mu_t, \sigma_t, \nu_t, \tau_t &\sim SST(\mu_t, \sigma_t, \nu_t, \tau_t) \\ log(\mu_t) &= s(gdp_t/population_t) + s(price_t) + efficiency_t \\ \log(\sigma_t) &= s(time) \\ \log(\nu_t) &= s(time) \\ \log(\tau_t) &= s(time) \end{aligned}$$

Equations 1.1 and 1.2 define the demand function of the ACEGES agents. For an explanation of the terms of these equations, see text.

Because of its simplicity, Equation 1.1 is used during the exploration stage of the scenario development process when the focus is on exploring the dynamics of the supply side. Specifically, g^t_a is exogenously specified based upon assessment of empirical data and extensive literature review, or on specific studies such as the *World Energy Outlook* (*WEO*) by the International Energy Agency (IEA). In the latter case, by fixing the demand based upon existing studies of the *WEO*, we can explore the supply dynamics of the crude oil market and compare the results of the ACEGES model with the results of *WEO*, and also to other studies that are based upon *WEO* estimates.

Alternatively, Equation 1.2 can be used, which explicitly models g^t_a as a stochastic process with explanatory variables (e.g., GDP per capita, price). This postulates that the demand growth rate following the Skew student t distribution while we assume a multiplicative model for μ (resulting from the log link for μ, which represent the location (mainly expectation) of the distribution) because of a change in one of the explanatory variables is likely to result in a change in g^t_a as a fixed percentage rather than a fixed amount.

Specifically, the expected growth rate is a smoothed function of country-specific variables such as GDP per capita, the oil price, and energy efficiency. The other distribution parameters (affecting the scale and shape of the predictive distribution of g^t_a) change over time (no explanatory variables is assumed). Clearly, the above generic model for g^t_a can be extended to include additional variables (or distributions) if the scenario team wants to try alternative model specifications. Note the function s(.) is the P-splines of Eilers and Marx (1996).

An alternative approach is to model the demand as the sum of a number of end-use energy demand projections (see Figure 2 and Figure 3). For example, the demand for crude oil can be the sum of crude oil demand from transport, industry, residential and commercial end-use energy demand sectors.

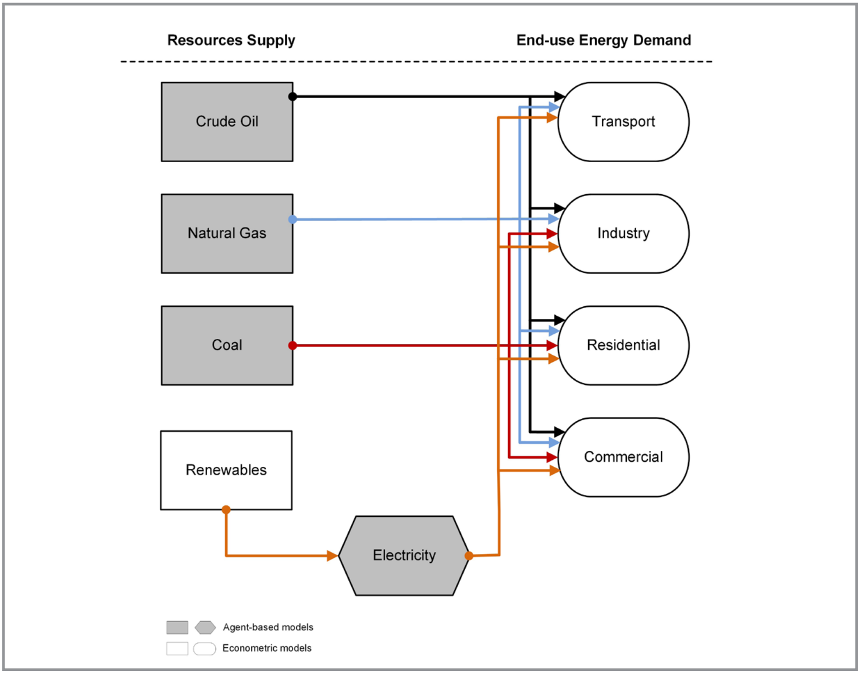


Figure 2: Model architecture of the extended ACEGES model.

Taking as an example the transport end-use energy demand sector, the demand for crude oil can be estimated by the Box 3.a of Figure 3 below. Effectively, the demand for crude oil is a function of the growth rate of the demand for total energy for transport and the growth rate of the share of crude oil. The growth rate of the total demand for energy transport and the growth rate of the share of crude oil are estimated using economic and social indicators (e.g., growth rate of income per capita, growth rate of total freight turnover, growth rate of total passengers turnover, urban population growth rate and growth rate of energy demand in preceding year).

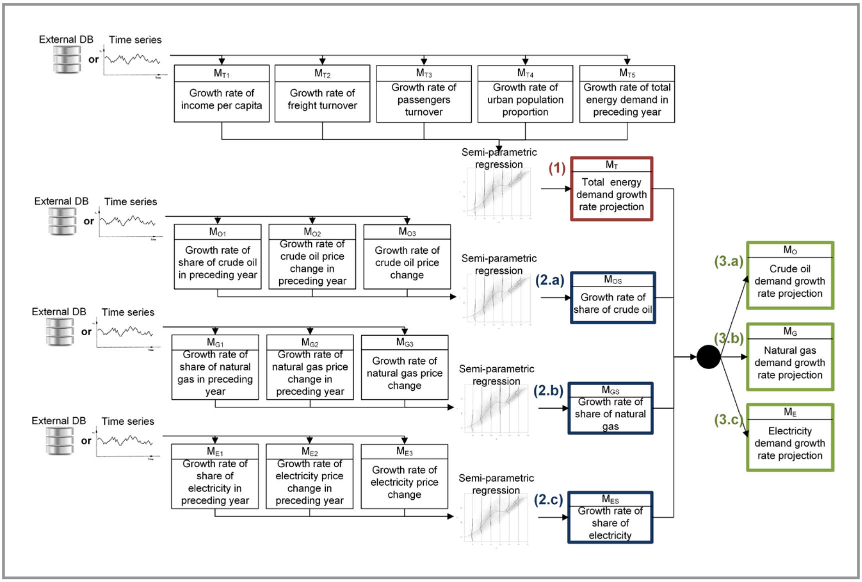


Figure 3: Structure of the model for demand of crude oil in transport

To better demonstrate the flexibility of the demand functions, Figure 4 below shows, by way of an example, the two dimensional surface of gasoline demand based upon the age of consumers and the price of gasoline. This surface has been fitted using a survey data in Canada (see Yatchew and No, 2011, for a description of these data).

The important point here is that the elasticity of price depends on the age of the consumer. For example, when a consumer is over 65, his elasticity is much higher (a small price increase causes a sharp decline in demand). This is not the case when a consumer is under 35 where a price increase has almost no effect on demand for gasoline. These different effects are important to be captured by respecting the heterogeneity of the demand agents within an agent-based model. This is why the demand agent's within the ACEGES model use the flexibility of the equations 1.1 and 1.2 above.

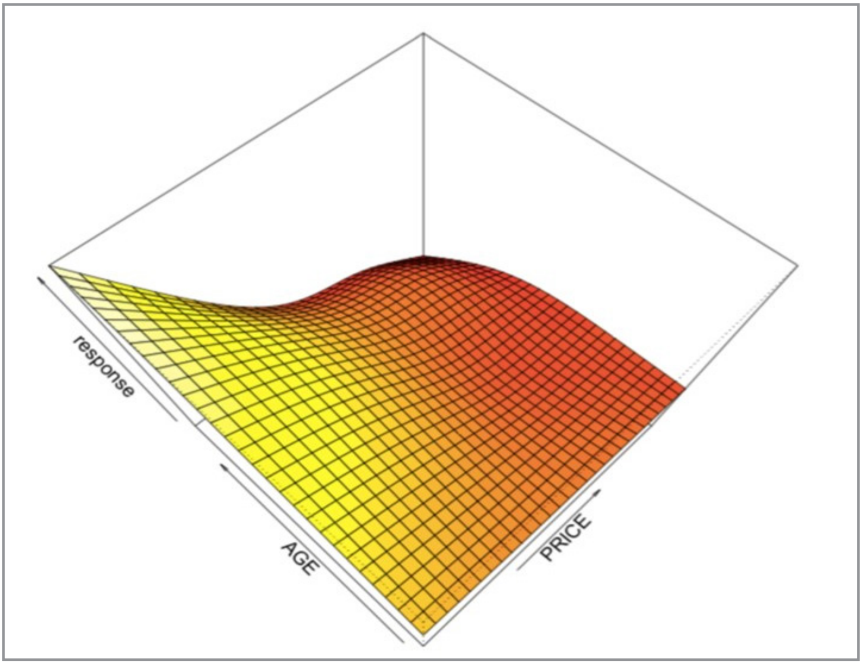


Figure 4: Example of a two dimensional surface of gasoline demand (response)

3.2 Agent's supply function

Now we turn to the agent's supply function. This is given by Equation 2, which is made up of 4 sub-equations, and defines the supply of oil (and gas) for the heterogeneous agents (two or more agents might be unlike in their characteristics or decision rule). Equation 2.1 represents the production decision of the swing-producer countries. This decision is based on the assumption that (a) the swing-producer countries will continue to produce oil to fulfil the net unfulfilled global demand for oil and (b) the swing-producer countries will not produce oil at their maximum capacity, unless it is necessary. This is, effectively, an approximation of the 'consumers logic', an approach first developed by Royal Dutch Shell (Jefferson and Voudouris 2011).

Equation 2.2 is adjusted (as needed) based on the maximum allowable (country-specific) production growth from time t to t + 1. This model specification is important, for example, in cases where a country (e.g., a pre-peak producer) has enough reserves but cannot meet its domestic demand for oil because of below- and/or above-ground constraints, or because it is uneconomical to further stimulate capacity growth (as it can be less expensive to import oil, until the 'organic' growth in the production capacity from t to t + 1 meets the domestic demand). Equation 2.3 shows the production decision of post-peak producers.

The above supply function of Equation 2 can become probabilistic by developing regression-type functions similar to Equation 1.2. For example, the production could be a non-linear function of remaining reserves, short-term price elasticity (to account for the possibility of immediate supply response to sudden increased/decreases of oil prices) and long-term price elasticity (to account for increase of production capacity because of long-term investments).

Equation 2.1

$$production_{a_t}A = production_{a_{t-1}} + (\exp(g_a^t) - 1) * demand_{a_{t-1}} + wd_{a_t},$$

Equation 2.2

$$production_{a_t}B = production_{a_{t-1}} + (\exp(g_a^t) - 1) * demand_{a_{t-1}},$$

Equation 2.3

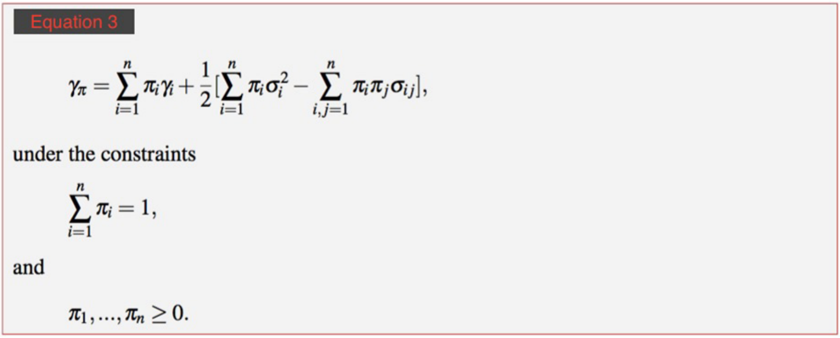
$$production_{a_t}C = production_{a_{t-1}} * (1 - production_{a_{t-1}} / remainingOil_{a_{t-1}}),$$

Equations 2.1 to 2.4 define the Supply Function of the ACEGES agents.

How many variations of the production function are needed depends on the scenarios that are being developed. The basic idea is to start with the simple production functions and then enhance the supply side of the ACEGES model as required.

3.3 Agent's trade/interaction

Finally in this section, we turn to an agent's ability to trade in oil (or gas). This is because an agent's decision rule should not only determine the production or demand decision of that agent. It should also define the interactions (trading) of the agents. Although there are many interactions that can be modelled within ACEGES model, Voudouris (2013) suggests the use of the stochastic portfolio theory of Equation 3 (proposed by Fernholz (2002) for the construction of equity portfolios).



