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Beyond GDP

National accounting in the age of resource depletion

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Chapter 1
Introduction: The end of an era

Need a motto. [1, p. 26]

—author

1.1 Economic growth has stalled for mature economies

The world is entering a new economic era. There is widespread agreement that economic growth in mature economies is unlikely to reach the rates seen in the 20$^{\text{th}}$ century again. Indeed, over the last fifty years, the economic growth rate of the OECD has fallen precipitously. The long-term forecast from the OECD is that mature economies will grow only 1.5–2.0% annually over the next fifty years. Similarly, the US Congressional Budget Office forecasts an average growth rate of 2.2% for the US economy from 2018–2024.[2, 3]

The stagnation of economic growth (as measured by annual percentage change in GDP per capita) for mature economies is even more striking when compared to the explosive growth in emerging economies. Figure 1.1 shows the 5-year trailing average of economic growth rates for the OECD, China, and India since 1965. The trendline of the OECD is clearly downward, while the trendline of Chinese and Indian growth is sharply upward. Indeed, the OECD itself says that the "combined GDP of China and India was 33% of the OECD in 2010 (on a PPP basis), but is expected to rise to 73% by 2060." [2, p. 214] Slowing OECD growth illustrates that mature economies are hitting a wall.

Is stalled economic growth a problem? Most analysts believe it is. History suggests that growth of GDP raises living standards and well-being, as measured by various indices. Julian Simon's volume, *The State of Humanity*, catalogues the great improvements in life span, housing, environment, food quality and availability, water cleanliness, etc. that have coincided with economic growth over the last three centuries.[4]

Thus, stalled economic growth can be expected to be accompanied by slowing or reversing of the upward trend in quality of living. The economic establishment's prescription to avoid backsliding of quality of life and well-being is continued economic growth by (nearly) any means necessary. At the moment, continued economic growth appears to be the only politically-viable policy instrument.

Fig. 1.1 Source: Authors' calculations using data obtained from World Bank databank (Indicator NY.GDP.PCAP.KD.ZG accessed August 1, 2014.) [**?**]

1.2 Time for a fresh approach

What do economists believe is causing the slowdown of economic growth in mature economies? Mainstream economic theory considers economic growth to be driven by four factors: (1) increased labor utilization as a result of increasing the number of workers or worker hours, (2) increased human capital through improved education levels, skill levels, or health, (3) increased capital/labor ratio because of expanded capital investments, and (4) increased worker productivity due to technological innovation.

The economy has deteriorated on all fronts in recent years. Economist Tyler Cowen argues that large productivity gains through innovation have permanently plateaued leading to a "great stagnation" in economic growth.[5] The Cato Institute's economic growth specialist, Brink Lindsey, suggests that growth has permanently stalled, because *all four* of the primary drivers of economic growth have plateaued; hours worked, worker skill level, and the amount of capital invested per worker have reached a low, slow, steady state and are unlikely to rebound.[6]

The Cowen and Lindsey analyses represent mainstream explanations for the growth slowdown, and they are based squarely on the assumption that technology augments capital and labor, the inputs to economic growth.[1] If economic slowdown

[1] The mainstream model for economic growth is encapsulated in the Cobb-Douglas production function, which takes the mathematical form

$$y = Ak^{\alpha} l^{1-\alpha}$$

is caused by anything besides technology, capital, or labor, mainstream economic analysis can't provide any assistance in either diagnosing the problem or prescribing a cure.

We believe that the mainstream approach is too narrow and that there may be other factors that cause economic slowdown. In particular, we contend that binding constraints on economic growth may arise from at least two sources: material inputs from the biosphere and the energy to run the economic engine.

Our approach may be outside the economic mainstream, but we are not alone. There are several inter-disciplinary fields (industrial ecology, ecological economics, biophysical economics, and materials flow analysis) where the relationship between the economy and the biosphere is a natural feature of the intellectual landscape and assessment of patterns of economic growth and economic downturns includes consideration of biophysical limits. This emerging paradigm is taking shape with the leadership of theorists such as Robert Ayres, Kenneth Boulding, Robert Costanza, Herman Daly, Charles Hall, Marina Fischer-Kowalski, and others. [**** others? ****] In this book, we'll refer to this approach as a "biophysical" approach to the economy.

