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RESEARCH ARTICLE

Pricing strategies in inelastic energy markets: can we use less if we can't extract more?

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Abstract Limited supply of nonrenewable energy resources under growing energy demand creates a situation when a marginal change in the quantity supplied or demanded causes non-marginal swings in price levels. The situation is worsened by the fact that we are currently running out of cheap energy resources at the global scale while adaptation to climate change requires extra energy costs. It is often argued that technology and alternative energy will be a solution. However, alternative energy infrastructure also requires additional energy investments, which can further increase the gap between energy demand and supply. This paper presents an explorative model that demonstrates that a smooth transition from an oil-based economy to alternative energy sources is possible only if it is started well in advance while fossil resources are still abundant. Later the transition looks much more dramatic and it becomes risky to rely entirely on technological solutions. It becomes increasingly likely that in addition to technological solutions that can increase supply we will need to find ways to decrease demand and consumption. We further argue that market mechanisms can be just as powerful tools to curb demand as they have traditionally been for stimulating consumption. We observe that individuals who consume more energy resources benefit at the expense of those who consume less, effectively imposing price externalities on the latters. We suggest two transparent and flexible methods of pricing that attempt to eliminate price externalities on energy resources. Such pricing schemes stimulate less consumption and can smooth the transition to renewable energy.

Keywords peak oil, price externality, alternative energy resources, EROEI

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1 Introduction

In 1826, Thomas Malthus wrote: "Man is necessarily confined in room. When… all the fertile land is occupied the yearly increase of food must depend upon the melioration of the land already in possession. This is a fund… which must be gradually diminished." (Malthus, 1826, I.I.17). Since then, this idea has been largely debated and, seemingly, proven wrong (Simon, 1998; Trewavas, 2002). For some time, with resource substitution and technological advances we have been largely avoiding, or rather delaying, the depletion of the fund that Malthus was predicting. It may have seemed that we would be successfully continuing this into the future, especially if we agree with the premises of conventional economics, which were distilled by Simon (1998), saying that "the concept of entropy simply doesn't matter for human well-being" (p. 81). So far the laws of thermodynamics have not been proven wrong. In reality, with the technological advances we have been mostly shifting from one diminishing resource to another, increasing the human footprint (Rees et al., 1998), or recycling resources at the expense of additional use of energy. There is mounting evidence that we may be reaching a critical point, when entropy may actually start to matter and some quite significant measures and adaptations will need to be taken to avoid a much more serious collapse of the modern civilization (Day et al., 2009; Hall and Day, 2009; Ehrlich and Ehrlich, 2013).

At present we are at a nexus of three very much interrelated processes, which, taken jointly, may prove to be quite devastating. First, we are seeing clear evidence that our climatic system is changing (Pachauri and Reisinger, 2007; Solomon et al., 2009). It is still hard to foresee the extent and rate of this change, but it is widely accepted that climate is changing. This change will inevitably require adaptation (Levermann et al., 2013). Any adaptation, transition from one state or dynamic equilibrium to another, always requires additional investments of resources (Stern, 2008). To build new infrastructure that would accommodate higher sea levels, to switch to new agricultural patterns in response to changing patterns of precipitation and altered temperature regimes, to rebuild after increasingly damaging floods and hurricanes — all this requires additional resources, first of all energy.

Secondly, at this same time we are running out of the conventional energy supply largely dependent on oil. There is increasing consensus that the peaking of global oil production, after which its supply perpetually decreases, has already happened (Kerr, 2008; Murray and King, 2012). This may not be because the resource becomes physically unavailable, but largely because it becomes too expensive (in terms energy, material, and costs) to extract it. At the time when we need additional energy and other resources to adapt to climate change, we find that we are rapidly running out of some of the most essential of those resources. Here we choose not to take into account the so-called unconventional oil and gas, which has been booming over the last decade. We do so because of the synergy between energy production and climate change, where concerns about climate put clear limits on the amounts of CO_2 that we can still afford to add to the atmosphere (Levermann et al., 2013). According to Meinshausen et al. (2009) 80% of remaining fossil fuels should stay in the ground if we are to avoid dramatic climate change. Unconventional oil and gas, as well as coal have a remarkably high (though often unaccounted) CO_2 footprint, which makes their further exploitation very dangerous.

Thirdly, and quite alarmingly, all this is happening globally. While earlier we have witnessed collapse of numerous civilizations, those collapses were more or less local (Gumilev, 1990; Diamond, 2005). They were limited to regions, perhaps even continents, but they could never impact the global system. At present through the processes of globalization humans have unified the various ecosystems, regions, cultures and civilizations into one global system, where crisis cannot be localized any more (Ehrlich and Ehrlich, 2009; Fader et al., 2013). Climate change will impact all areas and continents, no matter what role they played in causing it. Peak oil will happen globally, since we are now transporting resources between continents, and will be extracting oil worldwide until the last drop of cheap oil. While there will be plenty of oil left, it will become climatically dangerous and energetically increasingly useless since energy spent on its pumping and delivery will exceed the produced energy. Oil will be still extracted for chemical and other purposes, but it will no longer be useful as a source of energy.

The economic crisis now is also occurring at a global level, and impacting most countries and civilizations, even the most primitive ones if they depend on imported goods.

There is a clear need for strategies to resolve this triple crisis. It is unlikely that we will be able to get out of the triple crisis within the conventional paradigm of unlimited economic growth. Assuming that new technologies will be developed in time to ‘save the planet’ may be a risky strategy, especially when we no longer have any back-up systems in reserve on this planet. Development of alternative energy resources also requires investments of economic and environmental resources (Chow et al., 2003). In the meanwhile ‘use less’ appears as the most straightforward economic solution. There is no other technology that can be as cheap and as cost efficient. The only problem is that all methods of reducing demand are connected to social and psychological drivers that may be hard to change. This is especially so after all the decades of manipulating the cultural and psychological drivers toward stimulating demand and consumption. (By consumption in this paper we mean household consumption of resources, specifically of energy, and gas. It is clear that energy use of a single household is not be compared to the energy use of a large enterprise. However, similar analysis of pricing regulations for energy consumption among businesses can be applied.)

Throughout this paper we focus on two research questions.

First, how supply and demand laws manifest themselves in a market for a nonrenewable resource, such as oil or gas, which have natural limits for supply, and how can alternative energy technologies impact this market? When talking about limits in supply of non-renewable resources, we mean that in contrast to other scarce but “producible” goods there is a moment in the dynamics of resource use when it cannot be supplied any more even if increasing price creates additional incentives to do so. Alternative renewable energy requires additional investments, which will be only harder to afford the less the elasticity of the conventional energy markets. Second, what kind of positive market solutions can be implemented at operational level for energy markets in the situation of a triple crisis? How can we use market incentives to reduce consumption instead of stimulating it?

The paper proceeds as follows. First, we note that in markets with inelastic supply and demand, price becomes especially vulnerable to small changes in supply, when supply becomes limited and can no longer be increased to meet a growing demand. As a result, higher demand only pushes the price up, effectively penalizing those who consume less. This is in spite of the fact that those who consume less help to lower demand and prices, which in turn rewards those who consume more. We then consider a simple model that describes the transition to alternative technologies as a way to avoid the supply crunch. We find that this transition is possible, provided that it starts early enough, when there are enough resources to adapt. Since we are at a stage when supply is likely to start declining, it may be too late to rely entirely on technological solutions. Most likely in parallel to searching for ways to increase energy supply, we will need to find ways to decrease demand and consumption. We suggest two methods of pricing that are transparent and attempt to eliminate price externalities on energy resources created by those who consume more at the expense of those who consume less. We finish with conclusions and discussion.

2 Inelastic supply, inelastic demand and price externalities

One of the pillars of conventional economics is the theory of supply and demand. In fact it makes perfect sense to assume that the more abundant a good is the less it should cost and, reciprocally, the scarcer a good, the higher its price, other factors constant. At a higher price firms have more incentive to produce, therefore the supply increases. Increasing supply leads to the decrease in price for a commodity. Thus, if economic equilibrium is disrupted, either by changes in demand, or in supply, market forces work to get the system back to a new equilibrium.