Equation 3

$$\gamma_\pi = \sum_{i=1}^{n} \pi_i \gamma_i + \frac{1}{2}\left[\sum_{i=1}^{n} \pi_i \sigma_i^2 - \sum_{i,j=1}^{n} \pi_i \pi_j \sigma_{ij}\right],$$

under the constraints

$$\sum_{i=1}^{n} \pi_i = 1,$$

and

$$\pi_1, \ldots, \pi_n \geq 0.$$

Equation 3: Agent's trade using the stochastic portfolio theory.

By way of an example, the portfolio growth rate γ_π of an oil import portfolio is equal to the weighted average oil export capacity growth rate + the excess growth rate. The excess growth rate is half the weighted average of oil export capacity variance (denoted by σ_i^2) - the portfolio variance that is based on the covariance (denoted by σ_{ij}) of oil export capacities. While a country j constructs its portfolio, if trade between a country i is not desirable for political or any other above ground or below ground factors, then π_i can be set to 0 or restricted to a very small number [see Voudouris (2013) for details].

4. An Example of ACEGES-based Scenarios for Crude Oil Production

Now we turn to the application of the ACEGES model, and use it here by way of example to examine possible scenarios of future global oil production.

Perhaps the most common way to forecast the future of oil production is to make a single line forecast, where the forecast itself can be generated via a variety of methods, such as using historical data and a curve-fitting approach. An alternative approach is to reject the 'surprise-free' approach and introduce more than one line pathways by incorporating specified uncertainties, for example, three estimates for the size of oil reserves. This approach is used, for example, by the US Department of Energy's Energy Information Administration and others. It results in a finite number of lines, and in a discrete scenario approach to the handling of uncertainties. The general idea of presenting more than one line pathway is sound as a way of communicating the inherent uncertainty around the outlook of, say, conventional oil production.

An alternative approach is to use density-based pathways, as shown in Figure 5, to quantify the risks facing an executive in order to emphasize the inevitable uncertainties. Figure 5 depicts the scenario planner's judgment of the probability of various outcomes for oil production in the future conditional on a set of key uncertainties. The shaded bands represent–probabilistic statements of oil production levels, where the most likely outcome is represented by the darker shading. Because of the finite nature of oil, the uncertainty decreases as we move into the future. The shape of the 'probability bands' represents:

- Central projection of oil production, which determines the profile of the central darkest band;
- Degree of uncertainty, which determines the width of bands; and
- Skewness and/or kurtosis, which determines the probability of extreme outcomes.

The assumption behind the two scenarios shown in the Figure 5 are detailed in Voudouris *et al.* (2011). For example, Scenario 2 is the high–high heterogeneity scenario (H–H scenario). For Scenario 2, the

ACEGES Monte Carlo engine is used for all the four key uncertainties:

(i) Estimated Ultimate Recovery (EUR). The EUR is defined as an agent-specific distribution. If the purpose of the scenario is to explore the dynamics of conventional crude oil, the EUR needs to be specified for this class of oil.

(ii) Demand growth for oil – what is the expected demand for crude oil (see section 3.1).

(iii) Maximum allowable production growth rate (this is the maximum allowable increase of production capacity).

(iv) Peak/decline point (i.e., the percentage of a producer country's EUR at which production decline is assumed to occur).

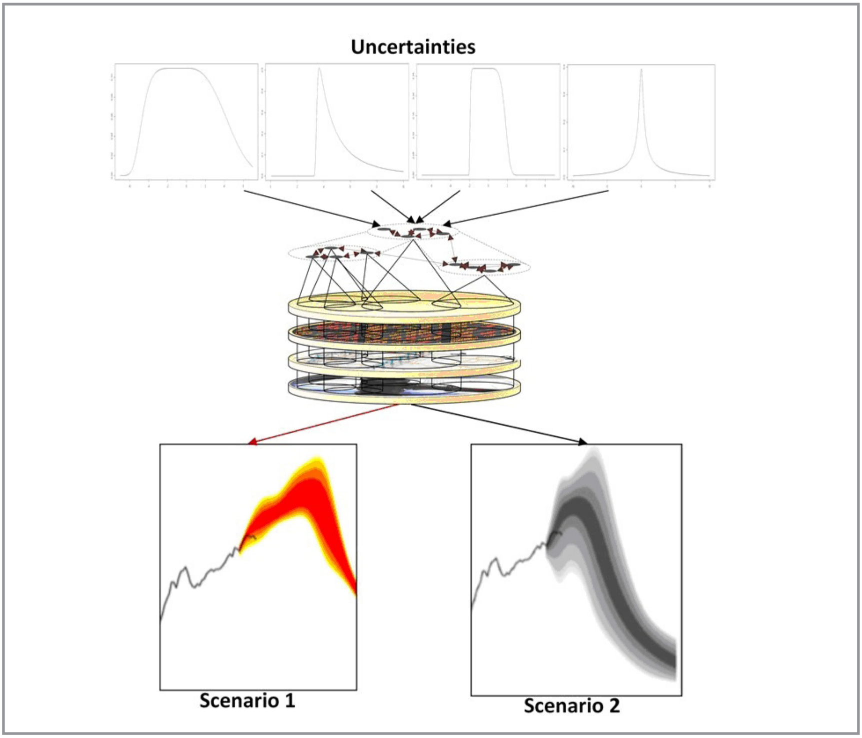


Figure 5: ACEGES-based oil scenarios (adopted from Voudouris et al., 2011 & Voudouris et al., 2014)

Given the uncertainty of these four key drivers of the scenario (using data as of 2010), the H–H scenario shows that the global peak of oil production is likely to happen in the vicinity of 2020. However, the upper centile (99th centile) suggests that peak might happen in the vicinity of 2030.

Voudouris *et al.* (2011), Matsumoto *et al.* (2012), Voudouris (2013), Voudouris *et al.* (2014), and Matsumoto and Voudouris (2015) have published a range of different oil (and gas) ACEGES-based scenarios corresponding to a range of model assumptions, input data values, and classes of modelling functions selected.

Scenario plots: Vertical axis: World Oil Production. Horizontal axis: Date.

Below is an example of the data used to initialise the ACEGES model (depending on the requirements of the scenario):

- The domestic demand of oil in 2001 (total petroleum liquids - an 'averaged proportion' of the demand for liquefied petroleum gas) from the United States Department of Energy (USDOE), Energy Information Administration (EIA). The 'averaged proportion' represents the part of the liquefied petroleum gas (LPG) consumption covered by the natural gas plant liquids (NGPL) production rather than crude oil production.
- The volume of oil originally present before any extraction (EUR), variously taken from:
    - Campbell and Heapes (2008): Data available for 62 countries, with a global EUR of 1.9 trillion barrels;
    - US Geological Survey (USGS) *World Petroleum Assessment* 2002 (*WPA02*) EUR 5%-likely: Data for 52 countries, with a global EUR of 3 trillion barrels (excluding reserves growth);
    - Central Intelligence Agency (CIA) World Factbook 2010 (*WFB10*): Data available for 93 countries, with global EUR of 2.4 trillion barrels. Note that CIA provides estimates of the *proved* reserves of oil. Therefore, the CIA EUR is the sum of the cumulative production for all the using the data sources discussed below and proved reserves. Note that the CIA EUR does not include 'oil-yet-to-discover'. The main advantage of

the CIA EUR is the construction of EUR for 93 countries. This is to say that by modelling more of the nations of the world, and having both production and demand data for these, the model has a more accurate picture of the net demand for imports, which is what is being apportioned among the pre-peak net producers. Having said this, note that the CIA EUR should not be used alone, as this is potentially a large underestimate of actual EURs for selected countries.

- The annual oil production (crude oil including lease condensate) from the EIA 'International Energy Data, Analyses, and Forecasts' dataset. Because of the use of crude oil, we are really testing whether the EUR estimates, in the form of crude oil, generate results consistent with the empirical data. The difference between crude oil production and conventional oil production is significant for some countries such as Brazil, Angola, Canada and Venezuela. If the aim were to explore the outlook of conventional oil as defined by Campbell and Heapes (2008), we would need to adjust starting oil production, cumulative oil production, oil demand, and all production to remove oil unconventional by their standards.
- The cumulative production is based on:
  - API - Petroleum Facts and Figures (1971) from 1964 to 1994;
  - DeGolyer and MacNaughton inc. (1994) from 1964 to 1994;
  - EIA's International Energy Data, Analyses, and Forecasts.

5. Conclusions

It is generally recognised that agent-based models have the potential to improve the theory and the practice of modelling complex real-world phenomena. Yet, to-date, there has been little systematic analysis at the conceptual and practical levels of how to develop data-driven agent-based models for the representation and reasoning of energy systems.

We recognize that it is nearly impossible to predict the exact future evolution of country-specific oil production and export capacities and to construct long-term energy portfolios for oil trade. However, the ACEGES model is a computational laboratory that enables us to explore plausible futures of export and production of oil and gas. The key advantage of the ACEGES model is the high degree of heterogeneity that can be incorporated in the scenarios in order to quantify the uncertainties within each scenario.

Our longer run goal for the ACEGES model is a complete computational laboratory that rings true to industry participants and policymakers, and which can be used as a tool for long-term planning and investment processes as well as for the construction of active oil and gas portfolios for physical trade.

As the research programme of energy modelling progresses, the aim of building an integrated theory of agent-based models for energy systems will be within sight. The work presented here suggests a way forward through the development of the ACEGES model.

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EROI Ratios: Implications for Energy Forecasting and Long-Term Prosperity

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Abstract

This paper describes the concept of energy return on energy invested (EROI), and sets out some of the various approaches to calculating EROI ratios that exist, particularly in terms of boundary conditions. The paper presents a range of current estimates of EROI ratios for conventional oil and gas, and shows that these have generally fallen in recent years. EROI values for non-conventional oil and gas, and for a range of other energy sources, are also presented. These show that with the exception of coal and hydroelectricity, most of these other energy sources have lower EROI ratios than conventional oil and gas, and more so if energy storage is needed to compensate for intermittency of supply. The reasons that EROI data should be incorporated into energy forecasts, and the implication in terms of the EROI required to support modern society, are then briefly explored.

Note: This paper is an extract, with permission, from Chapter 9: Charles A.S. Hall, Energy Return on Investment (EROI) and its Implications for Long-term Prosperity, pp 197-224, of Matthias Ruth (ed.) Handbook of Research Methods and Applications in Environmental Studies, 2015; Edward Elgar Publishing Ltd., Cheltenham, UK and Northampton, MA, USA. website: www.e-elgar.com. This text has been slightly expanded and updated. See the original chapter for additional information on concepts and history of net energy, for methodologies and data sources for calculating EROI values, and on the minimum EROI required by society.

1. Introduction

Energy is usually taught as an independent entity; as something that lives unto itself. In truth it is a component of everything around us that moves and most that does not: the skies, seas, land, all geological, meteorological and hydrological processes, all plants, animals and microbes, all ecosystems, including those human-dominated ecosystems called cities and societies; essentially everything. Consequently, energy is associated with, indeed drives, all that society and its economies do.

Many observers from different disciplines who have thought deeply about the long-term relation of humans and wealth production have concluded that the best general way to think about how different societies evolved over time is from the perspective of surplus energy, sometimes called net energy. These have included the chemists Frederick Soddy and William Ostwald, anthropologist Leslie White, archaeologist and historian Joseph Tainter, sociologist Fred Cottrell, historian John Perlin, systems ecologist Howard T. Odum, economist Nicolas Georgescu-Roegan, and energy scientist Vaclav Smil.

But this fundamental fact seems to have escaped the attention of most economists, who seem impervious to energetic reality despite a century of intelligent criticism. The latter includes that from Georgescu-Roegan (1975), Leontief (1982), Hall et al. (2001) and Piketty (2014). Three of these are distinguished economists, and two Nobel Prize laureates. Instead, economists have continued to consider energy as just another commodity, and the drivers of economic production to be solely capital and labour.

Moreover, it is not just energy that is important, but *cheap energy* (Campbell and Laherrère, 1998; Hall and Klitgaard, 2012), and this is only possible when there is a large surplus of net energy; that energy left after the energy cost of getting the primary energy. This applies whether the source energy is food, wood or fossil fuels. A society must have a net energy surplus for there to be division of labour, creation of specialists and the growth of cities; and a substantially greater surplus for there to be widespread wealth, art, culture and other social amenities.

This ratio of energy gained divided by the energy cost of getting it is measured by energy return on investment (EROI). This ratio reflects the basic physical situation, including depletion and the state of present technology. This ratio also largely drives and explains the critically important energy return on monetary investments, which appears to be driven in large part by the underlying EROI value (King and Hall, 2011).