Historically, the biophysical approach led to the insight that material and energy constraints could lead to the end of the era of economic growth based solely on increased consumption. A striking example comes from inter-disciplinarian Robert Ayers who, in 1996, presciently described how it would end in a financial collapse similar to the "Great Recession:"

> It is difficult to say when, or how, the current economic growth "system" will collapse; it has proved more resilient than many would have predicted. But, unless job-creating growth can be sharply accelerated the choice facing governments is stark: either there will be very sharp and painful cuts in entitlements and social welfare or there will be a financial crisis, probably sudden (like the onset of the Great Depression) and probably within twenty years. The traditional Keynesian job creation mechanisms are ineffective or inapplicable, while trade liberalization and "globalization" are making the unemployment problem worse, not better. Western democracies are, like the passengers on the Titanic, heading "full steam ahead" into extremely dangerous waters. Icy reality lies dead ahead, already dimly visible through the fog. Collision is inevitable, unless we change course sharply.[**?**]

1.3 (Mis)measuring the wealth of nations

An ironic consequence of re-connecting economic analysis to the biosphere is a re-emergence of the discussion about a nation's wealth. Today's mainstream quantification of economic health, GDP, measures only *income*, a *flow*. To understand how GDP relates to *wealth* and mis-measures economic health, we need to discuss *capital*.

A nation's wealth consists of physical *stock*, including both manufactured and natural capital. The word "capital" is used in many ways, usually referring to assets

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where y is economic output, A is technological progress, k is capital stock, l is labor, α is the factor share of capital, and $1-\alpha$ is the factor share for labor.

of one form or another: financial capital, natural capital, human capital, social capital, physical capital, and manufactured capital, to name a few. In this book, we use the term “capital” to indicate things such as machines, buildings, roads, vehicles, and computers, all physical items used in and necessary for the production process. Manufactured capital is not normally used up during production of goods and rendering of services, although it depreciates over time. As manufactured capital depreciates, future income is put at risk. A nation’s natural capital includes oil, coal, and natural gas reserves. But, clean air and water, forests, and natural areas[2] are counted as natural capital, too. Natural capital depletes when consumed (fossil fuels) or degrades when soils are mistreated, clean air and water are polluted, and wetlands are contaminated. As natural capital dwindles, the future capacity for income generation dwindles.

Manufactured and natural capital (as well as human, social, and financial capital), provide the services an economy uses to produce income. To maintain a constant or increasing standard of living, the current generation must forego some of its consumption to invest in maintenance, repair, and replacement of capital. From Robinson Crusoe to the US, every economy must answer this question: how much of our stock should be consumed today and how much should be saved for tomorrow?

Now, let’s turn back to GDP as a quantification of economic health. GDP is an estimate of the *income* of an economy. Because firms gain income from the consumption of and investment in natural and manufactured capital, estimates of GDP include these transactions. Thus, depletion of natural capital and consumption of manufactured capital (both stocks) are counted as “income” (a flow) in national accounts, and both are “good” for the economy. The focus on GDP as the indicator of economic health creates a perverse incentive to consume the very stocks upon which economic health depends. There is no incentive to manage a nation’s stock of natural capital for the future, because depletion of natural capital increases GDP today.

There are many examples of these perverse accounting that arises from the use of GDP to (mis)measure economic health. When Lake Erie turned toxic for several days in 2014 due to algae blooms caused by agricultural runoff, GDP grew by the amount spent on bottled water and goods and services to repair the damage. Clearcutting of forests improves GDP in the short run but eliminates opportunities for recreation-relatied income in the future. Sickness adds the cost of health care to GDP.