This theory works for commodity markets where there is a capacity for supply to meet demand. This holds under the assumption that resources needed for the production of a good, for which excess demand exists, are unlimited. This is hardly the case for nonrenewable resources such as oil. The discontinuities in the above-presented logic show when from marginal changes, close to equilibrium one moves further, toward the extremes. This is especially clear when dealing with critical resources that are essential for basic human needs. Those are also known as Critical Natural Capital (CNC) (Ekins et al., 2003).

Farley and Gaddis (2007) have looked at the demand curve for CNC (Fig. 1) and stressed that as stocks are depleted one gets perfectly inelastic demand with prices growing to infinity.

Data reported by the Energy Information Administration (EIA, http://www.eia.doe.gov/) allow us to build an aggregate supply curve that shows the quantity of a particular CNC, such as oil and petroleum products, supplied at different prices (Fig. 2). The Law of Supply promises that as demand drives prices up, supply will react by adjusting, i.e., by producing and delivering more to enjoy the benefits of these high prices. This does not seem to happen for resources, which supply and demand curves behave as in Figs. 1 and 2. Even as prices increase, supply does not go up. It appears as if there is a certain barrier after 90 millions of barrels of oil produced, which cannot be passed. As supply approaches these limits at the right in Fig. 2, we get into the vulnerable territory, where prices tend towards infinity and very small changes in supply or demand can result in huge price swings that easily destabilize the whole system.

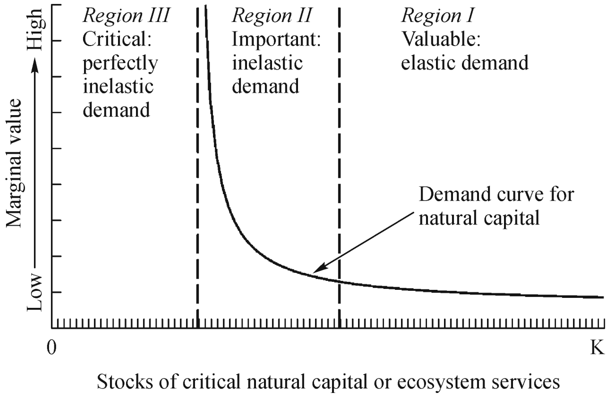

Fig. 1 Demand curve for Critical Natural Capital (Farley and Gaddis, 2007).

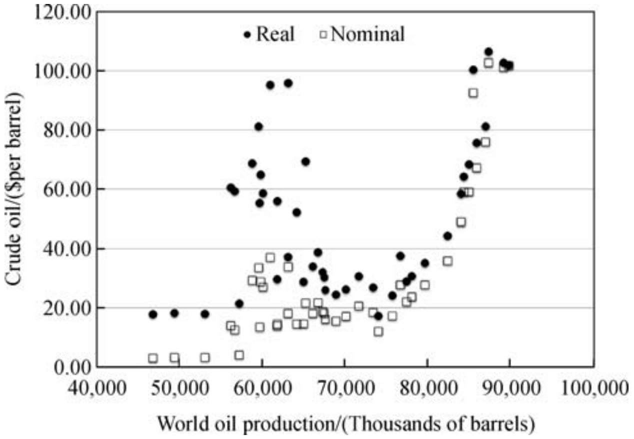

Fig. 2 Supply curve for crude oil (1970–2013). Price of oil (nominal and real, Aug. 2013 $$ per barrel) versus world oil production (thousands of barrels) (EIA, 2013a). The first peak of prices is during the oil crisis in the 1970's, which was mostly motivated by political reasons rather than the supply limits.

In this situation increasing demand only drives prices on resources up making them unaffordable to consumers. The effect is further exacerbated if financial resources available to the population also shrink (as is the case at present). All this could be perfectly fine for luxury goods, such as jewelry or Picasso paintings. The supply is indeed limited, so only the most affluent can afford it. However with energy, water and other CNC this is much more problematic, and if the equilibrium is beyond what is essential for the livelihood of the people, the situation goes out of control of economics into the policy arena and is likely to results in conflict, and, possibly, wars (Kahl, 2006).

This immediately defeats the assumption of equilibrium, which is another foundation of conventional economics. In case of limited resources and inelastic demand and supply there is no natural way for markets to adjust and to settle at a new equilibrium. In fact, inelastic supply and inelastic demand for natural capital have been discussed in several studies (Greene, 1997; Brock and Xepapadeas, 2004; Cheshire and Sheppard, 2005) making application of the theory of unique market equilibrium problematic for these goods. However, most of the standard economic analysis is based on the equilibrium model, which is beginning to appear very dubious since it does not accommodate out-of equilibrium analysis (Arthur, 2006).

Conventional economics tends to ignore these extremes, comfortably dancing in the middle area where supply is not limited and can easily adjust to demand, and where one is not pricing the last drop of water in a desert. For example, when resources are abundant and demand is elastic, we see that when demand increases and supply remains the same, prices increase. Higher prices attract new suppliers, who bring both more quantity and lower prices. With more supply, economies of scale are realized leading to cheaper goods. Therefore economies stimulate demand and in a way those who consume less also benefit from the lower prices that are produced in response to the demand of those who consume more.

This changes quite dramatically in the extreme zone, when in fact more demand does not produce more supply, but only pushes up the price. Economies of scale have limited power in markets for nonrenewable natural resources. With resources such as oil, the law of diminishing returns asserts itself (when each marginal unit of production produces less profits). Here supply is limited and is not able to follow growing demand, as a result the price continues to grow. Ironically, those who consume more, i.e., who contribute to growing demand, are effectively subsidized by those who consume less. In fact, if everybody were consuming more, the price would only go higher.

Economic agents who consume less lead the market to settle with lower prices. Individuals who consume more are driving total demand up and are inflating the average market price at which everybody else also make purchases. At the same time, with the current pricing scheme, which gives price discounts for those who consume more, they end up paying lower price per unit of a good-energy in this case. Consequently, those who consume more create a price externality (Goldin, 1975; Bhattacharyya, 1996) for those who consume less. Markets do not allocate resources efficiently in the presence of externalities (Lipsey et al., 1993). In other words, those who consume a lot of energy resources make themselves better off by making those who consume less, worse off. The main explanation that conventional economics offers for avoiding these extremes is that they are not supposed to occur in reality, primarily because of perfect substitutability of resources and new technologies that arrive to compensate for supply limitations. Indeed, so far new science and technology has helped humans avoid serious crisis, and Malthus was claimed to be wrong (Simon, 1998). For example with the Green Revolution new crop varieties and agricultural techniques allowed such nations as India to become self sufficient in food, which only stimulated further population growth. So can the current crises be also resolved through technology and innovation?

3 Affecting supply: race for alternative technology

Let us consider the oil futures a bit closer. While most official sources have been quite reluctant to discuss this issue, in 2007 there were several publications that indicate a growing concern even in circles closely related to governments (IEA, 2007). The 2011 World Energy Outlook reiterates that after peaking in 2020 conventional oil supply will be slowly declining (IEA, 2011). The crude oil production from fields that were producing in 2010 is expected to drop from 69 mb/d to 22 mb/d by 2035 — a fall of over two-thirds. It is then assumed that the gross additional capacity needed to maintain the current production level will come largely from fields already discovered but yet to be developed, mainly in OPEC countries.

More recently we have seen a rush to new technologies to extract fossil fuels. Shale gas and oil production have substantially risen, especially in USA. The IEA projections in 2012 appeared to be much more optimistic and have been projecting USA to become a net exporter of gas and oil before 2035 (IEA, 2011). U.S. Energy Information Administration (EIA) is also projecting "continued strong growth in domestic crude oil production over the next decade — largely as a result of rising production from tight formations — and increased domestic production of natural gas" (EIA, 2013). However these projections seem to underestimate the increasing energy intensity of the energy extraction process (Hughes, 2013), as well as the fact that climate change may set other boundaries on what is possible to extract and burn. We may be seeing a different type of peak. If the estimates that up to 80% of fossil fuels are to stay undeveloped if we want to avoid a more than 2°C increase in global temperatures (Meinshausen et al., 2009) are true then the peak oil can become a climate cliff and may require substantial changes in our supply and demand patterns for fossil fuels.