More generally, economic conditions and their fluctuations tend to reflect, directly or indirectly, variations in a society's access to cheap and abundant energy (Cleveland et al., 1984; Tainter, 1988). Today, fossil fuel resources are among the most important global commodities and are essential for the production and distribution of most of the rest. Fossil fuels supply greater than 75 percent of the total energy consumed by societies, (see EIA data, as discussed in Hall et al., 2009). The prosperity and stability of modern society is thus inextricably linked to the production and consumption of energy, especially that of oil (Odum, 1973; Hall et al., 1986; Hall and Klitgaard, 2012; Tverberg, 2012; Lambert et al., 2014).

2. Energy Return on Investment (EROI)

The energy return on investment (EROI) is simply the energy gain from an energy-acquiring process. It is expressed as the ratio of the energy produced divided by the energy (or occasionally monetary or other) investment for that return, where numerator and denominator are in the same units. There are a number of potential benefits that proper EROI analysis can provide:

1. Much like economic cost–benefit analysis, EROI analysis can provide a numerical output that can be compared easily with other similar calculations. For example, the EROI of oil (and hence gasoline) is currently between about 10:1 and 20:1, whereas that for corn-based ethanol is below 2:1, and perhaps below 1:1 (for example, Farrell et al. 2006; Murphy et al. 2011a). From this perspective it is easy to see that substituting ethanol for gasoline would have significant energy, economic and environmental implications, since the same energy investment into gasoline yields at least a fivefold greater energy return (with a correspondingly lower impact per unit delivered to society) than that from ethanol. Thus good EROI analysis can save us from investing large amounts of our remaining fossil fuels into alternative fuels that contribute little or nothing

to our financial or energy well-being, as appears to have been the case with corn-based ethanol, and is likely to be the case with some other energy alternatives currently being considered.

2. The EROI ratio is a useful measure of resource quality. Here quality is defined as the ability of a heat unit to generate economic output (Hall et al., 1986). High EROI resources are considered to be, ceteris paribus, more useful than resources with low EROIs. If an EROI ratio declines over time then more of society's total economic activity goes just to get the energy to run the rest of the economy, and less useful economic work (that is, producing desirable goods and services) is done.

3. Energy return on investment, and especially its rate of change, offers the possibility of looking into the future in a way that markets seem unable to do. Advocates of EROI analysis suggest that in time market prices must approximately reflect comprehensive EROIs, at least if appropriate corrections for quality are made, and energy subsidies are removed (King and Hall, 2011).

4. Using EROI measurements in conjunction with standardised measures of the magnitude of energy resources provides additional insight about the total net energy gains from a potential energy resource. For example, the oil sands of Canada present a vast resource base, roughly 170 billion barrels of recoverable crude oil, yet the EROI of this resource is presently about 4:1 on average at the mine mouth, indicating that only 80 percent of the 170 billion barrels of recoverable oil, or 136 billion net barrels, will be available to society (that is, energy remaining after accounting for the extraction cost (see, for example, Poisson and Hall, 2013); and considerably less after the additional processing and transport costs are accounted for.

5. Time-series datasets of EROI measurements for a particular resource provide insights as to how the quality of a resource base is changing over time. For example, the EROI of US and presumably global oil production generally increased during the first half of the twentieth century and has declined since (see Gagnon et al. 2009; Guilford et al., 2011). The decrease in EROI indicates that the quality of the resource base is also declining, that is, either the investment energy used in extraction has increased without a

commensurate increase in energy output, or the energy gains from extraction have decreased.

Energy return on investment can tell us a great deal about the relative desirability of various possible energy paths into the future, and should be analysed routinely. In addition, it is important to consider the present and future potential magnitude of the fuel, how the EROI is changing over time, and how this might change if the use of a fuel is expanded. Nevertheless, the EROI by itself is not necessarily a sufficient criterion by which policy judgments should be made.

3. Economic cost of energy

To understand EROI more fully we start with the more familiar monetary assessment, and then develop how this relates to the energy behind economic processes. In real economies, energy comes from many sources – from imported and domestic sources of oil, coal and natural gas, as well as hydropower and nuclear, and from a little renewable energy – most of that as firewood but increasingly from wind and photovoltaics. Some of these are cheaper per unit energy delivered than oil and some are considerably more expensive. So let us look at what this real ratio of the cost of energy (from all sources, weighed by their importance) is relative to its benefits. We may think of this as the investment cost necessary to make gross domestic product (GDP):

Monetary return on investment

= GDP / (Dollars to get the energy required for that GDP)
Eqn. 1

By this token the relation of the proportional energy cost in dollars is similar, as we shall see, to the proportional energy cost in joules; in 2007 roughly 9 percent (1 trillion dollars) of the US GDP was spent by final demand for all kinds of energy in the US economy to produce the 12 trillion dollars' worth of total GDP, and hence the monetary return on investment was about 12:1.

Energy return on investment (EROI, or sometimes EROEI with the second E used to refer to the use of energy in the denominator) is similarly the ratio of energy returned to society (i.e. not including the investment energy) from an energy-gathering activity compared to the energy invested in that process. Energy return on investment is calculated from the following simple equation, although the devil is in the details:

EROI = (Energy returned to society) / (Energy required to get that energy) Eqn. 2

Since the numerator and denominator are usually assessed in the same units (an exception is treated later is when quality corrections are made) the ratio so derived is dimensionless, for example, 30:1 which can be expressed as '30 to one'. This implies that a particular process yields 30 joules on an investment of 1 joule (or kcal per kcal, or barrels per barrel). Energy return on investment is usually applied at the mine-mouth, wellhead, farm gate, and so on, that is, at the point that the energy leaves the production facility. We call this more explicitly $EROI_{mm}$. (Note that energy return on investment is not to be confused with conversion efficiency, that is, the efficiency of a process when converting one form of energy to another, such as upgrading petroleum in a refinery, or converting the energy in diesel fuel to electricity.)

4. Types of EROI and the Effect of Boundaries and Data Sources

There are a number of dimensions along which a system boundary may vary. One dimension runs 'parallel' to the energy process chain from extraction ('mine-mouth') to intermediate processing ('refinery gate') to distribution (final demand) and determines the numerator in the EROI ratio, in answer to the question: 'What do we count as energy outputs?' This dimension is depicted with the three system boundaries in Figure 1.

A second 'perpendicular' dimension over which the system boundary may vary is to include a greater variety of direct and indirect energy and material inputs which determine the comprehensiveness of the denominator of the EROI ratio, in answer to the question: 'What do we count as inputs?' Level 1 includes only those 'on site' inputs from the energy chain under investigation, level 2 incorporates energy inputs used off site required to make physical infrastructure (such as steel used on site), levels 3 and 4 incorporate energy embodied in supporting labour and economic services.

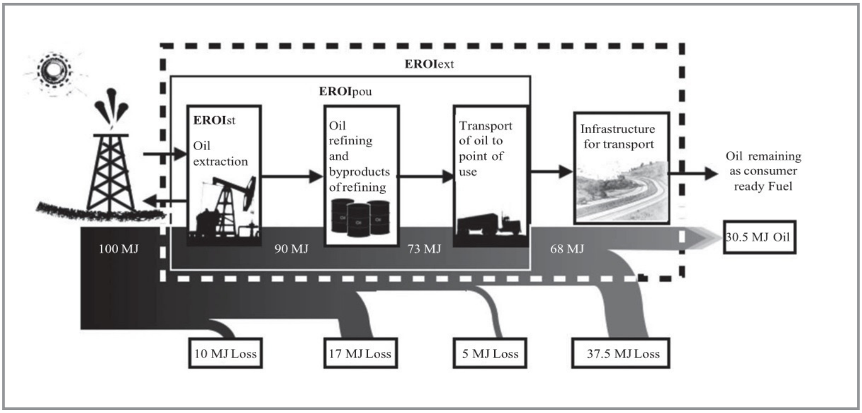

Figure 1. Boundaries of various types of EROI analyses and energy loss associated with the processing of oil as it is transformed from 'oil at the well-head' to consumer ready fuels. Source: Lambert and Lambert (in preparation) based on calculations by Hall et al. (2009).

Much of the recent EROI literature tends to focus on the net or surplus for a given project, industry, nation, fuel, or resource, for example discussions on the 'energy break even' point of EROI for corn based ethanol, that is, whether the EROI is greater or less than 1:1. The apparently different results from this relatively straightforward analysis generated some controversy about the utility of EROI. But, the variation in these findings is mostly the result of the choice of inclusion or exclusion of various direct and indirect energy costs associated with energy production/extraction: that is, the boundaries of the denominator (Hall et al. 2011). The investigator should be explicit in what is included and why.

Any method of calculating EROI must have two, somewhat contradictory, attributes; consistency and flexibility. The methodology must be consistent so that researchers can replicate calculations accurately, yet flexible so that meaningful comparisons can be made across disparate energy extraction or conversion pathways or to accommodate differing objectives or philosophies. Thus we need to ascertain a straightforward and universally accepted approach to EROI even while accommodating different approaches or philosophies.

Hall et al. (2008), and especially Murphy et al. (2011b), gave specific subscripts to EROI in an attempt to standardize the boundaries used at different points in the 'food chain' of energy from well head (and so on) to final consumption and/or by using different degrees of comprehensiveness of inputs. Of greatest concern are the boundaries of the analysis: should co-products (such as hulls left from generating biodiesel from sunflower seeds that can be fed to animals, reducing energy needed to make the animal feed) be included, or should we include the costs of the energy to support a labourer's pay check? Since there are no clear and unambiguous answers to those questions, Murphy et al. advocated a basic EROI approach using simple standardized energy output divided by the direct (that is, on site) plus indirect (that is, energy used to make the steel used on site) to generate a standard EROI, EROIstnd. Thus Murphy et al. also advocate the use of additional EROIs, including new approaches that allow for special consideration of other aspects of that EROI.

$$\mathrm{EROI}_{\mathrm{stnd}} = \text{(Energy returned to society)} / \text{(Direct and indirect energy required to get that energy)} \qquad \text{Eqn. 3}$$

The standard EROI ($\mathrm{EROI}_{\mathrm{stnd}}$) divides the energy output for a project, region or country at the wellhead, farm gate, and so on by the sum of the direct (that is, on site) and indirect (that is, offsite energy needed to make the products used on site, such as steel, machinery and so on) energy used to generate that output (that is, level 2 above). It does not include, for example, the energy associated with supporting labour, financial services and the like.

This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (well-head, mine mouth, farm gate, and so on). It is the approach most generally used. Prieto and Hall (2012) see this as a departure point for comprehensiveness of assessing energy costs. This standard but flexible approach allows for the comparison of different fuels even when the analysts do not agree on the rest of the methodology that should be used (Murphy et al. 2011a). Murphy et al. recommend always using $\mathrm{EROI}_{\mathrm{stnd}}$, and hence enabling comparison, but also using any other approach the authors may wish.

Other classes of EROI sometimes considered are: 'Point of Use'

EROI, 'Extended' EROI, and 'Societal' EROI. See the original chapter from which this paper is drawn for the definitions of these. There are also similar formulae for deriving or expressing net energy used by other authors. Three variants are the 'Fossil Energy Ratio' (FER), often used in the discourse on biofuels, which compares the total energy gains from fossil fuel investment only; 'External Energy Ratio' (EER) which excludes *in situ* energy such as the bitumen used for *in situ* tar sands extraction, and net energy yield ratio (NEYR) which has as the numerator the net energy from the energy production process and all of the inputs necessary to produce that net flow as the denominator (Brandt and Dale, 2011). The absolute energy ratio (AER) also includes in the denominator the energy content of the energy resource, from the natural environment, which is being processed. At this time EROI is most commonly used.

5. Exemplar Results: EROI of Petroleum Oil and Gas

Most industry data is maintained in dollars, not energy, so there are relatively few places where it is possible to undertake energy-based EROI analysis. Fortunately, some countries (the US, Canada, the UK, Norway and China) maintain reasonably good data files and it is possible to use these direct energy inputs, plus make some inferences on the indirect energy used to make equipment. The most useful data are those for which one can derive an EROI time series.