Using GDP as the measure of economic health mis-measures economic health, because it blurs the distinction between stocks and flows and masks the fundamental tradeoff between today and tomorrow. Economic expansion (as measured by GDP) beyond the rate at which stocks can be replenished deprives the economy of the wealth it needs to generate income! And, continued economic expansion (in GDP terms) is likely to reach biophysical limits in terms of both the stock of non-renewable resources supplied by the biosphere and the capacity of the biosphere to assimilate all of society’s pollution and physical waste.

[2] Natural areas provide eco-system services such as water purification, carbon sequestration, and erosion control.

Thus, both natural and manufactured capital are important, and both should be accounted and reported in addition to GDP in Systems of National Accounts (SNA), which gather, evaluate, and disseminate data on economic activity at the national level. The UN's international standards for SNAs suggest accounting for natural capital that is both owned (by firms or the government) and used in production. However, not all countries base their national accounts on the SNA (the United States, China, and France do not, for example), and not all natural capital is "owned." Clean air and water are not accounted in the SNA, for example. The US ignores natural capital outright.

Although there is nothing in the SNA framework that prevents accounting for assets (manufactured and natural capital), the focus of national accounting is squarely on income (GDP), not wealth (manufactured and natural capital).[8, p. 415] This predilection results in national accounting, particularly in the US, that collects and analyzes a trove of data to produce a robust *income statement* of financial flows withing the economy (GDP), yet mostly ignores the data needed to produce a similarly rigorous *balance sheet* of assets (stocks) that measure the value of a nation's wealth, including manufactured and natural capital.

By focusing nearly-exclusively on income, today's national accounting is blind to an important aspect of the modern world: economies deplete natural capital in the pursuit of income. Without a complete national balance sheet alongside an income statement, policy-makers can unwittingly draw down a nation's wealth (natural capital) to generate today's income (GDP). In so doing, future living standards are put at risk.

Because of insufficient national accounting, some countries are putting future generations at risk to provide today's income. The UN *Inclusive Wealth Report 2012* accounts for the wealth of nations by counting all forms of productive capital (natural, human, and manufactured).[9] Examination of these data demonstrates that, indeed, a nation's wealth can decline even as its GDP grows. For the years 1990–2008, Saudi Arabia, Russia, Venezuela, South Africa, and Nigeria had declining wealth coincident with income growth, thereby dimishing the productive capacity of future generations to support consumption by the current generation. Saudi Arabia's GDP per capita grew at 0.4% per year, while its wealth declined at a rate of 1.1% per year, and Nigeria's GDP per capita grew at 2.5% per year, while its wealth declined at a rate of 1.8% per year. Not all nations consume their wealth in pursuit of today's income. However, wealth is growing at a slower rate than income in most countries. For example, GDP per capita for the US grew on average 1.8% per year, while the nation's wealth grew at only 0.7% per year.[9, p. 44]

Economies with consumption-enhancing policies and high flow-to-stock ratios are more likely to deplete natural resources due to unsustainable extraction rates, because there is little incentive to protect or invest in natural capital. As a result, we end up consuming manufactured and natural capital (wealth) in the hopes of generating income, as is happening in countries such as Nigeria. As Robert Ayres foresaw, this is not a sustainable approach.

Given the above, we contend that nations need both income statements and balance sheets to ensure sustainability. Nations must monitor and manage not only the goods and services they produce today, but also their stocks of capital (both natural and manufactured) and the state of that capital. Many questions, such as those found in Section 2.5, are unanswerable without both.

But, how could we do better? How could we structure a biophysical approach to national accounting? We must first understand the biosphysical economy. We must go beyond GDP!

1.4 Understanding the biophysical economy

As mentioned in Section 1.2, very little of the discourse about mature economy slowdown in mainstream economic circles involves biophysical factors.[3] Mainstream economics considers biophysical factors to be *exogenous* to the economy.[4]

Arguably, the most important (but not the only) biophysical factor vis-à-vis the economy is energy. If we are to understand how exogenous factors cause economic slowdown and, conversely, drive economic growth, we would do well to understand how energy operates in the economy. Thus, we first discuss the correlation between energy consumption and economic activity (Section 1.4.1). Then, we show how economic demands for energy and materials are related to important stocks of raw materials and energy resources in the biosphere (Section 1.4.2) and the stocks of manufactured capital in the economy (Section 1.4.3).