The major problem is that on the one side of the market we have an exponentially growing demand, while on the other side we have a limited resource that eventually will be producing only diminishing returns. The outcome is easy to anticipate. But let us assume that there are alternative technologies that can gradually replace the resource, so that the demand is met by a mix of conventional resources and additional supply coming from alternative renewable sources. In other words, let us explore the situation when elasticity of oil supply is increased by introducing alternative energy sources as liquid fuel substitutes. This can be described using the following simple system dynamics model (Voinov, 2008).

Let us suppose that our supply (S) is driven by exponentially growing demand (D). Besides satisfying demand, supply should also produce enough to provide for the production of the supply itself (oil extraction requires investments of energy). This is what is known as the EROEI (Energy Return on Energy Invested) index (Mulder and Hagens, 2008). If E_{out} is the amount of energy produced, and E_{in} is the amount of energy used in production then EROEI (e) is

$$e = E_{\text{out}}/E_{\text{in}}.$$

In some cases the net EROEI index is used, which is the amount of energy we need to produce to deliver a unit of net energy to the user:

$$e_{\text{net}} = E_{\text{out}}/(E_{\text{out}} - E_{\text{in}}) = e/(e-1).$$

Account for EROEI the dynamics of available World reserves of oil, R, can be described as:

$$R(t) = R(t-dt) + (-S)\cdot dt,$$

where $S = D\cdot e\ /\ (e–1) = D\cdot e_{\text{net}}$ is the supply of energy necessary to clear the oil market. So in fact to satisfy a unit of demand, supply should deliver that unit multiplied by e_{net}. Note that as e approaches 1, S approaches infinity, meaning that all the energy we produce will have to be used to produce new energy.

We will also assume that demand is growing exponentially, as it has been over the past:

$$D(t) = D(t-dt) + c_{\text{d}}\cdot D\cdot dt,$$

where c_{d} is demand growth rate. (See more about modeling Demand in the Appendix. We certainly realize that exponential growth of demand is not an option in the long term, however that is the trend that was more or less followed in the past and that is also the trend very much advocated by the growth economy. Therefore the assumption in the model.)

EROEI is not constant. In early years of oil exploration it was fountaining out of the ground, so energy was needed only to collect and deliver it. At present very energy intensive drilling and pumping is required to get oil out of the ground or from under water, and even more energy intensive technologies are considered to produce oil from shale. The data shows that the EROEI of oil has declined from over 100 : 1 in the 1930s to 30 : 1 in the 1970s to around 10 : 1 in 2000 (Cleveland et al., 1984; Hall et al., 1986), and is still falling.

To account for this change, let us assume that EROEI drops with reserves (R) going down according to a parabolic function (Gever, 1986). (See more about modeling EROEI in Appendix, Fig. A3). Until now the model accounts only for traditional energy resources. The output is straightforward: demand grows, resources are depleted, and the system crashes.

Let us add alternative sources of energy to our model. Suppose that the infrastructure for alternative energy is being produced at a certain slow rate (a_{c}) with no big success until the EROEI for oil falls below a certain threshold value, e_{T}. After that, like nowadays, we start rapidly investing in alternatives making them grow at a rate of a:

$$A(t) = A(t-dt) + A_{\text{growth}}\cdot dt,$$

where

$$A_{\text{growth}} = \begin{cases} a \times A, & \text{if } e<e_{\text{T}} \\ a_{\text{c}}, & \text{otherwise} \end{cases}$$

Here A are alternative energy resources, A_{growth} is the newly produced alternative capacity.

The assumption is that as production of alternative energy takes off, it becomes cheaper and more energy-efficient due to accumulated R&D knowledge and other features of the economies of scale.

The EROEI for alternatives (e_A) will most likely grow as new alternative infrastructure is put in place. Suppose we use a Mono type function with saturation (Voinov, 2008):

$$e_A = e_{A\_\text{min}} + e_{A\_\text{max}}\cdot A/(A + e_{A\_\text{hs}}),$$

where e_{A_min} is the minimal starting e_A, when new technologies are only starting to be deployed. It may be even less than one, reflecting the fact that at first we may need to invest much with very little return. e_{A_max} is the maximal gain in e_A and e_{A_hs} is the half-saturation coefficient that tells us at which level of development of alternative energy A we get e_A increased from e_{A_min} to half of the maximal gain e_{A_max}.

The alternative energy should also enter the equation for energy supply, since now it can also meet part of demand. Moreover, once we produce more alternative energy than demanded to substitute oil, we can entirely stop extracting oil for energy purposes. (There is always the issue of energy quality and certainly the alternative energy produced may be of different quality than oil. However with due conversion, perhaps at higher overall energy uptake, we can always transform the alternative energy into a form that would substitute oil.) The net production of alternative energy is $A - A/e_A$. The amount of energy that the alternatives need to produce to cover the Demand, D, is $e_A\cdot D/(e_A - 1)$. Therefore if $A > e_A\cdot D/(e_A - 1)$ we do not need to extract petroleum any more. However until then we need to provide the energy from R. Therefore we can rewrite the above equation for S as follows:

$$S = \begin{cases} [D - A(1 - 1/e_A)] \times e/(e-1), & \text{if } A < e_A \times D/(e_A - 1) \\ 0, \text{ otherwise} & \end{cases}$$

The alternative energy helps (a negative term in the equation above), but to produce this alternative energy we need to invest A/e_A (a positive term in the equation, which adds to the demand). The higher e_A the less we need to invest to produce the alternative infrastructure. Let us try to choose some meaningful values for the model parameters. The best-case scenario and the justification of the parameters settings is given in Table 1. See Appendix for more explanations about the model.

Even with these very optimistic values (e.g., best-case scenario) the system runs out of resources earlier than the alternative technology (A) is developed (Fig. 3). Actually, investing in the alternative sector when we are already pumping out the second half of reserves only accelerates the crash. Changing different parameters related to alternatives efficiency does not seem to help. The system crash is unavoidable.

The sensitivity analysis showed that there are only three crucial parameters in the system by changing which we can avoid the crash. The first one is the timing of the switch to alternatives, which is given by the e_T parameter, i.e., a moment when oil EROEI reaches the threshold value to signal the need for alternative energy.

We could have avoided the crash if we have started developing alternative energy much earlier when $e_T = 58$ or higher (as noted above currently EROEI for oil stands at 10 – 20). In that case we could stay on the elastic part of the demand curve and enjoy a pretty smooth transition from fossil based energy to renewable energy, with extraction going down to zero while there is still plenty of oil left in the ground (Fig. 4).

But what if we are already at the point when $e_T = 10$? The second crucial parameter in the model is the growth rate of alternatives, i.e., coefficient a. We have a race of demand and alternative energy. If the alternatives are built much faster, growing at $a = 110\%$ per year, then the threshold EROEI can go down to $e_T = 10$. This means that the only way we can avoid a collapse is by more than doubling the alternative infrastructure annually.

It appears that by investing in the alternative sector when it is too late, we further strain the system: we need to produce even more conventional energy to satisfy the demand, while simultaneously creating the new infrastructure for alternative energy. Timing of investing energy in the production of substitutes is essential. If we start doing this only when it is too late we actually accelerate the crash. If we do it earlier we are able to transition towards alternative energy, which absorbs all the demand and we can continue with the exponential economic growth.

Other factors will become limiting, such as land, water and other finite resources, so it is a simplification to think that indeed we will be always able to provide for the exponentially growing demand. However, if we are looking only at energy, we can do it, or more likely could have done it. That is if we have started the transition early enough to provide for the new alternative infrastructure. However if this has not been done in time, there is hardly any way we can provide for the transition without reducing the demand. By no means we are pretending that this simple model can actually be used to forecast the future. Its only purpose is a qualitative explorative analysis of the possible trends.