The EROI for petroleum production appears to be declining over time for every place we have data, which is consistent with, and probably causes, the general increase in monetary costs for finding and exploiting oil and gas. Gagnon et al. (2009) were able to generate an approximate 'global' EROI for private oil and gas companies using the 'upstream' financial database maintained and provided by John H. Herold Company and industry-specific energy intensities. These results indicate that the EROI for publicly traded global oil and gas was approximately 23:1 in 1992, 33:1 in 1999 and 18:1 in 2005 (Figure 2). This 'dome shaped' pattern seems to occur wherever there is a long enough dataset, perhaps as a result of initial technical improvements being trumped in time by depletion.

Their analysis found that EROI had declined by nearly 50 percent in the past decade and a half after an earlier increase. New technology and production methods (initially, seismology, geophysics and enhanced recovery using, for example, water flooding, and later, deep water exploitation and horizontal drilling) are maintaining production but appear insufficient to counter depletion of conventional oil.

There are three independent estimates of EROI time series for oil and gas production for the US. These are plotted along with some important oil-related historical events in Figure 3 (Cleveland et al. 1984; Hall et al. 1986, Guilford et al. 2011).

The data show a general pattern of an increase and then a decline in EROI over time except as impacted by changes in exploration (drilling) intensity. During the mid-1970s to 1980s and late 2000s, the price of oil increased as did exploration intensity, as measured by increased feet drilled and energy used. Energy return on investment values tend to decline both over time (in mature industries) and when there is an increase in the energy used for exploration and drilling when oil prices ae high. However, increased drilling usually was linked to little or no additional oil discoveries; hence EROI values declined. At this time there is insufficient information to determine how the new technologies of horizontal drilling and fracking will affect these patterns.

Two independent EROI estimates for Canadian production of oil exist (Figure 4). Poisson and Hall (2013) found that the EROI of conventional oil and gas has decreased since the mid-1990s from

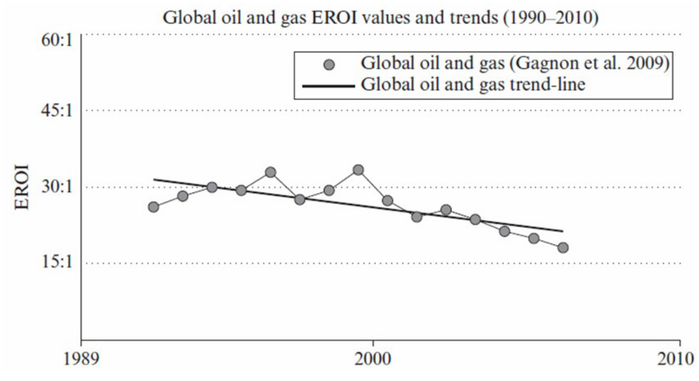

Figure 2. EROI for global publicly traded oil and gas. Source: Gagnon et al. (2009).

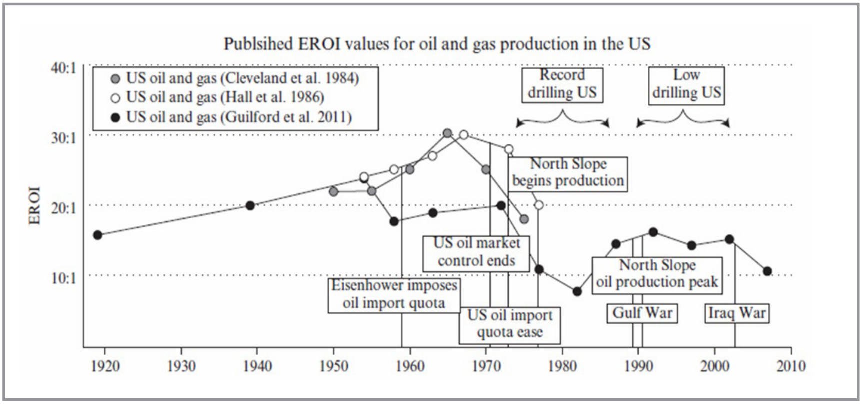

Figure 3. Time series analyses of oil and gas production within the US including several relevant 'oil related' historical events.
Source: Cleveland et al. (1984); Hall et al. (1986); Guilford et al. (2011).

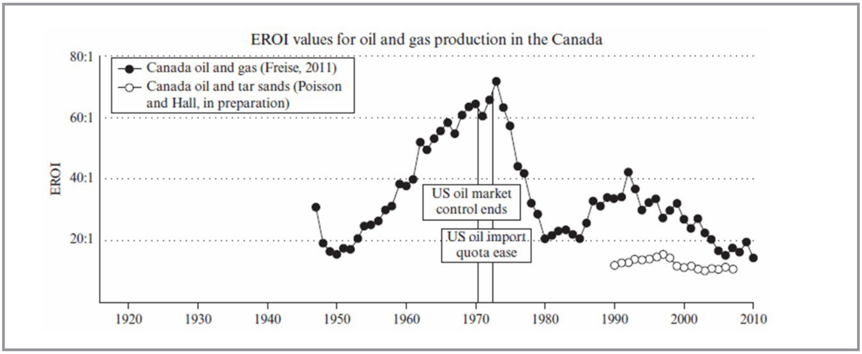

Figure 4. Two independent estimates of EROI for Canadian petroleum production: oil and gas (top line, from Freise 2011) and oil, gas and tar sands combined (bottom line, from Poisson and Hall, 2013). Source: Freise (2011); Poisson and Hall (2013).

roughly 20:1 to 12:1, a 40 percent decline. The EROI of conventional combined oil-gas-tar sands has also decreased during this same period from 14:1 to 7.5:1, a decline of 46 percent (Figure 5) (Poisson and Hall 2013). Poisson and Hall's estimated EROI values for Canadian oil and gas are about half those calculated by Freise and their rate of decline is less. Freise (personal communication) thinks that Poisson and Hall's values are more accurate.

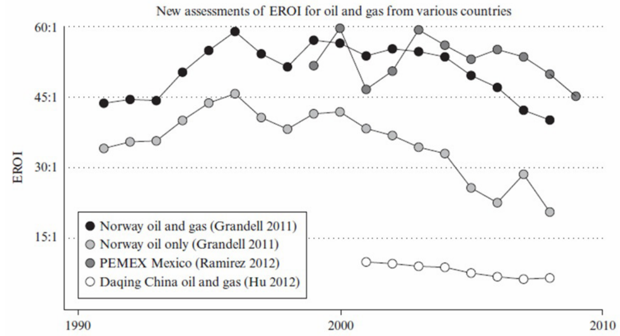

Figure 5. Time series data on EROI for oil and gas for Norway, Mexico and the Daqing oil field in China. Source: based on Hall and Hansen (2012) and Lambert et al. (2013).

Poisson and Hall's estimate of the EROI of tar sands is relatively low, around 4.5 (even though using a conservative, that is, low, estimate of costs at the front end of the life cycle); incorporating tar sands into total oil and gas estimates decreases the EROI of the oil and gas extraction industry as a whole. These estimates would be lower if more elements of the full life cycle (for example, environmental impact) were included in the calculation. On the other hand the energy inputs come from the resource itself, so it is possible.

Norwegian conventional oil and gas fields are relatively new and remain profitable both financially and with regard to energy production. Grandell et al. (2011) estimate that the EROI of oil and gas ranged from 44:1 (during the early 1990s) to 59:1 (1996), to approximately 40:1 (during the latter half of the last decade), again showing dome shaped pattern (Figure 5). Norwegian production, and presumably EROI, has continued on a strong downward trend through 2013.

Ramirez's preliminary oil and gas EROI trends for Mexico suggests that this country may have peaked twice in the past decade. The EROI for conventional oil and gas production in Mexico declined from roughly 60:1 in 2000 to 47:1 the following year, but returned to 59:1 by about 2003 (Figure 5). This was followed by a steady decline over the following six years reaching 45:1 by 2009. The collapse of production from the Cantarell field, once the world second largest, appears largely responsible for this decline.

The EROI for the Daqing field, China's largest conventional oil field, has declined continuously from 10:1 in 2001 to 6:1 in 2009 (Figure 5) (Hu et al. 2013).

The data represented in Figure 6 includes analyses for a portion of the US and for all of Canada. Since most published numbers combine data on natural gas with that of oil, it is usually, difficult or impossible to assess the production costs of these fossil fuel resources independently.

Sell et al.'s (2011) trends for EROI of natural gas trends for Pennsylvania (US) has an undulating decline; from roughly 120:1 in 1986 to 67:1 in 2003. This value is probably a high value as some indirect costs were not included. Freise (2011) estimated the EROI of western Canadian natural gas from 1993 to 2009 and found that the EROI of natural gas has been decreasing since 1993 through 2006, from roughly 38:1 to 14:1. This trend shifted in 2006 resulting in a steady increase and an EROI of roughly 20:1 by 2009 (Figure 6) (Freise 2011).

There are two published studies on the EROI of fracked natural gas for the Marcellus formation in Pennsylvania: Aucott and Mellilo (2013) and Hiroaki and Matsushima (2014). Both papers give high values (~60:1) for gas at the well head but much lower (about 12:1) after compression and pipeline shipping, so that the value for both is about 12:1 by the time the consumer gets it (Aucott, personal communication). Both papers also emphasize that these values are from 'sweet spots' and that future values are likely to be lower (Figure 6).

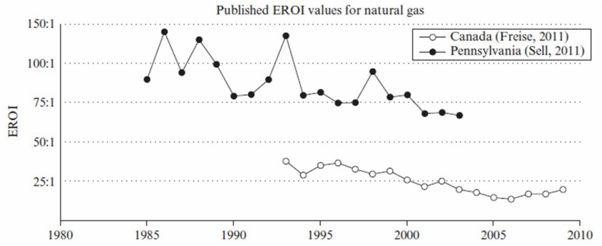

Figure 6. Two published studies on the EROI of dry natural gas (not associated with oil): Sell et al. (2011) examined tight natural gas deposits in western Pennsylvania in the US, and Freise (2011) analysed all convention natural gas wells in western Canada. Source: Freise (2011); Sell et al. (2011).

6. EROI of Other Fuels and Energy Sources

The other important fossil fuel, coal, has a relatively high EROI value and shows no clear trend over time. Coal has a mean EROI of about 46:1 based on 72 studies from 17 publications (Lambert et al. 2013). The energy content of coal has been decreasing even though the total tonnage has continued to increase (Hall and Klitgaard 2012). This is true for the US where the energy content (quality) of coal has decreased while the quantity of coal mined has continued to increase – at least until recently. The maximum energy (versus tonnage) from US coal seems to have occurred in 1998 (Hall et al. 2009; Murphy and Hall 2010). The only time series EROI analyses for coal production are from the US and China because information on the energy expended to extract coal in other areas of the world appear unavailable. Time series of EROI for coal production for the US and China are given in Figure 7. A great variability in EROI is evident from these figures. This data, however, has significant holes (for example, no data is reported for approximately 30 years, from the mid-1950s to the mid-1980s). Cleveland's work provides additional information for three non-contiguous years that is inconsistent with Balogh et al.'s (2012) findings. Hu et al. (2013) establishes annual data for Chinese coal production for the years 1994 through 2009. These show very little variation in EROI values (Figure 7).

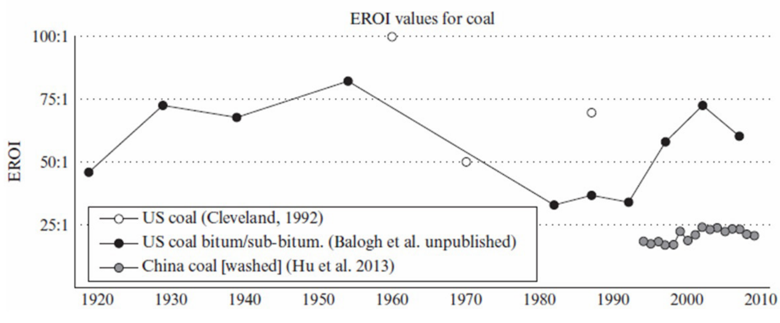

Figure 7. EROI for US and Chinese coal production. Source: derived from Cleveland (1992); Balogh et al. (2012); Hu et al. (2013).

Meta-analysis of EROI values for nuclear energy suggest a mean EROI of about 14:1 (Lambert et al. 2013; see also Lenzen 2008) (Figure 9). Newer analyses need to be made as these values may not adequately reflect current technology or ore grades. Whether to correct the output for its relatively high-quality electricity is an unresolved issue and a quality correction for electricity appears to contribute to those relatively high values given here.

Hydroelectric power generation systems have the highest mean EROI value, 84:1 of electric power generation systems (Lambert et al. 2013). The EROI of hydropower is extremely variable based on the wide variability of dam sites, although the best sites in the developed world were constructed long ago (Hall et al. 1986).