1.4.1 Coupling between energy and the economy

All manufactured goods are made and services provided from raw materials that have been manipulated, processed, transported, or otherwise transformed using energy. Indeed, energy consumption and economy activity are highly correlated, as Cleveland, et. al. [10] showed in a 1984 cover story for *Science*. (See Figure 1.2.)

Because of the high correlation between energy consumption and economic activity, it stands to reason that energy shortage relative to demand will hinder economic activity. Of course, there are degrees of shortage. In extreme cases, and in the absence of price controls, goods become hard to find and prices spike as observed in the US during 1970s oil crisis. (See Figure 1.3.)

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[3] In this context, we are using the term "biophysical factors" to indicate any factor related to the extraction, transport, processing, manipulation, and disposal of the physical (as opposed to financial) manifestation of any material or energy resource in the economy.

[4] Of course, mainstream economics discusses *prices* of raw materials, goods, and services. And, to the extent that biophysical factors affect prices, it could be said that mainstream economic discussions involve biophysical factors. However, biophysical factors are rarely acknowledged as causal for establishing the prices of goods and services and the raw materials of which they are comprised.

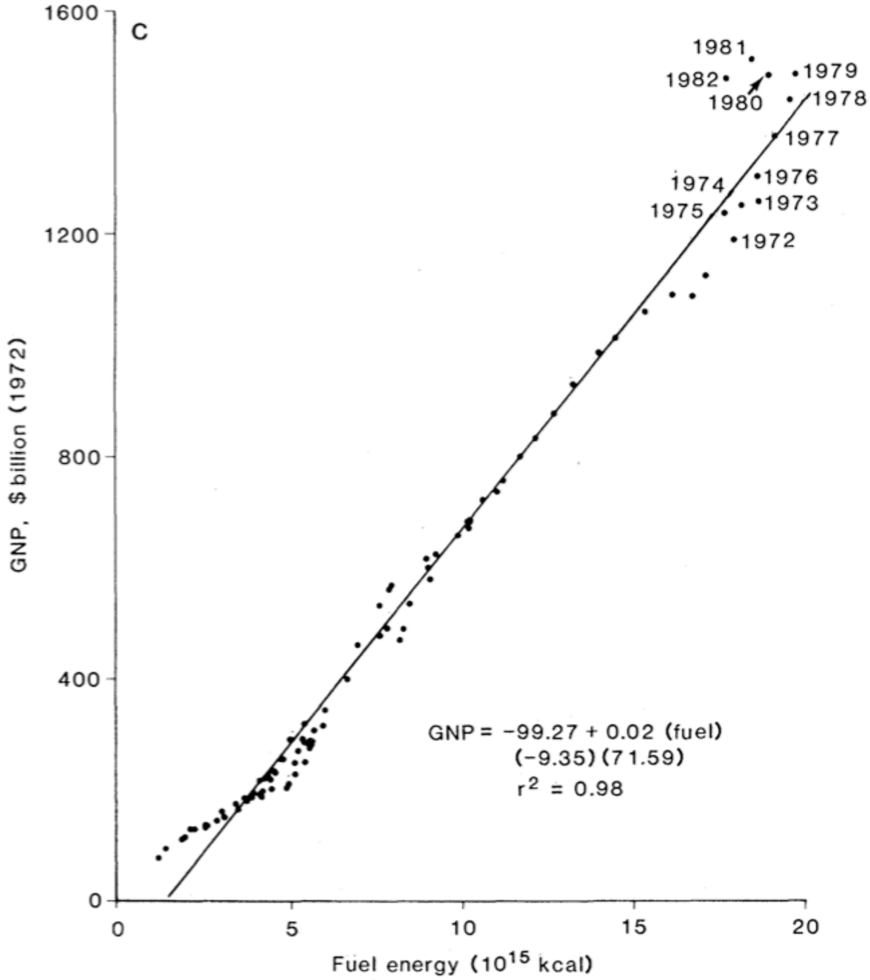

Fig. 1.2 The famous graph from Cleveland, et. al. [10] showing the strong correlation between energy and economic activity from 1890 to 1982. **** Need to obtain permission to use this graph? ****