To find out more exactly how late we are for a painless switch to alternative energy sources, we may need to further refine some of the parameters. However, qualitatively it does seem that the EROEI of conventional energy supply is an important factor in these dynamics. If we start the transition to the alternatives when the EROEI is high

Table 1 Model parameters

Variable	Meaning	Value
R_0	Initial World reserve of oil (Greene et al., 2004) in petaBTU (10^{15}).	16,000
c_d	The 0.025% growth rate of demand—see Appendix.	0.025
e_{ini}	Initial EROEI when oil was plentiful (Cleveland et al., 1984; Hall et al., 1986).	100
e_{A_min}	Original low EROEI for alternative sources of energy, meaning that they may have been explored even when at first they were energetically inefficient to use.	1
e_{A_max}	Maximal EROEI for alternatives. See http://www.theoildrum.com/node/3910 for a summary. For photovoltaics the range is 3 – 33. For wind the average is 25 and can be as high as 78 (Kubiszewski et al., 2008). For hydropower the range is 100 – 300 (Gagnon et al., 2002). The value can still grow in the future when new alternative sources will be discovered (cold fusion?).	40
e_{A_hs}	Coefficient that gives us the productivity of alternatives when their EROEI is half of the maximal. The smaller this value the faster we transition from the low initial e_{A_min} to the high e_{A_max} . With 500,000 EROEI for alternatives grows very fast so we can certainly use it for a best case scenario.	500,000
a_c	Constant supply of alternatives when they are not really recognized as such. It is some background research on various sources of energy that are still not quite economically feasible. The model is not sensitive to this coefficient.	0.00001
a	Growth rate of alternative technology once it is recognized as a feasible substitute for conventional energy sources (50% is actually a very optimistic estimate (El-Ashry, 2010)).	0.5
e_T	Threshold e when the decision is made to invest and develop alternatives. Let us use the higher estimate of the current E that we have for oil. In fact it is probably around 10 or less (Cleveland et al., 1984; Hall et al., 1986).	20

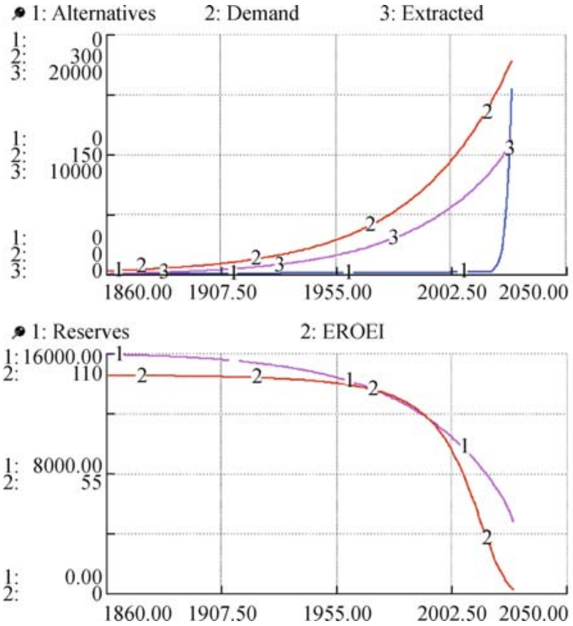

Fig. 3 The alternative energy is starting to develop but it is too late. The EROEI of conventional energy falls to 1 as the reserves dwindle, making further extraction impossible.

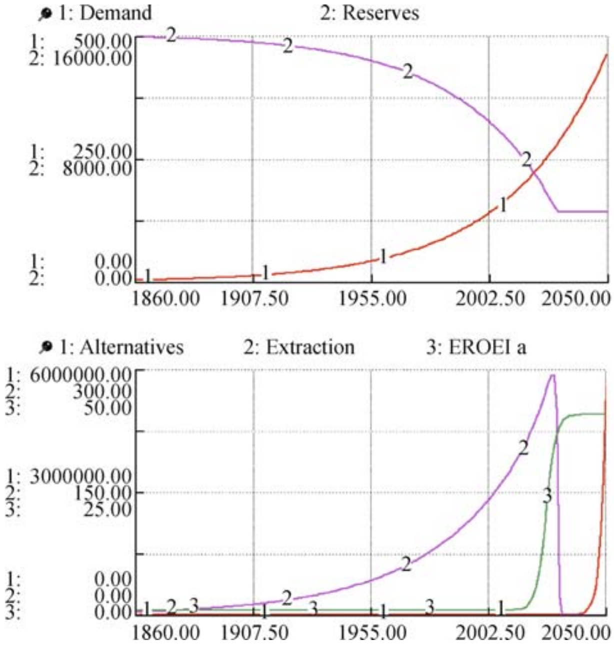

Fig. 4 Early investment in Alternatives, while there is still ample supply of conventional energy, allows for a smooth transition to renewable energy, which EROEI (EROEI a $= e_A$) substantially increases as technology become more advanced.

enough, there should be enough conventional energy to fund the development of the new alternative infrastructure. If we procrastinate any longer — an energy supply crash is imminent. It should be realized that the market by itself in the case of both inelastic supply and inelastic demand would not adjust smoothly as many of us hope. The right decision and right measures need to be made well in advance.

Certainly, the other option is to slow down the demand.

4 Affecting demand

Since the EROEI of most of oil production currently is in the 10–25 range and falling, it makes much sense to look at the demand side.

Investing in curbing the demand is probably the cheapest, safest and fastest solution. The problem is that it moves the focus from the technical, engineering arena primarily to the socio-psychological domain.

What we need are economic mechanisms, which are essential and complementary to alternative energy solutions, and which instead of stimulating demand and growth as has been traditionally overdone in the past, do the opposite: reward conservation and lower demand for energy and other CNC. In what follows we will describe several proposals for market mechanisms that can work exactly toward such a goal. In the situation of inelastic supply and inelastic demand as is the case in the energy market, those who consume more create price externality for those who consume less since the former drive the prices up. Markets are not efficient in the presence of externalities and regulations are necessary to eliminate misbalance between externality-creator and externality-receiver, as for example in the case with Pigovian taxes (Daly and Farley, 2004). In what follows we discuss market mechanisms to demotivate economic behavior that imposes external price effects. We propose measures intended to promote consumption patterns that lead to less aggregate demand for natural capital and, consequently, lower prices for resources, which together would enable more energy security and independence.

4.1 Case of electricity

Measuring consumption of a resource is certainly essential to keep track of how it changes due to a proposed intervention. Let us therefore first use the example of electricity since electric consumption is well metered and the promise of the Smart Grid should provide even better and more reliable accounting tools. A very similar approach could be suggested for domestic natural gas usage, which is also metered, or water, where it is metered. With meters, we always know how much was consumed by each individual consumer. Therefore it is also easy to determine the average consumption in discrete areas and tell whether an individual consumer is using more or less than the average per capita.

Next, in our scheme we penalize those who use more than the average and reward those who use less. There may be several ways to do that but the idea is the same: we set the price of electricity in such a way that those who consume less will be paying less per kWh, while those who consume more will be charged a higher per kWh per capita rate. This can be represented by a simple linear increase in price per unit of electricity as shown in Fig. 5. In this case the overconsumers will have to pay a disproportionally higher price, while the savers will be paying less than the average and will be rewarded more the less they consume. In a symmetric case the over-consumers simply compensate the under-consumers. The average power consumption is established as a break point. Every kilowatt consumed over the average comes at an extra cost.

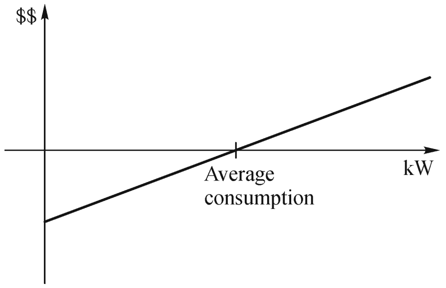

Fig. 5 A simple pricing scheme for electric consumption. Those who consume less than the average are rewarded by lower energy rates, while the big spenders get energy at a higher per kWh per capita rate.

Reciprocally, for every kilowatt that is consumed at a rate that is lower than the average, there is a bonus that is returned to the customer by lowering their rate.

If the average is maintained at a constant level, there is no extra tax burden required, and the system pays for itself. What we do not know is whether the price elasticity of savers is actually higher or lower than the price elasticity of the spenders. It is our expectation that the high spenders who are hit hard by the new rate will have every incentive to spend less electricity, and as a result the overall consumption will go down, pulling down the average.

This means that every once in a while the breakpoint will need to be reassessed and reduced, to track the actual average in the system. At the same time there is no guarantee that the savers, who will be now getting electricity at a substantially lower rate, are not going to increase their energy consumption, pushing the average up. However we should remember that the energy is provided at a cheaper rate only as long as it is used sparingly. If the savers decide that at the price they pay they may as well consume more, they will immediately see an increase in the price, since the more they consume, the higher the price per unit they pay. So there is an immediate disincentive to start consuming more.