We calculated the mean EROI value for ethanol from various biomass and data sources. The variability is extreme: for example, an EROI of 0.64:1 (Pimental and Patzek 2005) for ethanol produced from cellulose from wood, versus an EROI of 48:1 for ethanol from molasses in India (Von Blottnitz and Curran 2007). These values resulted in a mean EROI value of roughly 5:1 (Lambert et al. 2013). Diesel from biomass seems to be about 2:1 (Hall et al. 2013). We believe that EROI values at or below the 3:1 minimum extended EROI value are minimally useful to society (Hall et al 2008; Murphy et al. 2011b; see Section 9).

Wind power has a relatively high EROI value, with the mean perhaps as high as 18–20:1 (Kubiszewski et al. 2010; Lambert et al. 2013). However these values would presumably be much less if the energy cost of providing energy backups were included, as the wind does not blow all the time. With a wind capacity factor of typically only about 30 percent, systems - depending on load - can need up to twice as much energy from backup generation (or storage) as that generated by the wind.

An examination of the EROI literature on solar photovoltaic (PV) energy generation is effected by inconsistencies and ambiguities in the assumptions and methodologies employed, and in the type of EROI values calculated. These differ from study to study, making comparisons of EROI values between PV and other energy sources difficult and fraught with potential pitfalls unless extreme care is taken to ensure consistency. Nevertheless, we calculated a mean EROI value of roughly 10:1 from 45 publications (Hall et al. 2013).

It should be noted that several recent studies that have broader - but more appropriate, we feel - boundaries give lower EROI values of 2 to 3:1 (Prieto and Hall 2012; Palmer 2013; Weissbach et al. 2013), although these may already be out of date. All solar EROIs would be higher if weighed for the quality of the electricity and lower, probably much lower, if necessary backups for intermittency of the input were included. To this author's knowledge the latter has not been done except by Palmer (2013).

Geothermal electricity production has a mean EROI of approximately 9:1 (Atlason and Unnthorsson 2013, 2014). While geothermal is in principle renewable, good sites are rare and some (for example, geysers in California) are showing signs of depletion of heat. Ground heating of homes has an EROI of roughly 4:1 although the input is electricity and the output lower-quality heat, perhaps resulting in an approximate wash.

7. Summary of EROIs

Energy return on investment values for our most important fuels, liquid and gaseous petroleum and coal, tend to be relatively high.

World oil and gas has a mean EROI of about 20:1. That for publicly traded companies has declined from 30:1 in 1995 to about 18:1 in 2006. The EROI for discovering oil and gas in the US has decreased from more than 1000:1 in 1919 to 5:1 in the 2010s, and for production from about 30:1 in the 1970s to less than 10:1 today. Alternatives to traditional fossil fuels such as tar sands and oil shale deliver a lower EROI, having a mean EROI of 4:1 and 7:1, respectively. It is difficult to establish EROI values for natural gas alone as data on natural gas are usually aggregated in oil and gas statistics. Fracked oil and gas appear to be in the vicinity of conventional US oil and gas, although that may change as the 'sweet spots' are depleted (Figure 8).

A positive aspect of most renewable energies is that the output of these fuels is high-quality electricity. A potential drawback it that the output is far less reliable and predictable. Energy return on investment values for PV and other renewable alternatives are generally computed without converting the electricity generated into its 'primary energy-equivalent' (Kubiszewski et al. 2010) but also without including any of the considerable cost associated with the required energy backups or storage.

Energy return on investment calculations of renewable energy technology appear to reflect some disagreement on the role of technological improvement. Raugei et al. (2012) attribute low EROI values sometimes calculated for PVs to the use of outdated data and direct energy output data that represents obsolete technology that is not indicative of more recent changes and improvements in PV technology. Other researchers contend that values derived using this methodology do not represent adequately the ‘actual’ energy cost to society and the myriad energy costs associated with this delivery process. For example Prieto and Hall (2012; also Palmer 2013) calculated EROI values that incorporate most energy costs, with the assumption that where ever money was spent energy too was spent. They use data from existing installations in Spain, and derived EROI values of roughly 2.4:1, considerably lower than many less comprehensive estimates. (Note also that some recent data suggest that many PV structures are lasting considerably less than the 25 years assumed by Prieto and Hall.) Nearly all renewable energy systems appear to have relatively low EROI values when compared with conventional fossil fuels, especially if needed energy backups are included (Figure 9).

A question remains as to the degree to which total energy costs can be reduced into the future if there is a large programme to reduce the use of most fossil fuels, for - as it stands - most ‘renewable’ energy systems appear to be still heavily supported by fossil fuels. Nevertheless they may be more efficient at turning fossil fuels into electricity than are thermal power plants, although over much more time (Prieto and Hall, 2012).

8. Use of EROI Data in Energy Forecasting

If humankind is to properly understand its energy future, then EROI data such as those presented here must be incorporated into all energy forecast models, as for example is the case with Campbell’s latest oil and gas model (Campbell, 2015).

However, as explained above, due account must be taken of the purpose for which any given EROI ratio is used. For example, if forecasting future energy available from extensive use of retorted

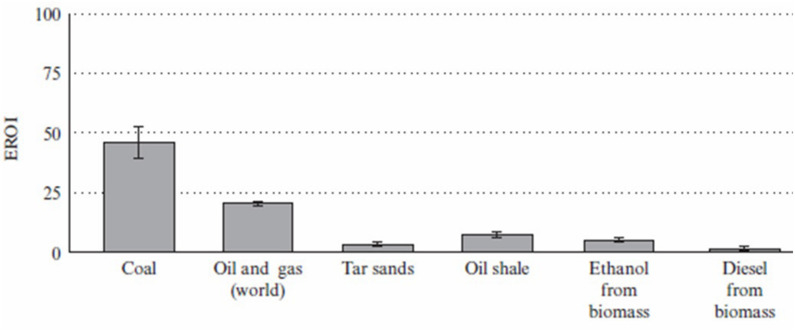

Figure 8. Mean EROI (and standard error bars) values for thermal fuels based on known published values. Source: Values derived using known modern and historical published EROI and energy analysis assessments and values published by Dale (2010).

Note: For this Figure, and Figure 9 below, see Lambert et al. (2013) for a detailed list of references; and see that paper also for discussion, as the values given here should not be taken strictly at face value.

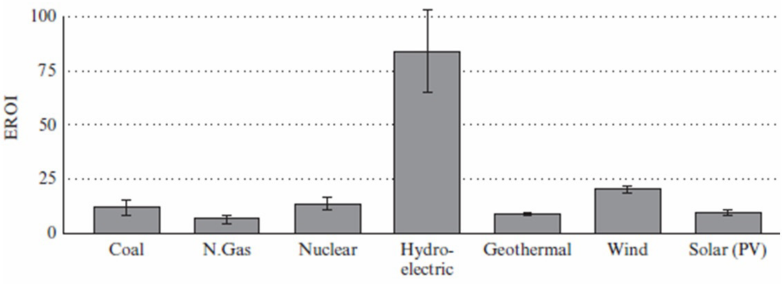

Figure 9. Mean EROI (and standard error) values for known published assessments of electric power generation systems.

kerogen from shale rock, then to understand the net energy available for productive use there may be no need to include in the denominator of the EROI ratio used that thermal energy provided on-site by combustion of the kerogen (although getting that kerogen can be energetically and monetarily expensive). However, if considering the CO_2 implications, then the burning of this kerogen does need to be considered.

To illustrate the importance of EROI ratios in energy modelling, consider the case of modelling the energy produced by photovoltaic (PV) systems.

Quite a number of recent well-respected global energy models have examined humankind's ability to meet all its energy needs from renewable sources, and where in most of these studies significant expansion of PV is often seen as one of the solutions. However, such an analysis faces a significant flaw, at least in the short and medium term. While there is discussion over what is the most likely value of EROI for PV (see above), even if we take a fairly high-end value of the EROI of a fully-installed large-scale PV system, of say, 7:1, then using EROI ratios paints a surprisingly gloomy picture of what might be achieved in the near or medium term.

The owner of a single PV plant having a life of, say, 28 years, at an EROI ratio of 7:1 has a good energy return; 'paying' for the system's embodied energy in the first four years of operation, and getting net energy back for the remaining twenty-four years. But by contrast, for society as a whole, where the rate of installed PV has been growing rapidly, and still needs to do so to meet a major fraction of total global energy, then it is easy to show that globally the embodied energy in building PV during this growth phase has been negative. In other words, to date the over 200 GWp of global installed PV has contributed *no net energy* to society (see, e.g., Dale and Benson, 2013). Admittedly PV, with its fairly modest EROI ratio, and very high growth rate, is a rather extreme example of this principle, but it reinforces the notion that energy modelling without incorporating EROI ratios can be very misleading.

9. What Level of EROI Does Society Need?

Those who focus on EROI and its decline believe that the concept has enormous implications for society (Jones et al. 2004; Hall et al. 2008; Lambert et al. 2013). At the societal level, declining EROI ratios mean that an increasing proportion of energy output must be diverted to attaining the energy needed to run an economy, leaving less discretionary funds available for 'non-essential' purchases which often drive growth and the better things of civilization.

This in turn leads to the critically important question of the level of EROI that society needs from its fuels to support modern life. This is discussed at greater length in the original chapter from which this paper is taken, and is discussed here briefly.

The real question revolves around what EROI is necessary to run society as we know it. Together with Jessica Lambert, this author developed a 'hierarchy of energetic needs', which represents the importance of the quality of energy (in terms of net energy delivered) devoted to the production and maintenance of infrastructure and activities required to support society. We analyse this using EROI (Hall et al. 2009, Hall and Klitgaard 2012).

If, for example, you lived on an island with one oil well as the only source of energy besides the sun, and the EROI for that oil was 1.1:1, then one could pump the oil out of the ground and look at it. If it were 1.2:1 you could both extract it and refine it. At a 1.3:1 EROI it could also be distributed to where it is useful but, once again, all you could do is look at it. Hall et al. (2009) examined the EROI required to run a truck. They found that an EROI of at least 3:1 EROI at the well-head was necessary to build and maintain the truck and the roads and bridges required to use one unit of oil in that truck, including depreciation. In a thought experiment Hall and Lambert found that in order to deliver a product in the truck, such as grain, an EROI of roughly 5:1 is required to include growing and processing the grain to be delivered. To include depreciation of the oil field worker, the refinery worker, the truck driver and the farmer, it would require the support of the families and an EROI of approximately 7 or 8:1. If the children of these families were to be educated, an EROI value in the region of 9 or 10:1 would be required. If the families and workers receive health care and higher education, then an EROI value of perhaps 12:1 at the wellhead is required. An EROI value of at least 14:1 is needed provide the performing arts and other social amenities to these families and workers.

In other words to have a modern civilization, one needs not simply surplus energy but a great deal of it, and this requires a high EROI (or, theoretically, a massive source of moderate-EROI fuels). Hall et al. 2008 found from both data analysis and a model that as EROI declines so does discretionary income; in their model to essentially zero by 2050.

It is astonishing, given the enormous size of fossil fuel investments, and the many poorly understood issues relating to their costs, including environmental costs, that we do not have a large national budget to assess EROI comprehensively, including the environmental and other externalities. Meanwhile there is a degradation of the needed statistics by governmental agencies, such as the Bureau of Census (Guilford et al. 2011).

Thus society seems to be caught in a dilemma unlike anything experienced in the last few centuries. During that time most problems (such as needs for more agricultural output, worker pay, transport, pensions, schools and social services) were solved by employing both technology and investment to solve the problems. In many senses this approach worked, for many of the problems were indeed resolved - or at least ameliorated, although at each step populations grew so that new potential issues had to be addressed. But in a general sense, all of this was possible only because there was an abundance of cheap (that is, high-EROI), high-quality energy - mostly oil, gas or electricity - which supported the research and the investments that occurred.

We believe that the future is likely to be very different, for while there remains considerable energy in the ground it is unlikely to be exploitable cheaply, or eventually at all, because of its increasingly low EROI. If any resolution to these problems is possible it is probable that it will have to come at least as much from an adjustment of society’s aspirations for increased material affluence, and an increase in willingness to share, as from technology.

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A Review of some Estimates for the Global Ultimately Recoverable Resource ('URR') of Conventional Oil, as an Explanation for the Differences between Oil Forecasts – Part 3

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Abstract

This paper is the final part of a three-part paper examining the link between estimates for the size of the global ultimately recoverable resource ('URR') of *conventional* oil and the differences between forecasts for global 'all-oil' production from different organisations.