In mild cases, shortage of any good relative to demand leads to rising prices, even when goods remain available. For example, Figure 1.4 shows oil prices (line) and worldwide oil production (vertical bars) before, during, and after the great recession. Demand for oil increased steadily in the early 2000s due to worldwide economic growth, and production mostly kept pace through early 2005. However, demand continued to increase while production flat-lined from early 2005 through late 2007, leading to a steep price increase. From late 2007 through the end of 2008, the small amount of remaining reserve oil production was brought online, but it was too little, too late. Prices spiked above $130/barrel in mid-2007. The great recession reduced

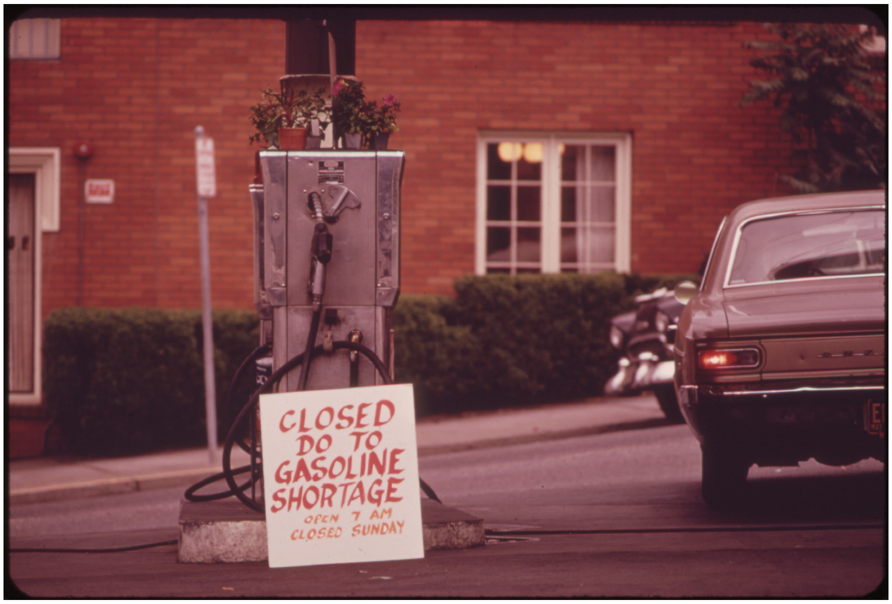

Fig. 1.3 Gasoline shortages in 1973. **** We probably don't need to obtain permission to use this photograph, because it is from the US national archives. `http://arcweb.archives.gov/arc/action/ExternalIdSearch?id=548053` `https://www.flickr.com/photos/usnationalarchives/4272321708/in/set-72157623204210352/` ****

demand slightly (by about 2 Mb/day) and the price collapsed to about $40/barrel. Thereafter, demand and price rose to their previous levels as the world pulled out of the great recession. In the years since 2008, oil production has risen slightly past the previous record highs as additional production capacity has come online.

In both cases (1970s and 2000s), significant slowing of economic activity (recessions) followed the oil shortages and prices spikes. These were not isolated cases. Hamilton noted that 10 of the 11 US postwar recessions involved the same pattern.[11, p. 45] It is clear that there is a correlation between energy consumption and economic activity.

But, what are the dynamics that cause economic slowdowns to follow energy price spikes? When prices rise faster than the cost of production, the profit motive should, according to economic theory, induce new firms to enter the market and established firms to increase production. However, the timing of supply and demand events is crucial. If firms can't or don't increase production to meet demand, prices will remain elevated. Even without increased production, falling demand will bring prices back to earth.