This pricing scheme is operational. In many places, including Florida, Colorado, Maryland, California, etc., the so-called ‘inclining block pricing’ schemes are used for water rates. The concept is similar to what we described, except the rate curve is step-wise rather than continuous as in our case. For example, in Florida[1] users are paying US $1.50 per 1,000 gal (3.79 m^3) for the first 5,000 gal (20 m^3), then the rate jumps to US$2.50/1,000 gal for the next 7,000 gal, and then increases again to US$3.50/1,000 gal for all consumption over 12,000 gal (45.5 m^3). The block rate approach also creates a difference between average price and the weighted marginal price without changing the average price, so it can be revenue neutral. It has been shown in several studies that block rates do work helping decrease overall water consumption by 3%-8% depending upon the use cluster, with high users cutting consumptions more than low users (Brookshire et al., 2002; Whitcomb, 2005; Kenney et al., 2008). Loaiciga and Renehan (1997) and Zetland (2008)[2] provide more evidence on the efficiency of pricing in controlling demand.

We argue that a continuous pricing scheme can be more efficient because it creates opportunities and incentives to save for all, not just for those who are between blocks. In fact, Kenney et al. (2008) report that customers use “smart meters” to use more water carefully tracking their consumption and making sure that they remain within the same block. We also think that it is important to introduce the pricing schemes as compensation methods rather than additional taxes or penalties. The goal is not to raise more money for the budget, but simply to compensate the savers for their efforts to cut their consumption.

Within one payment period, there may be a certain deficit of money in the system that will have to be compensated by additional money invested. This will have to come from the budget, but it will be only temporary since the break point can always be adjusted to make the system revenue neutral. Besides, if we do run into additional costs, they also bring societal benefits: this would be the payment for reduced power generation. This means that for every kilowatt that is saved, the same amount of new capacity will no longer be needed. The saving on new construction can certainly be the source of additional funds that the system may temporarily need during the adjustment period.

By tweaking the breakpoint proactively, anticipating the lower consumption and setting it to a value somewhat lower than the average, the deficit in funds can be compensated (Fig. 6). Now we penalize slightly higher than reward. As a result some additional funds to

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1) SFWMD (2009). Southwest Florida Water Management District. Water Rates: Conserving Water and Protecting Revenues. http://www.swfwmd.state.fl.us/conservation/waterrates/

2) Zetland D (2008). Conservation Pricing, Aguanomics. http://aguanomics.com/2008/10/conservation-pricing.html

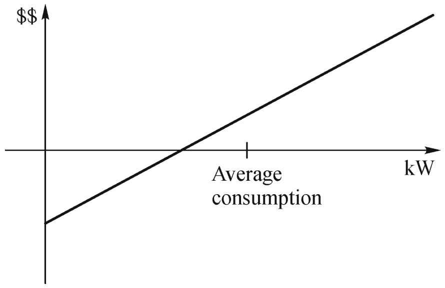

Fig. 6 Incentive pricing scheme with the break point set lower than average to make sure that there will be no deficit in the system.

compensate for the decreasing average in the future are generated.

In Fig. 7(a) we can also make the switch from rewarding to penalizing smoother by changing the shape of the curve as in Fig. 7(b). In this case for most of the customers that are consuming power at an approximately average rate, there will be no visible change in the cost. Only the major overconsumers will be penalized, and the major savers will be rewarded.

In these asymmetric cases the program can generate additional funds that can be then invested in promoting energy saving or further development of alternative technologies. A very similar program can be also used for water payments, wherever water is metered. One of the major advantages is that the scheme is not a tax. Instead, it can be positioned as a payment schedule, or a tariff on luxury consumption. By adjusting the gradient of the lines we can create situations when low consumption will be almost free, paid for by the customers that have exceptionally high consumption. It is a win-win arrangement, since as aggregated demand gets lower it drives the prices down and diminishes the chances of crisis when vital resources will become simply unaffordable.

4.2 Case of gasoline

Designing disincentive schemes for gasoline is more complicated, since total individual consumption is not metered and it is hard to keep track of how much each individual consumer uses over a certain period of time. In this case a quota mechanism can be appropriate. We do know the average per capita consumption of gasoline. This amount can be taken as the basis to issue a certain quota. Every individual can purchase an amount of gas within this quota at the current market rate. Every, say, one month each individual can load a debit card with gas dollars. If by the end of the month there is still gas on an individual debit card it can be offered for sale to those individuals who need more gas for their life styles. Since everyone gets the average, there will certainly be some individuals who actually consume less and others that need more. The excess on individual gasoline debit cards is pooled to a market of excess gas that can be purchased at a price potentially higher than what the individuals paid for the average.

The more excess gas an individual has on the gas debit card by the end of the month, the more can be sold in the market and the more revenue can be generated. Reciprocally, the more gas over the average individuals need, the more demand there will be, the higher the price they will need to pay in the residual market. In any case there is now an additional incentive to save gasoline to generate more income. Those who consume less have a chance to get extra benefits by selling their fuel surpluses at the prices that is equal or higher than the average price at which they bought the fuel. We can easily imagine a service like E-Bay, where one would trade the excess fuel quotas for the best price offered.

By the end of the month the average consumption is recalculated and the amount of gasoline offered at a base price to load the debit cards for the next time period is decreased accordingly. In a way this is also exactly similar to the cap-and-trade system, when, in this case, you set an average consumption based on your “cap” — the target reserve of gasoline that is for sale at the moment. And then whatever is available from those who under-consumed is sold at a market price to those who over-consume. While the creation of the secondary residual market of gasoline

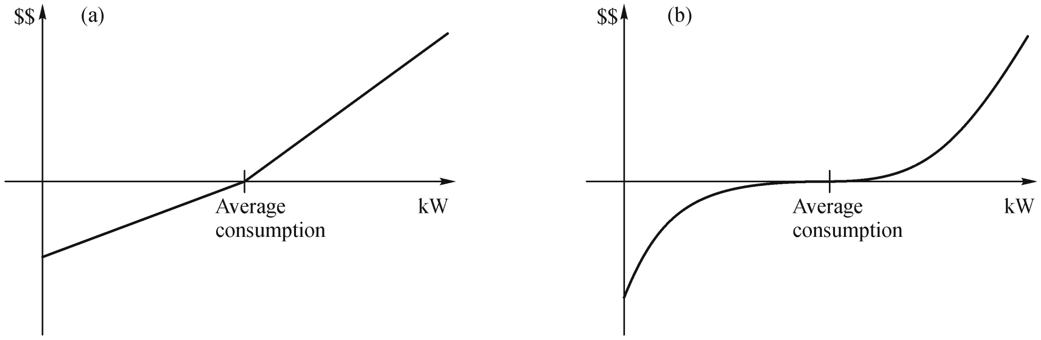

Fig. 7 Asymmetric pricing schemes.

can be a good first step to encourage less consumption, it still falls short of achieving the major goal: creating additional price disincentives for those who consume significantly more than the average. Without tracking the total consumption we cannot penalize those who consume disproportionally high volumes and reward those who consume significantly less. You may be purchasing the extra fuel in the residual market for a higher price, but it makes no difference how much you purchase — the price per liter you pay will be the same.

On the other hand, with the introduction of the gas debit card system we do get an opportunity to track total consumption. After all now all the gasoline consumption goes through the debit card and it is easy to figure out the levels of consumption for all individuals. This allows deployment of schemes similar to the one explained above for electricity or water.

Instead of offering excess gasoline in the residual market for the market price that is established by the supply and demand relationship, we will be selling the excess to a common pool at a price that can be made higher for larger amounts of gas that are sold and lower if there is an insignificant amount contributed. Similarly, the more gas you need to purchase from the residual market, the higher the price you will be paying per unit. It does not matter if you buy it in small increments or in bulk. The debit card allows to track what the total amount in excess of the average per month will be, and allows to price the purchase accordingly. The same on the seller side: you can either return excess gas to the pool little by little, or you can return it in bulk. The debit card will keep track of all monthly transactions, which will help to calculate the balance according to pricing schemes as in Figs. 6 and 7.