Firstly in this paper the historical estimates of global URR by category of oil contained in Hubbert's 1949 *Science* article are presented, and are compared to later estimates he used. Then an approximate current minimum value is given for the URR of global *conventional* oil based on three recent 'mainstream' oil forecasts, those from ExxonMobil, BP, and the IEA. A table is then presented that summarises the global URR estimates, by category of oil, covered in all three parts of this paper.

Finally, the difference between current URR estimates for global conventional oil is examined in terms of those estimates which are broadly in line with global proved-plus-probable ('2P') oil *discovery* data (in some cases, with adjustment for assumed data quality), and those estimates which differ significantly from this discovery trend. The paper concludes by suggesting that oil forecasts which use (or generate) global conventional oil URR estimates roughly in agreement with global 2P conventional oil discovery data are the more likely to be correct.

1. Introduction

This is the final part of a three-part paper examining the link between the estimated size of the global ultimately recoverable resource ('URR') of *conventional* oil and the results of forecasts of 'all-oil' production which have used these values. (Apologies are due, in that initially it was indicated that this paper would comprise only two parts, rather than three.)

The first part, Bentley (2015a), looked at the difference between oil forecasts from different organisations; firstly those forecasts covered by the UKERC *Global Oil Depletion Study* (Sorrell et al., 2009), and then in summary form a range of more recent forecasts. In order to understand the large difference between these forecasts, it was suggested that the primary factor is the difference between the values assumed for the global URR of *conventional* oil.

To examine this view, that part of the paper then presented historical URR estimates made between 1956 and 2005 for different categories of oil, and also the range of global URR estimates for *conventional* oil generated by the US Geological Survey (USGS) for the years from 1991 to 2012. It was shown that for many years the estimates for the global URR of conventional oil (less NGLs) were mostly in the range 1800 – 2500 Gb; and that the USGS mean estimates (also less NGLs) over the period examined were of a similar order, provided they did not include allowance for reserves growth.

However, if reserves growth were included in these USGS estimates (which was the case from the year 2000 onwards) the corresponding mean global URR values for conventional oil (and here, plus NGLs) was 3345 Gb in the 2000; and 3850 Gb (approximately) in 2012.

It was then shown that most 'mainstream' oil forecasts after the year 2000 used estimates of URRs, sometimes for conventional oil and sometimes for 'all-oil', that were either actually, or very probably, based on these USGS estimates of the global conventional oil URR.

The second part of the paper (Bentley 2015b) presented a number of more recent estimates of global URR, here by category of oil. These were estimates from the US EIA (2013 and 2015), the IEA's '*Resources into Reserves*' study (2013), IEA 2014 data, and URR estimates from IHS CERA (2014), Campbell (2015), Globalshift Ltd. (Smith, 2015), Laherrère (2015), and Miller (2015). Table 13 in that part of the paper summarised these URR values; where, for conventional oil plus NGLs *plus* reserves growth, they ranged from ~2500 Gb up to 4350 Gb. Not surprisingly, those forecasts which saw no production peak for 'all-oil' within their time horizons assumed higher URR values, while those that saw a near or medium-term 'all-oil' peak assumed lower ones.

In this third part of the paper we first return to history, and present Hubbert's 1949 global URR estimates, by category of oil, that were published in *Science* (Hubbert, 1949). Then we give an approximate current *minimum* value for the global URR for conventional oil as implied by extrapolation of three fairly recent 'mainstream' oil forecasts; those from the IEA (2011), BP (2015) and ExxonMobil (2015). Then a summary table is given of URR oil estimates covered in all three parts of this paper. This leads to the question: Which URR estimate is the most reliable, in terms of predicting future global oil production? This is discussed in the final section in this paper.

2. Difference between Forecasts

The reason for examining this topic of URR estimates is because oil forecasts from different sources give significantly different predictions.

This was particularly the case only a few years' back, see the report from the US National Research Council's *Trends in Oil Supply* workshop (Zucchetto, 2006), or that from the UK Energy Research Centre's *Global Oil Depletion* study (Sorrell *et al*., 2009).

But the problem still exists today, with, for example, current forecasts for the global production of 'all-liquids' varying as follows:

> - Forecasts which see the global production of 'all-liquids' as reaching a maximum within less than a decade, and then declining; e.g., the forecasts of Campbell (2015), or Laherrère (2015).
>
> - Those forecasts which see production of this class of oil as reaching a maximum, but not until perhaps 2025 to 2035, and then declining; e.g., Smith (2015), Miller (2015).
>
> - Those forecasts which see no maximum in the global production of all-liquids out to the end of their forecast horizons, typically out to 2035 to 2040. This group tends to be forecasts from the more 'mainstream' oil forecasting organisations; see for example

the charts of forecasts by the IEA, BP and ExxonMobil in *The Oil Age*, Vol. 1, No. 2.

There are a number of reasons for these wide differences between forecasts, but one of the main ones, already identified by the UKERC 2009 *Global Oil Depletion* study, is the size assumed by these forecasts for the global ultimately recoverable resource (‘URR’) of *conventional oil*. (To a lesser extent the difference between forecasts also depends on the rates-on-stream assumed for the non-conventional oils, and for other liquids.)

It is important therefore to understand what URR numbers the various forecasts have used (or their forecasts imply). For this it is necessary to be clear about the definitions used for conventional and non-conventional oil, and for ‘other liquids’, and this was covered in Part 1 of this paper.

It is also important to understand what forecasters mean by ‘URR’. This was also covered in Part 1, but here we recapitulate two key ideas:

- For most forecasters, ‘ultimately recoverable’ does not signify some truly ‘ultimate’ value, as who knows what future demand there may be for oil, nor what oil recovery techniques might be developed in the very long term. Instead, for most forecasters, URR signifies the quantity of a particular class of oil that will have been produced from a specified region by some distant future date, such as by 2070 or 2100.
- Secondly, in some modelling methodologies (such as those of Campbell and Laherrère) a URR value is first estimated from other determinants (such as a region’s discovery history), and then this URR determines the forecast that is made for the region’s production. In other methodologies the forecast is first generated (for example by forecasting production from known individual fields and from fields assumed to be found in future), and then a resulting URR can be calculated by summing past and future production as given by the forecast.

Note that some URR estimates (such as those from the USGS) are not used by the organisation generating them, but are used in forecasts by other organisations, such as the IEA and EIA. In other cases, URR estimates are both generated by, and used by, the organisations or individuals making the forecasts.

Finally, note that a more extensive list of past estimates of global URR values, plus an excellent commentary, is given in the paper by Andrews and Udall (2015) in a previous issue of this journal.

3. URR Estimates Published by Hubbert in 1949

In this first section of this paper we return to the topic of early estimates of the global URR for oil, and give here the data quoted by Hubbert in an article in *Science* (Hubbert, 1949). These data were overlooked in the first part of this paper, and are important as they underline how surprisingly consistent over time have been global URR estimates, both for conventional oil, as well as for some of the non-conventional oils.

Hubbert's paper gives a plot of world production of coal from 1870 (and estimated back to 1800) to 1947, and likewise for petroleum from 1860 to 1947. Note that by 'petroleum' Hubbert was referring to *conventional* oil (oil in fields), and this would have excluded NGLs as these only came to be produced in significant quantities relative recently.

For the global cumulative production of coal to end-1947 Hubbert gives ~81 Gt, and for petroleum to the same date, ~8 Gt. For gas he says: "*Because of lack of world production statistics, the energy from natural gas has not been included.*" (But based on US data says the that annual global production in 1939 "*may be assumed to be at least 40% of that of petroleum*".)

Hubbert then discusses the global population trend, writing: "*One of the most disturbing ecological influences of recent millennia is the human species' proclivity for the capture of energy, resulting in a progressive increase in human population.*" He gives data on human population growth since 1650, and notes: "*That the present rate of growth cannot long continue is also evident when we consider that at this rate only 200 more years would be required to reach a population of nearly 9 billion – about the maximum number of people the earth can support.*"

The global population in 1940 was just over 2 billion, and the 9 billion figure Hubbert mentions arises from his simply extrapolating forward the 0.7%/yr. growth rate that had prevailed "*over the last half-century*". By contrast, in the population graph Hubbert that includes in the paper, an inflection point in global population growth is indicated (at about 1950), where the asymptote of the resulting trend results in a significantly lower predicted global population, of only about 4 billion people. In reality of course, population did continue to grow strongly, where now the current asymptote is expected to reach ~9 billion, Hubbert's '*maximum number of people the earth can support.*'

However, in terms of the challenge we currently face, we now know in Hans Rosing's phrase that the world has reached 'peak child', and the problem is no longer the risk of unchecked population growth, but on how to navigate the energy/population difficulties from now into the medium-term.

Hubbert's paper then looked at the question of whether the world contains enough energy to support such population growth. He looked at both fossil fuels as well as solar energy, and it is the data on the former that we cover here. (In the following, the text is edited slightly, and some units converted to Gb.) Hubbert wrote:

"PHYSICAL LIMITS TO EXPANSION

… One cannot refrain from asking, "Where is [this trend of energy use and population growth] *taking us? How long can we keep it up?"*

This leads us to consider what physical limitations there may be upon the various types of energy whose expansion we have noted. In the case of the fossil fuels the answer is simple. As remarked before, these fuels represent an accumulation over 500 million years of geologic time, and any additional accumulation that may be expected within the next 10,000 years is negligible. When these fuels are burned, their material content remains upon the earth in a relatively useless form, but the precious energy, after undergoing a sequence of degradations, finally leaves the earth as spent, long-wavelength, low-temperature radiation. Hence, we deal with an essentially fixed storehouse of energy which we are drawing upon at a phenomenal rate. The amount which remains at any given time equals the amount initially present less that which has been consumed already.

The amount consumed up to any given time is proportional to the area under the curve of annual production plotted against time. This area may approach but can never quite equal the amount initially present. Thus we may announce with certainty that the production curve of any given species of fossil fuel will rise, pass through one or *several maxima, and then decline asymptotically to zero. Hence, while there is an infinity of different shapes that such a curve may have, they all have this in common: that the area under each must be equal to or less than the amount initially present.*

AMOUNTS OF FOSSIL FUELS

While the quantities of fuels upon the earth are not known precisely, their order of magnitude is pretty definitely circumscribed. The most accurately known is coal. At the Twelfth International Geological Congress at Ottawa in 1913 a world review of coal was made and the amount capable of being mined was estimated to be about 8000 Gt. Since that time some adjustments in the estimates have been made, giving us a present figure of about 6300 Gt of coal initially present.

Within the last few years this figure has been criticized by mining engineers (Ref. 2, Ref. 5) on the grounds that while the estimated amount of coal may in fact be present, the amount recoverable by practical mining operations is but a fraction - possibly as small as one tenth – of the foregoing estimate. The degree of validity of this criticism still remains to be determined.

For petroleum the estimation is considerably less accurate than that for coal but still it is probably reliable as to the order of magnitude. The method of estimation in this case is that of sampling. In the better-known areas the amount of petroleum produced per unit volume of certain classes of rocks has been determined. The areas and volumes (within drillable depths) of similar rocks over the earth are fairly well known. By application of the same factor for the undrilled areas as for those now well known, an order of magnitude of the petroleum that may exist may be obtained.

The most comprehensives studies so far made public appear to be those of Weeks, which are cited by Wallace E. Pratt (Ref. 7 to Ref. 9). According to these studies, in a volume of 10-12.5 million cubic kilometres (2.5-3.0 million cubic miles) of sediments in the United States there have already been discovered 8.4 x 10^9 cubic meters (53 Gb) of oil. This represents about 10 percent of the total volume of such sediments of the land areas throughout the world. Hence, it is estimated that for the world there should have been present initially about ten times as much oil as for the United States. A similar volume of sediments occurs on the continental shelves, which may contain *about as much oil as the land sediments.*

Assuming that the land areas of the United States will produce 16 x 10^9 *cubic meters (100 Gb), then a reasonable estimate for the world would be:*

Land:	*1000 Gb*
Continental Shelves:	*1000 Gb*
Total:	*2000 Gb*

These figures are regarded as being somewhat liberal and the quantity of oil may actually be considerably less. Not included in the figures are the Athabaska Tar Sands (Ref. 8), estimated to contain about ~200 Gb of oil.

The amount of natural gas may be estimated at 400 cubic meters of gas for one of oil, or at an energy content of 40 percent that of oil.