In terms of energy, and oil in particular, the *rate* at which production can be increased is of the utmost importance, and there are physical and technological limits. Consider this series of thought experiments: We know that increasing the

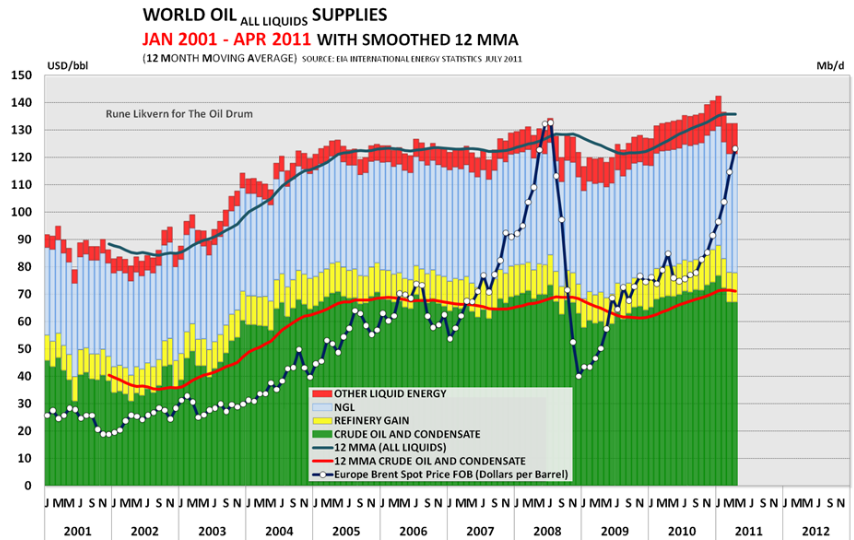

Fig. 1.4 Oil prices and production. **** Recreate this graph from our own data? `http://www.theoildrum.com/node/8162`
****

worldwide oil production rate by, say, 20% involves finding additional oil deposits, drilling additional wells, installing new pumps, and expanding transport and delivery infrastructure worldwide. In 1960, would it have been possible to achieve such an increase over a span of 5 years? Yes. In fact, the worldwide oil production rate increased at a faster rate during the 1960s. There was enough oil in the ground, and the economy could absorb the demand for additional steel, vehicles, energy, etc. required to emplace the required infrastructure. The impact on the financial system was minimal, because the cost of materials, equipment, labor, and energy was spread out over a long-enough timeframe (in this thought experiment, 5 years). But, in 1960 could worldwide the oil production rate have been increased by 20% in 3 months? No. There was enough oil in the ground, but it would have been practically impossible to manufacture, transport, and put into service the all the necessary capital in such a short time. Biophysical constraints limit the rate at which oil production can be increased. What about 2 years? Probably not. It might have been physically possible, but the financial cost would have been too much to bear over such a short timeframe, and the profit motive would be lost.

This thought experiment shows that time constraints, layered upon physical and technological constraints, are the ties that bind the financial to the biophysical. Put another way, time constraints are the point at which the economy becomes coupled to the biosphere.

In economic terms, biophysical constraints reduce the price elasticity of supply, the percent change in supply for a one percent change in price during a given period of time.[5] Figure 1.4 shows that a *very large* percentage change in the price of oil was required to increase production by only a *very small* percentage in the 2005–2008 timeframe. World oil production rose from 78 million barrels per day to 86 million barrels per day, an increase of only 10%.[12] However, the inflation-adjusted price of oil increased 260%, from around \$35 to a peak of \$126 per barrel (in constant 2010 USD). Thus, the price elasticity of oil supply is very low, about 0.04. Since 2010, the price of oil has remained over \$80 per barrel, suggesting that production cannot increase quickly enough relative to demand to bring prices back down to historical levels. Persistently high prices for such an important commodity suggest very real limits to production; supply is constrained relative to demand.

In these circumstances, oil supply is said to be very *inelastic* to price. The observed price inelasticity is caused by the biophysical limits to oil production discussed above. Nothing, not even historically-high prices, can induce producers to increase the rate of supply in the short term (say, a 5-year time span), because it is physically impossible to do so. In 2008, the world was running at full oil production capacity, but economies demanded more! Because it was physically impossible to meet that demand, prices spiked.