5 Discussion and conclusions

Demand for energy resources is growing globally, while supply of oil has its natural limits. This paper analyzed markets for natural capital, specifically energy markets, in which both supply and demand are inelastic. Such markets are characterized by two features. First, with growing demand for CNC price grows indefinitely and markets cannot adjust smoothly since there are no means for supply to meet demand. Second, those who consume more create price externality on CNC for those who consume less. We discuss different measures to increase elasticity of both demand and supply, including such measures as developing alternative energy resources and employing market mechanisms to affect the demand. The proposed operational measures are essential in the current crisis at the nexus of a resource crunch and adaptation to climate change, on a global level.

The energy depletion pattern is likely to be different on the global scale than it is locally. The peak oil curve predicted by Hubbert (1950) and observed in numerous local and regional cases may not be so smooth and symmetric at the global level. When individual wells start to show high decline rates, they are usually replaced by wells at a different location: regionally or internationally. When regional, say, USA production went beyond the peak, we moved to other locations to extract oil still relatively cheaply, with a higher EROEI than we could obtain in USA. It is different in the global scale, where we have nowhere else to go. We have to move to a different technology and create new infrastructures for production and distribution. That will require considerable investments of energy, which we will try to get from the traditional sources, even if we will have to continue pumping at lower EROEIs. In line with the Hotelling model (Gowdy and Roxana, 2005), this can somewhat delay the peak oil, but will also significantly increase the rate of decline. We will climb higher to fall down harder. The rapid decline of the Cantarell oil field in Mexico is a good example of how this may look like. Production enhancement techniques such as nitrogen pumping allowed faster short-term oil extraction at the expense of field longevity, marking one of the most dramatic declines ever seen in the oil industry (Höök et al., 2009; Cobb, 2013[1)]). The current excitement about fracking and shale oil may be short lived bearing in mind the extremely high energy inputs required and yet to be determined environmental and social costs associated with these new technologies. Again, the externalities are hardly taken into account when another delay of peak oil is celebrated.

Another important factor we need to account for is global climate change. There is no way we can stop it at this time, so we will need to adapt to it (Stern, 2008). But adaptation also requires new infrastructure, which will be yet another burden on the dwindling resources and energy investments. We are getting into a race against time, which may be a loosing game. And the price of further procrastination may be exceedingly high.

Currently we are at a stage when finding more of cheap (high EROEI) oil is unlikely, so the supply side is limited. In this case more demand only increases the price rather than motivates more supply. As you move closer to the asymptote in Figs. 1 and 2, even small increases or decreases in demand have a dramatic effect on prices. Increasing elasticity of supply and demand curves would help avoiding energy markets to settle with high energy prices. Alternative energy may increase price elasticity of supply. However, alternative technologies need time to become real substitutes for the traditional energy resources. Investments in alternatives are also energetically expensive. In other words, they compete for remaining

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[1)] Kurt Cobb (2013). "The decline of the world's major oil field." Christian Science Monitor: 1–3. http://www.csmonitor.com/Environment/Energy-Voices/2013/0412/The-decline-of-the-world-s-major-oil-field.

conventional energy resources with current societal needs. Whether they will be a solution of energy crisis or its accelerator depends on timing of investment in alternatives and rate of their growth. The model of dynamics of demand and supply of such CNC as energy presented in section 3 demonstrated that at current EROEI levels the build up of alternative energy should go on very aggressively at a very high rate. Otherwise it will be just a loss of time, energy and effort. Recent research showed that we are either approaching or have already passed peak oil (IEA, 2007, 2011; Murray and King, 2012). Thus, timing of substitution of traditional energy resources by alternatives is crucial. Alternative energy can also come at different costs and EROEIs (Murphy et al., 2010; Firrisa et al., 2013) and has to be carefully analyzed to take into account the full life cycle before any policy recommendations are implemented.

Only by reducing consumption and, therefore, demand we can effectively buy back some time for transition to alternative supplies of energy. So far, market mechanisms have been successfully used to boost consumption and generate more economic growth. Such encouragement of consumption was always the purpose of advertisement, which capitalizes on some of the very basic human behavior principles, which are carefully studied by behavioral scientists to increase the power of advertisement. However market mechanisms can also become a powerful tool to promote less consumption. Less consumption does not necessarily mean lower quality of life (Costanza et al., 2009). It implies eliminating wasteful spending and more efficient use of resources to support certain ecologically friendly life styles. Besides, one should also realize that it is not a life style that determines the use of resources, but, on the contrary, it is the resources available that define the life style that can be afforded.

At present the goals are exactly the opposite. Economics of consumption assumes that more growth is powered by more consumption for the sake of more growth (Ayres et al., 2003). The prices are also set to stimulate consumption: when you buy more you can pay less. The so-called ‘economy of scale’ is based on the premise that it is cheaper to produce a large quantity of a good (Krugman, 1979; Lipsey et al., 1993). Therefore, when buying in quantities, wholesale, one could always obtain a lower price (e.g., stores offer sale items, so called ‘family packs’ that contain a larger amount of good and would be priced lower per unit).

If one wishes to create disincentives for large-scale luxury consumption, the pricing schemes should be designed to make consumption in high amounts unattractive. The idea is similar to progressive tax scale. Except in our case instead of punishing the ‘good’, (the hard work and more income), we punish the ‘bad’ — higher consumption that is in the basis of living beyond our means. One may argue that a sales tax would do that, since you would be paying a higher total tax if you buy more. However the per unit tax will be the same, no matter how much of these units one purchased.

Price incentives have proven to be very effective in shaping human behavior and consumption decisions. Humans react to price signals (Loaiciga and Renehan, 1997; Bartusch et al., 2011). It really matters what is the goal of these signals. So far in conventional, say, energy markets most research has been focused on finding “… optimal conditions for price and capacity levels that must be simultaneously satisfied to maximize the net social benefits of electricity consumption” (Munasinghe and Meier, 1993, p.143). We would argue that currently the society might be better off by reducing consumption. The existing pricing schemes that reward high consumption impose externalities on those who consume less. Individuals, who consume more than the average, are the ones that drive demand. Therefore they are the ones who are more responsible for higher prices. The price externality created by those who consume more adds to inefficiency of energy markets. This is especially clear in markets for limited natural resources that are served by mature markets for energy products, such as electricity and gasoline. If there is no discrimination for consumption levels, and everybody gets the product at the same price, it means that those who consume less are effectively subsidizing those who consume more. This subsidy of the spenders by the savers is even further exacerbated in case of oil or gas prices. If everybody were consuming less, the good will be less scarce and, as a result, the price would be lowered. In the presence of externalities markets need regulation. Therefore it makes perfect sense to make the big spenders, who create a price externality for the savers, pay a higher price, while compensating those who consume less. It should be understood as a fair mechanism of adjusting pricing to the role individual consumers play in forming the current market prices. In fact, relatively more expensive energy creates greater incentives to be more energy efficient (Chow et al., 2003). With the pricing schemes as described in section 4 policy makers can stimulate less consumption and creating means for a softer transition to sustainable development instead of promising the impossible: unlimited growth under limited resources supply. It should be much easier to adjust and adapt to new consumption patterns in a smooth way, rather than wait for an energy crisis and a big shock for economy. Certainly introducing new pricing methods in such a politically charged area as energy is not an easy task. However the proposed schemes have an important selling point. For the majority, at least initially, they may mean that the energy rates will be same or even lower. Only the big spenders who are in minority will be penalized.

To a certain extent there is already something happening in this direction. There is growing interest in improving efficiency and understanding that every Megawatt saved is the same as a Megawatt produced. The term Negawatts is used to measure the amount of energy saved[1)]. Some markets for CNC already dictate higher prices associated with higher consumption. For example, pricing schemes that charge a higher per kWh rate during peak hours and a lower than average rate at night, when demand is low are already quite widely used (Irastorza, 2005). However this charge treats equally those who would spend just a little to run an air-conditioner in one room, and those who will be cooling all the rooms in a mac-mansion. The total they pay will be different, but the rate per unit of energy at which they pay will be the same.

Economic laws guiding markets and individual behavior are powerful if conventional assumptions of economics are fulfilled. However, real world markets are often filled with inelastic demand or supply, or both and exhibit presence of externalities. In these cases we should not expect market to provide efficient solutions by itself. Specifically, when an energy crisis is looming it is quite unrealistic to expect that markets for energy would adjust smoothly, and that driven by competition and profit maximization the innovators will bring in new alternative technologies overnight and at a cheap price. Fossil fuel energy resources, as other CNC, are limited. Moreover, its investments are needed to research and develop alternative energy resources, and then even more is needed to build the new alternative infrastructure. Not only supply but also demand needs to be affected. Real economics should certainly take into account the real limitations of our real world and work with models and theories that deal with finite resources and existing technologies. The bright side is that happiness and life quality has little to do with standard economic indicators, such as GDP (Costanza et al., 2009). Perhaps then it will be only easier to transition to the new consumption patterns, sustainable livelihoods and energy scarcity for the coming generations.