The oil shales of the world are less well known. Those of the United States, especially the Green River shales, are estimated to contain at least 350 Gb of oil. Assuming that the rest of the world has about three times the amount of oil shales in the United States, we would obtain, for an order of magnitude, 1,000 billion barrels of oil from this source.

The results of these estimates are given in Table 1 … It will be noted that 92% of the estimated total [energy] *is represented by coal - a figure which will not be greatly altered by any reasonable adjustments of the estimates of the* [other] *fuels, but may be considerably altered if the minable amount of coal is less than usually assumed.*

Table 1: *Energy in Fossil Fuels*[1]

	Quantity	**[Gt coal equiv.[2]]**
Coal[3]	6300 Gtonne	4600
Petroleum[4]	1000 Gb	135
Canadian Tar Sands[5]	200 Gb	25
Natural Gas[6]	420 Gboe	60
Oil Shale[7]	1000 Gb	135
Total		**~5000**

1. [Table truncated from the original, edited, and data rounded.]

2. [Hubbert used a conversion factor of 1 Gt of coal = 7.3 x 10^6 kcal, presumably assuming a mix of hard and soft coal. Conversion using BP *Stats. Rev.* data for hard coal gives Gt (hard) coal equiv., as used here.]

3. Revised from estimate. Twelfth International Geological Congress (1913).

4. Based on estimate of Wallace E. Pratt: "Petroleum on Continental Shelves" (Bull. A.A.P.G. 31, 1947, 657-672). [Based on Hubbert's earlier text, this probably refers only to the conventional oil on land.]

5. Wallace E. Pratt. Oil in the earth. *Lawrence: Univ. of Kansas Press, 1942, p. 44.*

6. Based on gas/oil ratio of 400 m3/m3, or energy of gas = 0.4 energy of oil.

7. Carl Belser: "Oil Shale Resources of Colorado. Utah and Wyoming" (A.I.M.E Tech. Publ. No. 2358, May, 1948). [Where Hubbert refers to 'oil shales' he is referring to oil retorted from kerogen (and not to today's 'light-tight' shale oil).]

[Hubbert's references are:

Ref. 2. Carlow, C. A. A.I.M.E., October 1946.

Ref. 5. Parsons, A. B. Mining and Metallurgy, 1948, 29, 63-64.

Ref. 7. Pratt, W. E. A.A.P.G. Bull. 28, 1944, 1506-1509.

Ref. 8. Pratt W. E. Oil in the earth. *Lawrence: Univ. of Kansas Press, 1942.*

Ref. 9. Pratt W. E. A.A.P.G. Bull. 31, 1947, 657-672.]

Hubbert then looked at the implication of the data given above in terms of the future production curve for fossil fuels, and thus in turn at the 'time perspective' of human affairs. His Figure 8 plots, against a time-scale running from effectively 10,000 years ago to over 10,000 years in the future, the following parameters:

- production of energy from fossil fuels;
- production of energy from water power and solar radiation;
- energy per capita per unit time;
- population;

and from which he draws the following conclusions:

"These sharp breaks in all the foregoing curves can be ascribed quite definitely, directly or indirectly, to the tapping of the large supplies of energy stored up in the fossil fuels. The release of this energy is a unidirectional and irreversible process. It can only happen once, and the historical events associated with this release are necessarily without precedent, and are intrinsically incapable of repetition. … it will still be physically possible to stabilize the human population at some reasonable figure, and by means of the energy from sunshine alone to utilize low-grade concentrations of materials and still maintain a high-energy industrial civilization indefinitely. Whether this possibility shall be realized, or whether we shall continue as at present until a succession of crises develop - overpopulation, exhaustion of resources and eventual decline - depends largely upon whether a serious cultural lag can be overcome. … it is upon our ability to eliminate this lag and to evolve a culture more nearly in conformity with the limitations imposed upon us by the basic properties of matter and energy that the future of our civilization largely depends."

Is not intended here that a detailed analysis of Hubbert's 1949 paper be given in light of today's knowledge, but the main things to note are:

- The estimate he gives of the conventional oil expected from US land areas, of ~100 Gb, was not unreasonable for that date, but certainly on the low side; his 1956 paper used US Lower-48 estimates of 150 Gb and 200 Gb (including continental shelves).

- For global oil, the data that Hubbert was using predated the discovery of Ghawar, so would be expected to be on the low side. Nevertheless, the estimate of global conventional oil URR, less NGLs, of 2000 Gb is surprisingly accurate, and well within 'an order of magnitude'.

- On shale oil (oil from kerogen), Hubbert wrote: "*A third source* *of fossil energy, oil shale, although exploited on a small scale for almost a century, is only now approaching its phase of rapid development.*" He probably expected use of this class of oil to increase faster than turned out to be the case, primarily because Middle East oil, and later that from other overseas provinces, came on-stream rapidly to compensate for the declining production of US conventional oil.

- On coal, Hubbert warns of mining engineers' doubts over the URR value then generally assumed. We will return to this topic in a future issue of this journal.

Next we summarise the global conventional oil URR data that Hubbert used over a sequence of publications, Table 2.

Table 2. Global Oil URR estimates quoted by Hubbert, 1949 – 1981.

Date of Paper	Global conv. oil URR (ex-NGLs) (Gb)	NGLs (Gb)	Tar sands (Gb)	Shale (kerogen) oil (Gb)
1949	1000 (a) 2000 (b)	n/a	200 (c)	1000
1956	1250 (d)	~225 (e)	400 – 800 (f)	1300 – 3000 (f)
1962	1250 (g)			
1969	1350 & 2100 (h)			
1977	2000 (j)			
1982	2000 (k)			

Notes:

(a). From Table 1 above (Hubbert, 1949); probably onshore only.

(b). From text above (Hubbert, 1949); onshore & offshore.

(c). Athabasca only.

(d). Hubbert (1956). Data from ESSO's L.G. Weeks, but increased based on new data from the Middle East, plus USGS information.

(e). Estimate derived here (i.e., not Hubbert's), based on the global crude oil URR ex-NGLs of 1250 Gb, and applying the US ratio of all-liquids to crude oil that Hubbert quotes.

(f). Ranges for global tar sands and shale oil URRs quoted by in the text of Hubbert (1956). Note that single-point estimates are used in Figure 16 of that paper.

(g). Hubbert (1962). Assumed same global conv. oil URR as in 1956.

(h). Hubbert (1969).

(j). Hubbert (1977). 'Best estimate' from Nehring's range 1700 - 2300 Gb

(k). Source: Andrews & Udall (2015). Says: "Hubbert and Root; reviewed [URR] estimates by others."

Note. In assembling these data, except for Hubbert (1949 and 1956), Hubbert's original papers have not been re-read, so this table may contain simplifications or errors.

Sources: Hubbert (1949); Hubbert (1956); Bentley (2016; which reviewed Hubbert 1962; Hubbert 1969; and Hubbert 1977); and Andrews & Udall (2015).

Note also that global URR estimates by Weeks increased from 650 Gb in 1942 up to 3600 Gb by 1978 (Andrews and Udall, 2015), but one would need to look at Weeks' papers in detail to be sure what categories of oil were included. For detail on Hubbert's life and views, see Mason Inman's forthcoming book: *The Oracle of Oil – A maverick geologist's quest for a sustainable future.* W. W. Norton.

4. Some Current Minimum Estimates of the Global URR of Conventional oil, deduced from 'mainstream' forecasts

We now move from history to relatively current data, and look not at global conventional oil URR estimates as such, but at a minimum URR value that is implicit in forecasts from a number of the ‘mainstream’ oil forecasting organisations.

We can do this because - relatively recently - such organisations have become much more circumspect on the amount of conventional oil production they foresee; and now explicitly forecast that such production will not increase in any significant way going forward; instead holding it flat out to the end of their forecast time horizons. This then lets us make a minimum estimate of the URR estimates for conventional oil that they must be using (or implicitly assuming), by allowing production of this oil to decline at a reasonable rate beyond the forecast horizon.

The three forecasts we examine are those of IEA (2011), BP (2015), and ExxonMobil (2015), the charts for which are on the web, and also in Volume 1 No. 2 of this journal.

As these forecasts are very similar we will only analyse that of ExxonMobil. As this shows (Chart 6 of Vol. 1 No. 2), here global production of conventional oil is forecast as staying essentially flat from 2005 out to 2040. If we then assume that production of this oil declines away exponentially from 2040, we get the following approximate data:

	Gb
Cumulative production to end-2014	~1250
Produced 2015 to 2040 (at 73 Mb/d)	670
Exponential decline down to ~7M/d (80 years)	800
Total conventional oil (~URR)	~2700

Note that there is no reason to think that this estimate, of 2700 Gb, is the URR for conventional oil that these organisations are assuming. But this calculation does give a likely *minimum* URR value. In future issues of this journal we will look at the actual data used by these organisations.

5. Summary of URR data presented in this paper

Now, with these extra historical and current data to hand, we are in a position to summarise the global conventional oil URR estimates that have been presented in all three parts of this paper. This is done in Table 3.

Table 3. Summary of URR estimates by category of oil. Data in Gb (rounded).

Author	Date of study	Conv. oil RG	Conv. oil (incl. RG)	NGLs	Total Conv. oil (incl. RG & NGLs)	'Light-tight' oil	Very heavy Oils	Total All-oil (excl. kerogen)
Hubbert	1949		2000				200 (a)	
"	1956		1250	225 (b)			400-800	
"	1969		1350 & 2100					
"	1977		2000					
"	1982		2000					
Others: 1972 - 2015								
ESSO	1972		2100					
Ward & Dubois	1972		2500					
SPRU, UK	1974		1800 - 2480					
Ehrlich et al.	1977		1900					
WEC / IFP	1978		1803					
World Bank	1981		1900					
Meadows et al.	1992		1800 - 2500					
Petro consultants	1995		1800					
Ivanhoe	1996		~2000					
Laherrère	1997							2700
BGR	2002		2670					
Shell	2002							4000
Bauquis	2003							3000
Laherrère	2003							3000
EU WETO study	2003							4500
Energyfiles Ltd.	2003		2338					
IHS CERA	2014	760			4000	485	470	5000

Author	Date of study	Conv. oil RG	Conv. oil (incl. RG)	NGLs	Total Conv. oil (incl. RG & NGLs)	'Light-tight' oil	Very heavy Oils	Total All-oil (excl. kerogen)
Campbell	2015		2250	220	2470		260 (c)	2730
Globalshift	2015		2500	370	2900	150	150	3200
Laherrère	2015		2200	300	2500	In conv.	500	3000
Miller	2015		~~2400 (d)	~~300	~2700	In conv.	225	~2900
ExxonMobil (min. value from forecast)	2015		>2700					
USGS (mean)	1991		~2300					
"	1994		2400					
"	2000	700	3000	400	3345			
"	2012	720	~~3400 (e)		~3850			
IEA								
(ref. case)	1998		2300					
(ref. case)	2000				3345			
	2013	500			4350	215	1,470	6000
See ExxonMobil(from forecast)								
US EIA	2001		3303					
"	2013				4250	345		
"	2015					420		

Notes:

- RG: Reserves growth. NGLs: Natural gas liquids.

- A number of assumptions have been made in assembling these data. These assumptions are believed to be correct, or at least reasonable, but the author would be very pleased to receive corrections. It is fairly certain that all authors would accept that the data here are more uncertain than the degree of rounding shown above would indicate. For additional information, and caveats, on these data see the discussion in the relevant parts of this paper.

- Definitions by category of oil are not consistent between authors, such that exact comparisons between these data are not possible.

(a). Athabasca tar sands only.

(b). Estimate derived here (i.e., not Hubbert's); see Table 2.

(c). For Campbell, this figure combines 'light-tight' oil plus very heavy oils (tar sands & Orinoco oil).

(d). For Miller, the NGLs data of ~300 Gb is imputed, based on other sources; where hence the ~~2,400 Gb value for 'Conv. oil + reserves growth' is derived.

(e). Approximate reconstruction of value implied in USGS 2012 data if NGLs at ~400 Gb are assumed.

Table 3 may seem a little complex, but it is fairly easy to draw out the main conclusions. Concentrating on the URR data for conventional oil plus reserves growth (but ex-NGLs), as this is the focus of this paper, we can see that:

(a). URR estimates in the table, in the thirty or so years from about 1970, when the full scale of the Middle East finds were appreciated, up to the year 2000 varied over a surprisingly small range, from 1800 – 2500 Gb. (Note that while Hubbert's 1949 estimate of 2000 Gb meets this range, as explained earlier, it was based on analogy with the US, rather than on global discovery data.)