But, what caused the recession that followed? Recently, a few authors have found that *energy cost share*, the fraction of GDP spent on energy, is an explanatory variable for these dynamics. [6] To our knowledge, Bashmakov was the first to identify a long-term sustainable range for energy cost share in mature economies.[13] He also showed that developed economies can sustain high total energy cost share for a short period of time (possibly 2–3 years) before recessionary pressures destroy energy demand,[7] stimulate energy efficiency,[8] reduce energy prices, and return total energy cost share to its long-term sustainable range. On the other hand, reduction of total energy cost share below a lower bound provides economic stimulus, increases energy demand, provides upward pressure on energy prices, and returns energy cost share to its long-term sustainable range. Bashmakov speculates that "energy affordability thresholds and behavioral constants" are responsible for the stable range of energy

[5] The mathematical definition of elasticity of supply (E_s) is

$$E_s \equiv \frac{\frac{1}{Q}\frac{\partial Q}{\partial t}}{\frac{1}{P}\frac{\partial P}{\partial t}} ,$$

where Q is quantity of production, P is price, and t is time.

[6] Mathematically, energy cost share (f_E) is defined as

$$f_E \equiv \frac{1}{GDP}\sum_i P_i Q_i , \tag{1.1}$$

where the subscript i indicates types of energy (electricity, gasoline, natural gas, etc.), P indicates the price of energy, Q indicates the quantity of energy purchased within the economy, and GDP is gross domestic product.

[7] Note that "destruction of energy demand" is accomplished through recession in the short run.

[8] Like increasing oil production, increasing energy efficiency also has physical and technological limits. Improving energy efficiency is a medium- to long-term process.

cost share over many decades.[13, p. 3585] The long-term stable range for economy-wide energy cost share (which includes all forms of energy, including oil, natural gas, and electricity) is 9–11% for the OECD. For oil only, Murphy and Hall found that the oil cost share threshold that correlates with US recessions is about 5.5%.[14]

The picture emerging from this research shows that the cost share of energy in the economy (and, perhaps more narrowly, oil cost share in the economy) is an important factor in stimulating or restraining economic growth, despite its small value (typically, less than 10%).[9] It appears that the economy-biosphere system has a built-in feedback mechanism that enforces alignment between biophysical limits and the economy.

This may be somewhat surprising in light of mainstream economic theory, which ascribes economic importance based on financial cost share, not biophysical factors. Indeed, the cost share of energy in mature economies is low, and viewing energy as relatively unimportant is justified if one's view of "importance" is limited to financial information only. But, many have noted that the physical importance of energy to the economy far exceeds its cost share.[16] And, as discussed above, because the economy is coupled to the biophysical world through time constraints (as manifest by the low price elasticity of energy supply), the physical importance of energy far exceeds its financial importance.

The connection between energy and the economy may be difficult to see, but, eventually, it becomes impossible to ignore.

1.4.2 Stall is related to non-renewable stocks

Given the tight coupling between the biosphyical world and the economy, especially regarding energy, discussed in Section 1.4.1 above, it is prudent to consider the important economic role of material and energy stocks in the biosphere.

The Best First Principle [17] indicates that the economy will extract the easiest-to-obtain stocks of mineral and energy resources first. "Best" and "easiest" can be measured in several ways, but it usually comes down to cost. For example, inexpensive-to-obtain West Texas crude oil was extracted before expensive-to-obtain offshore oil. Surface deposits of gold and diamonds are exhausted before subsurface veins and kimberlite pipes are exploited. High-purity mineral deposits are exploited before low-purity deposits. As a result, it becomes more "difficult" to continually increase extraction rates as time proceeds. To continue with our energy example, historical oil production trends reflect these realities. Through time, the annual rate of increase of oil production has declined from 7.8%/year to 0.7%/year. (See Figure 1.5.)

It is important to realize that it takes energy to make energy available to society. Oil production requires energy for the ongoing operation of pumps, transportation

[9] Embarking on an economic growth path appears to reduce the energy cost share in an economy from very high values (indicating that nearly all economic activity is focused on procuring energy) to small values that remain within a stable range. For example, Sweden's energy cost share has stabilized at 12% since 1970, although it was nearly 100% in 1800.[15].