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Appendix

We can estimate the growth of demand in oil, based on the history of oil petroleum consumption in the USA ((EIA, 2002); see p.355 for historical data). We will extrapolate those numbers to the world consumption by assuming that USA oil consumption is roughly one quarter of the World consumption and that this pattern has been always the case. Before the oil crisis of the 1970's the growth of oil consumption was very well approximated by the equation $y = 0.7\ e^{0.045t}$, where t is time (Fig. A1). After the oil crisis a better approximation is given by the curve $y = 4\ e^{0.025t}$ (Fig. A2). We will use this more conservative estimate in the model, assuming that demand is growing at 2.5% per annum. Keeping in mind our assumption about the fraction of USA oil consumption in the world, we can then multiply this equation by four to present the overall global oil consumption as $y = 12e^{0.025t}$.

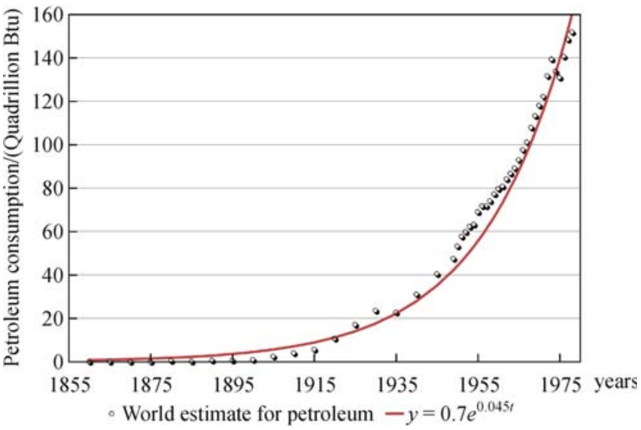

Fig. A1 Before the oil crisis of the 1970's the growth of oil consumption was very well approximated by the equation $y = 0.7\ e^{0.045t}$, where t is time.

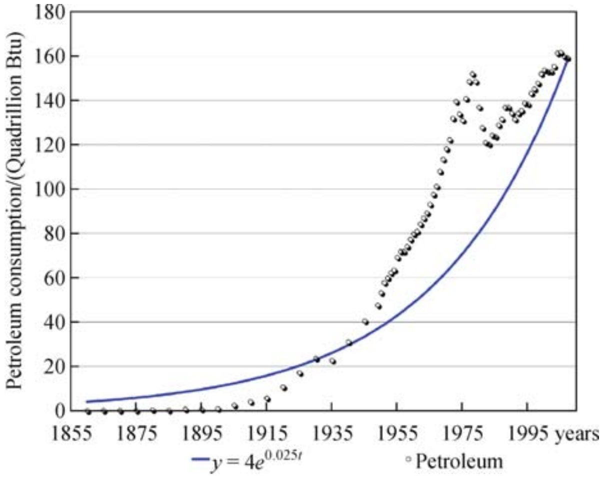

Fig. A2 The oil crisis of the 1970's has changed the equation to $y = 4\ e^{0.025t}$, where t is time. Overall the growth rate is now better estimated at 2.5% per year.

The most optimistic estimate of oil reserves at the end of 2007 (http://www.eia.doe.gov/emeu/international/reserves.html) was $1{,}184.208\times10^9$ Barrels. Assuming

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[1)] Lott M C (2011). Negawatts and Megawatts—When Less Makes Money. Sci Am, 11:1–4. Available at: http://blogs.scientificamerican.com/plugged-in/2011/11/02/negawatts-and-megawatts/

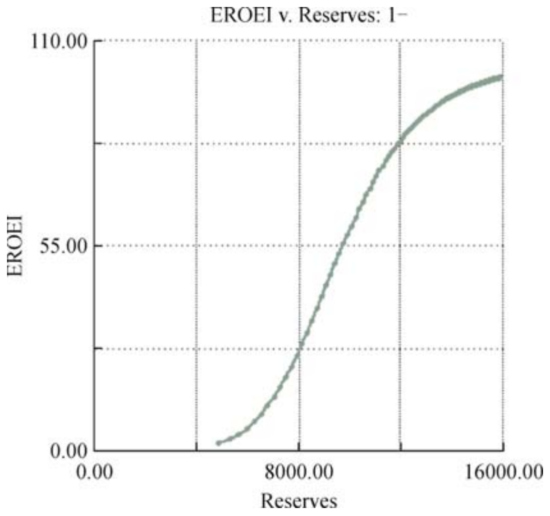

Fig. A3 The *s*-shaped dependency between EROEI index and the amount of reserves still available. The less reserves are left the more we need to invest to produce it.

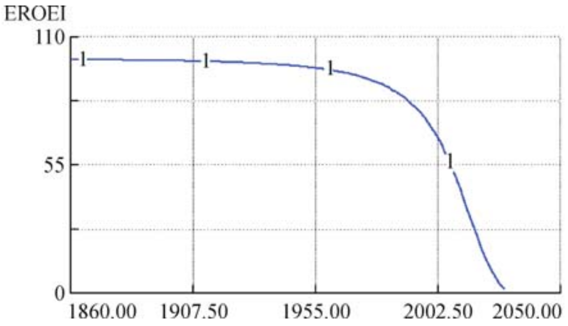

Fig. A4 Dynamics of EROEI as resources become scarcer.

that 1 Barrel = 42 U.S. gallons = 5,800,000 BTU based on U.S. consumption in 2007, we can convert this to petaBTU: $1{,}184.208\times10^9\times5.8\times10^6$ = 6,868 pBTU.

If we run our model with the consumption rate defined above, we find out that by 2007, over 6,240 pBTU had to be extracted to provide for the demand. This seems to be very much in tune with the "peak oil" projections, which say that we are currently at about half of the total oil resources on the planet. In fact if we run the same scenario further on until 2009, we will find that we should have already extracted 6,575 pBTU, which would put us right over the peak by today. Anyway, let us assume that there will be more oil found and let us set the total recoverable amount of petroleum at R_0 = 16,000 pBTU instead of 6,240 + 6,868 = 13,108 pBTU as we should have done based on the data.

Next let us figure out the EROEI function. EROEI, e, was about 100 when oil was abundant, it is decreasing as less oil is left and it is about 10 at present when about half of oil reserves are used. This dynamics can be presented by an s-shaped curve in Fig. A3. The equation will be:

$$e = e_{\max}\, R^s/(R^s + e_{\mathrm{h}}^s)$$

where $e_{\max}$ is the maximal EROEI, 100 in our case; R are the remaining resources, s is the curvature, $s = 6$ in Fig. A3; and e_{h} is the half-saturation point, which is the amount of resources R when $e = e_{\max}/2$. In our case $e_{\mathrm{h}} = 0.6\ R_0$. This will make e equal 50 when we are somewhat over one half of the reserves and push it down to 10 by the time we have passed the half mark. The dynamics of EROEI over time is presented in Fig. A4.