(b). Subsequent to the year 2000, when the USGS included a global allowance for reserves growth for the first time, higher URR estimates were generated, from 3400 Gb up to ~4000 Gb (after deducting as assumed ~400 Gb for NGLs), and where these estimates are mostly from the 'mainstream' forecasters.

(c). By contrast, the recent URR estimates from the 'independent' forecasters (Energyfiles, Campbell, Globalshift, Laherrère, Miller) still sit at relatively low values, from 2200 to 2500 Gb. (Note that on inclusion of reserves growth in these estimates, some of these authors may recognise that quite large quantities of such growth are technically possible over time, but do not reflect this in the data shown here. This is almost certainly the case for both Campbell and Laherrère; where, since they predict peak production of this class of oil as soon, the URR values given are those that help calculate their dates of peak.)

In summary, from Table 3, we really have two distinct sets of URR estimates: The first is the mainstream estimates from about 1970 up to the year 2000, plus the recent estimates from the 'independents', where these all sit in a 1800 – 2500 Gb range. The second set is the 'mainstream forecasters' estimates since the year 2000, where these now sit between about 3400 - ~4000 Gb (if the 2013 data given here for the IEA and EIA are correct); and where also today (2015) 'mainstream' URR estimates must be at least greater than 2700 Gb, if the 'extrapolation calculation' given above based on recent forecasts is correct.

The next section looks at which of these two sets of URR estimates would seem to be the more likely. However, before we do so, here is an aside on how the URR estimates of the 1970s and 1980s given above were collected. All simply came from textbooks on the bookshelf of this author's then supervisor, George Whitfield. As the period post-1973 was characterised by a widespread acceptance that global oil would soon 'run out' - based almost certainly simply on the size of global proved reserves at that date - most textbooks on energy in the 1980s contained at least some reference to oil. As a result, and not surprisingly, the list of URR estimates given here for these dates is not complete; at least one notable absence being the WAES study. It would be useful to assemble and analyse a more comprehensive list, where the paper by Andrews and Udall (2015) would provide a good starting point.

6. Comparing URR Estimates with the Global Volume of Oil Discovered To-date

So now we turn to the question of which URR estimate for conventional oil (including reserves growth, but excluding NGLs) is likely to be the most accurate, at least in terms of forecasting global 'all-oil' production over the near and medium term? Is it a value lying in the range 2200 - 2500 Gb; or one well over 1000 Gb higher, lying between ~3400 - 4000 Gb?

This is an important question. If the lower range is correct, with ~1250 Gb of conventional oil produced to-date, and if the approximate 'peak at mid-point' rule is used, then the global production of conventional oil is about at mid-point, or passed. If the higher URR range is correct, then with ~25 Gb of conventional oil being produced per year, the mid-point is some 25 years into the future.

To answer this question, we turn to recent industry data on global oil discovery. Figure 1 gives IHS Energy global proved-plus-probable ('2P') backdated oil discovery data, drawn from Miller and Sorrell (2014). The data are for IHS Energy's 'Liquids' category, which includes NGLs, light-tight oil, extra-heavy oil (the latter mainly tar sands and Orinoco oil), and oil from kerogen, but excludes GTLs, CTLs and biofuels.

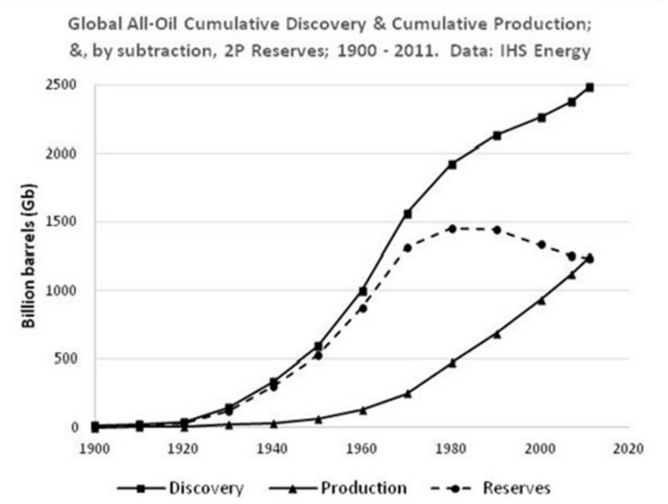

Figure 1. IHS Energy data on World cumulative 2P backdated oil Discovery, and Cumulative oil Production; and hence 2P Reserves by subtraction: 1900 – 2011.

Source: Miller and Sorrell (2014).

Notes:

- The plot shows IHS Energy 'Liquids' data, stated to include: "crude oil, condensate, NGLs, liquefied petroleum gas, heavy oil and syncrude". The data thus include light-tight oil, and oil from tar sands and Orinoco oil, but exclude GTLs, CTLs, biomass, and refinery gain.
- The plot is generated by reading data at 10-year intervals from Figure 7 of Miller and Sorrell (2014) for cumulative discovery from 1900 to 2007, and from the corresponding Figure 3 for cumulative production over the same period.

Included in this plot are the data for end-2011 as given in the text of the Miller and Sorrell paper.

- Data are 2P, except for the US and Canada non-frontier areas, where the data are proved ('1P') data. The 2P data are backdated, in that they reflect information available to the IHS Energy as of 2007 (for the discovery curve), and to 2011 (for the final discovery data point). Reserves are calculated here (as done also by IHS Energy) by subtracting cumulative production from cumulative discovery.
- IHS Energy data are for oil in fields for conventional oil; and as announced in projects for non-conventional oils. The 'up-tick' in global discovery of this 'all-oil' visible from about the year 2000 (and hence the slowing in the fall-off of 2P reserves) is due to increasing inclusion of data for tar sands projects, and subsequently for US shale (light-tight) oil projects. Data are hence largely for conventional oil plus NGLs up until about the year 2000, after which significant amounts of tar sands and Orinoco projects were included, and most recently also data for 'light-tight' oil projects.
- As the plot shows, the global proved-plus-probable (2P) all-oil reserves at end-2011 were ~1,250 Gb. This contrasts with the corresponding end-2011 value for global proved only (1P) all-oil reserves (from BP Stats.) of 1,652 Gb. The difference is partly in the amount of non-conventional oil include in the two sets of reserves figures, and partly in the likely overstatement of Middle East OPEC proved reserves.

We can see from Figure 1 that the global discovery of *conventional* oil (incl. NGLs) might be judged (based on the pre year-2000 trend) to be heading for an asymptote URR around 2500 Gb, thus supporting the lower URR range outlined above, and where the corresponding production 'mid-point' is around 2011. (Note, incidentally, that this Figure shows that the rate of global *discovery* of conventional oil peaked around the mid-1960s; and the volume of oil in global 2P *reserves* peaked about 1980, at about 1450 Gb.)

A more conservative view of global oil discovery is that produced by Jean Laherrère, again using oil industry 2P data, and is given in Figure 2. Like Figure 1, this shows proved-plus-probable backdated global oil discovery, but here the data exclude NGLs and extra-heavy oil (the latter mainly tar sands and Orinoco oil). Also from the industry discovery data Laherrère here has subtracted 300 Gb to allow for Middle East 'quota wars' overstatement; 100 Gb to allow for FSU field data being closer to 3P than 2P; and 200 Gb to allow for inclusion of early Orinoco heavy oil fields. In this view, a reasonable asymptote of global conventional oil discovery (ex-NGLs) is thus about 2200 Gb;

and hence the corresponding 'mid-point' production date is somewhat earlier than for Figure 1, at around 2005.

(Also shown are the corresponding discovery and production data for gas.)

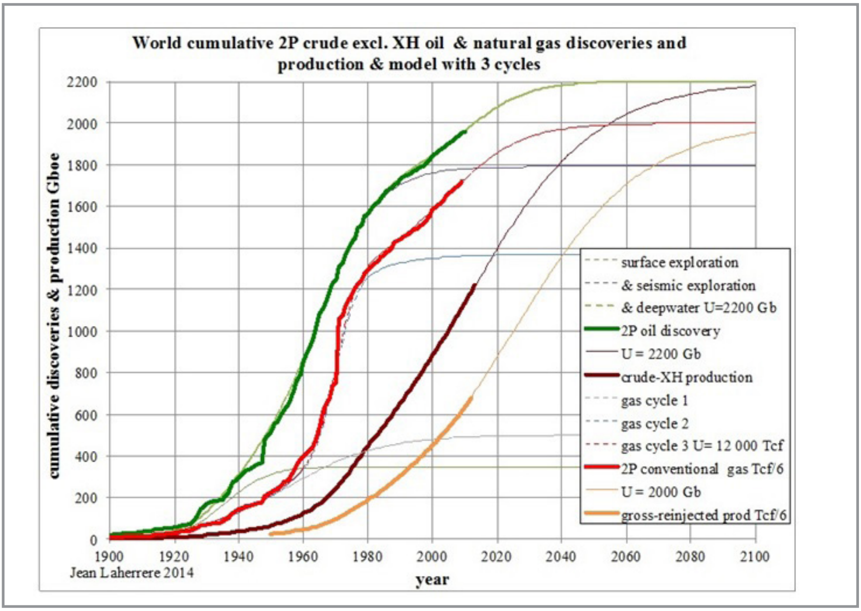

Figure 2. World: Cumulative 2P Backdated Oil Discovery 1900 - 2010, and forecast to 2100; Cumulative Oil Production, 1900 – 2013, and forecast to 2100.

- Leftmost line: Laherrère's judgement of 'most probable' backdated 2P cumulative global discovery data for crude oil plus condensate, less extra heavy oil (the latter mainly Athabasca tar sands and Orinoco oil), and not including NGLs.
- Next left line: Corresponding data for gas, calculated as Tcf/6.
- Next leftmost line: Cumulative global production of crude oil less extra heavy oil and NGLs.
- Rightmost line: Cumulative global production of gas, Tcf/6.
- Laherrère writes: 'The 2P discovery data reflect data from industry 'scout' sources, but reduced by: 300 Gb to allow for overstatement of the OPEC Middle East original reserves data (as confirmed by Sadad Al-Husseini, former VP Aramco, 2007 Oil & Money conference London); by 30% of the FSU data (~100 Gb) to allow for the datasets ABC1 holding probably closer to 3P than

> 2P data (as indicated by field decline plots, and by Gazprom audits in annual reports); and by 200 Gb to allow for Orinoco 2P discovery data reflecting non-conventional oil.'

Source: J. Laherrère.

The data in Figures 1 and 2 are hard to fully reconcile, perhaps partly due to differences in data definitions, but both show that an estimate for the global URR of conventional oil (ex-NGLs) probably at the lower end of the lower range given above (2200 - 2500 Gb) looks realistic if based on the discovery trend to-date.

Thus the higher URR range, of 3400 - 4000 Gb, looks unrealistic on solely the discovery trend. It is certainly true that a high URR value is theoretically possible over a longer term, resulting from a combination of above-trend discovery plus significant technologically-driven reserves growth, both brought on by a long period of high oil price. But in terms of near and medium term forecasts for 'all-oil' production, forecasts which use (or imply) global URRs for *conventional* oil (ex-NGLs) significantly above the 2200 - 2500 Gb range seem unrealistic.

7. Conclusions

From the above, we conclude as follows:

Global URR estimates for *conventional* oil (ex-NGLs) have been remarkably consistent over many years. Once the big Middle East finds were solidly in, though there have been higher values, many such URR estimates have ranged between 1800 Gb to 2500 Gb.

This in turn has allowed the date for the global peak in production of *conventional* oil, as occurring around the year 2000, to be predicted with reasonable confidence for many years. (This is contrary to the view, still held by many analysts, that all such 'fixed resource' oil forecasts have no merit; see, e.g., Aguilera and Radetzki, 2016.)

If oil industry backdated proved-plus-probable discovery trend data are used, a global URR value for *conventional* oil (ex-NGLs) at the lower end of a 2200 - 2500 Gb range looks most likely, at least in the near or medium term.

As a consequence, those global forecasts which use (or imply) URR values for this class of oil significantly above this range, mostly the forecasts from the 'mainstream' oil forecasting organisations, need to justify their assumptions on use of a URR value that is out-of-line with the discovery trend.

These findings in turn support the view that the major rise in oil price since 2004 was caused primarily by the world approaching its peak production of conventional oil, and hence needing to meet demand increasingly from production of the significantly more expensive non-conventional oils (see, e.g., Bentley & Bentley, 2015).

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