References

Arthur W B (2006). Out-of-equilibrium economics and agent-based modeling. In: Tesfatsion L, Judd K L eds. Handbook of Computational Economics Volume 2: Agent-Based Computational Economics. Amsterdam: Elsevier B.V., 1551–1564

Ayres R U, Ayres L W, Warr B (2003). Exergy, power and work in the US economy, 1900–1998. Energy, 28(3): 219–273

Bartusch C, Wallin F, Odlare M, Vassileva I, Wester L (2011). Introducing a demand-based electricity distribution tariff in the residential sector: demand response and customer perception. Energy Policy, 39(9): 5008–5025

Bhattacharyya S C (1996). Domestic energy pricing policies in developing countries: why are economic prescriptions shelved? Energy Sources, 18(8): 855–874

Brock W A, Xepapadeas A (2004). Management of interacting species: regulation under nonlinearities and hysteresis. Resour Energy Econ, 26(2): 137–156

Brookshire D S, Burness H S, Chermak J M, Krause K (2002). Western urban water demand. Nat Resour J, 2(4): 873–898

Cheshire P, Sheppard S (2005). The introduction of price signals into land use planning decision-making: a proposal. Urban Stud, 42(4): 647–663

Chow J, Kopp R J, Portney P R (2003). Energy resources and global development. Science, 302(5650): 1528–1531

Cleveland C J, Costanza R, Hall C A S, Kaufmann R (1984). Energy and the U.S. economy: a biophysical perspective. Science, 225(4665): 890–897

Costanza R, Hart M, Posner S, Talberth J (2009). Beyond GDP: the need for new measures of progress. The Pardee Papers 4: 46

Daly H, Farley J (2004). Ecological Economics. Washington D C: Island Press

Day J W Jr, Hall C A, Yanez-Arancibia A, Pimentel D, Marti C I, Mitsch W J (2009). Ecology in times of scarcity. Bioscience, 59(4): 321–331

Diamond J (2005). Collapse: How Societies Choose to Fail or Succeed. New York: Penguin,1–576

Ehrlich P R, Ehrlich A H (2009). The Dominant Animal: Human Evolution and the Environment. Washington D C: Island press, 480 p

Ehrlich P R, Ehrlich A H (2013). Can a collapse of global civilization be avoided? Proceedings of the Royal Society B: Biological Sciences, 280 (1754). http://rspb.royalsocietypublishing.org/cgi/doi/10.1098/rspb.2012.2845

EIA (2002). Annual Energy Review 2001. Energy Information Administration : DOE/EIA-0384, 432p

EIA (2013). Annual Energy Outlook 2013. US DOE, 244p

EIA (2013a). Short-term Energy Outlook. Release Date: August 6, 2013, Energy Information Administration. http://www.eia.gov/forecasts/steo/index.cfm

Ekins O, Folke C, De Groot R (2003). Identifying critical natural capital. Ecol Econ, 44(2–3): 159–163

El-Ashry M (2010). Renewables 2010 Global Status Report. Paris: REN21 Secretariat. Copyright Deutsche (GTZ) GmbH

Fader M, Gerten D, Krause M, Lucht W, Cramer W (2013). Spatial decoupling of agricultural production and consumption: quantifying dependences of countries on food imports due to domestic land and water constraints. Environmental Research Letters, 8 (1): 014046. http://stacks.iop.org/1748-9326/8/i = 1/a = 014046?key = crossref.7dd1e79e39bbfb5d7423efaecb00e003

Farley J, Gaddis E (2007). An ecological economic assessment of restoration. In: Aronson J, Milton S, Blignaut J eds. Restoring Natural Capital: Science, Business and Practice. Washington DC: Island Press

Firrisa M T, van Duren I, Voinov A (2013). Energy Efficiency for Rapeseed Biodiesel Production in Different Farming Systems. Energy Efficiency, 1–17. http://link.springer.com/10.1007/s12053-013-9201-2

Gagnon L, Belanger C, Uchiyama Y (2002). Life-cycle assessment of electricity generation options: the status of research in year 2001. Energy Policy, 30(14): 1267–1278

Gever J (1986). Beyond Oil (3rd edition). New York: Harper Business

Goldin K D (1975). Price externalities influence public-policy. Public Choice, 23(1): 1–10

Gowdy J, Roxana J (2005). Technology and Petroleum Exhaustion: Evidence from Two Mega-Oilfields. Rensselaer Working Papers in Economics

Greene D L (1997). Oil dependence: the value of R&D. Proceedings of the Intersociety Energy Conversion Engineering Conference. Volume 3, 2148–2153

Greene D L, Hopson J L, Li J (2004). Running out of and into oil: analyzing global oil depletion and transition through 2050. Energy and Environmental Concerns, 2004(1880): 1–9

Gumilev L N (1990). Ethnogenesis and the Biosphere. Moscow: Progress Publishers

Hall C A S, Cleveland C J, Kaufmann R (1986). Energy and Resource Quality: The Ecology of the Economic Process. New York: John Wiley and Sons

Hall C A S, Day J W (2009). Revisiting the limits to growth after peak oil In the 1970s a rising world population and the finite resources available to support it were hot topics. Interest faded-but it's time to take another look. Am Sci, 97(3): 230–237

Höök M, Hirsch R, Aleklett K (2009). Giant oil field decline rates and their influence on world oil production. Energy Policy, 37(6): 2262–2272. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301421509001281

Hubbert M K (1950). Energy from fossil fuels. Washington D C, American Association for the Advancement of Science Centennial: 171–177

Hughes J D (2013). Energy: a reality check on the shale revolution. Nature, 494 (7437): 307–8. http://www.ncbi.nlm.nih.gov/pubmed/23426309

IEA (2007). Medium-Term Oil Market Report. Eagles L ed, International Energy Agency: http://omrpublic.iea.org/currentissues/mtomr2007.pdf

IEA (2011). World Enegy Outlook. In IEA, 666

Irastorza V (2005). New metering enables simplified and more efficient rate structures. Electr J, 18(10): 53–61

Kahl C H (2006). States, Scarcity, Civil Strife in the Developing World. Princeton, NJ and Oxford: Princeton University Press

Kenney D S, Goemans C, Klein R, Lowrey J, Reidy K (2008). Residential water demand management: lessons from Aurora, Colorado. J Am Water Resour Assoc, 44(1): 192–207

Kerr R A (2008). Energy. World oil crunch looming? Science, 322 (5905): 1178–1179

Krugman P R (1979). Increasing returns, monopolistic competition, and international-trade. J Int Econ, 9(4): 469–479

Kubiszewski I, Cleveland C J, Endres P K (2008). Energy return on investment (EROI) for wind energy. In: Cleveland C J ed. Encyclopedia of Earth. last updated June 18, 2008

Levermann A, Clark P U, Marzeion B, Milne G A, Pollard D, Radic V, Robinson A (2013). The multimillennial sea-level commitment of global warming. Proceedings of the National Academy of Sciences (July 15): 1–6. http://www.pnas.org/cgi/doi/10.1073/pnas.1219414110

Lipsey R G, Courant P N, Purvis D D, Steiner P O (1993). Microeconomics (10th Edition). New York: Harper Collins College Publishers Inc

Loaiciga H A, Renehan S (1997). Municipal water use and water rates driven by severe drought: a case study. J Am Water Resour Assoc, 33 (6): 1313–1326

Malthus T R (1826). An Essay on the Principle of Population. London: John Murray. Library of Economics and Liberty [Online] available from http://www.econlib.org/library/Malthus/malPlong1.html; accessed 18 May 2009

Meinshausen M, Meinshausen N, Hare W, Raper S C B, Frieler K, Knutti R, Frame D J, Allen M R (2009). Greenhouse-gas Emission Targets for Limiting Global Warming to 2 °C. Nature, 458 (7242): 1158–1162

Mulder K, Hagens N J (2008). Energy return on investment: toward a consistent framework. AMBIO: A Journal of the Human Environment, 37(2): 74–79

Munasinghe M, Meier P (1993). Energy Policy Analysis and Modeling. Cambridge: Cambridge University Press

Murphy D J, Hall C, Powers B (2010). New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. Environment, Development and Sustainability, 13 (1): 179–202. http://link.springer.com/10.1007/s10668-010-9255-7

Murray J, King D (2012). Climate policy: oil's tipping point has passed. Nature, 481(7382): 433–435

Pachauri R K, Reisinger A (2007). Climate Change 2007: Synthesis Report. Geneva, Switzerland, IPCC

Rees W E, Wackernagel M, Testemale P (1998). Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island:

New Society Publishers

Simon J L (1998). The Ultimate Resource II. Princeton: Princeton University Press

Solomon S, Plattner G K, Knutti R, Friedlingstein P (2009). Irreversible climate change due to carbon dioxide emissions. Proc Natl Acad Sci USA, 106(6): 1704–1709

Stern N (2008). The Economics of Climate Change: The Stern Review. Cambridge: Cambridge University Press

Trewavas A (2002). Malthus foiled again and again. Nature, 418(6898): 668–670

Voinov A (2008). Systems Science and Modeling for Ecological Economics. Elsevier, Academic Press

Whitcomb J B. (2005). Florida water rates evaluation of single-family homes. Report to South Florida Water Management District: 113