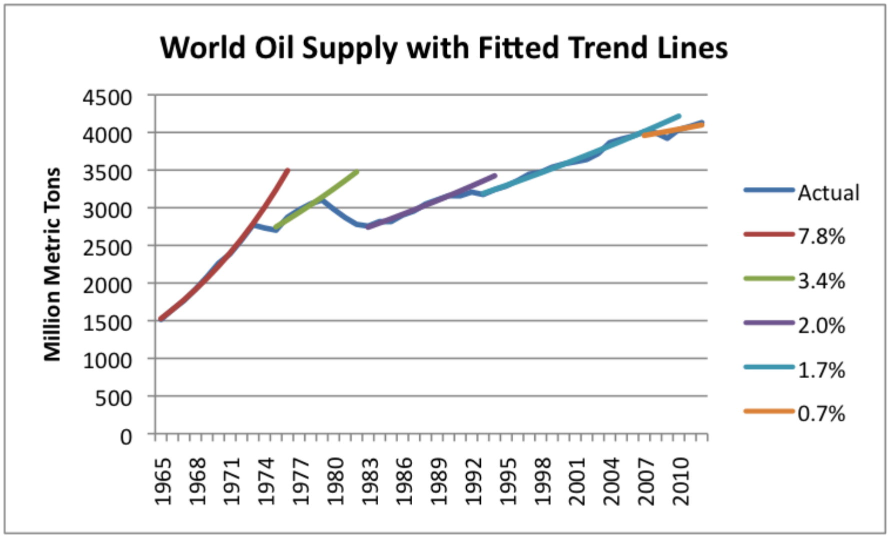

Fig. 1.5 Slowing growth in world oil supply. `http://ourfiniteworld.com/2013/10/02/our-oil-problems-are-not-over/` **** Becky–can you obtain this data and plot it similarly? ****

of crude to the refinery, refinement of crude to useable petroleum products, and transportation of refined products to consumers and firms. In addition, it takes energy to manufacture the wells, pumps, tankers, pipelines, and refineries used in oil production and distribution. Furthermore, it takes energy to use energy. The economy uses energy to manufacture the machines (vehicles, mostly) that consume refined oil products.

Application of the Best First Principle to the energy production process indicates that it will take more energy to make energy available to society as natural energy resources are depleted. The metric that measures the energy impacts of the Best First Principle is Energy Return on Investment ($EROI_{soc}$), the ratio of energy provided to society by the energy consumed in making it available.[10] As energy resources in the biosphere are depleted, the Best First Principle entails that $EROI_{soc}$ will decline. Indeed it has. Turning again to our oil example, $EROI_{soc}$ for oil has declined from a value of 100 in the 1930s [18, p. 781] to around 20 today.[19, Fig. 2] In other words, it takes 5 times more energy today than it did in 1930 to make a barrel of oil available to society.

[10] Energy return on investment ($EROI_{soc}$) at the societal level is defined as

$$EROI_{soc} \equiv \frac{\dot{E}_a}{\dot{E}_c}\,, \tag{1.2}$$

where $\dot{E}_a$ is the rate of energy made available to society in MJ/year and $\dot{E}_c$ is the rate of energy consumed in the energy production process in MJ/year.

Furthermore, declining $EROI_{soc}$ for oil has economic impacts. Both Heun and de Wit [20] and King and Hall [21] show that declining $EROI_{soc}$ correlates with higher prices for oil, because declining $EROI_{soc}$ provides upward pressure on production costs, and therefore, prices as time proceeds.

All other things being equal, the Best First Principle indicates that the additional physical "effort" required to extract increasingly-marginal resources will lead to decreased extraction rates. In the race against the Best First Principle, technological advances can bring about higher extraction rates, despite the additional physical "effort" required. Ricardo applied this principle to the theory of land rents. As the population increases, the demand for food increases as well. Because arable land is not reproducible, less prodcutive land will have to be put into food production. This leads to increasing profits accruing to theowners of the best land.

For example, the recent shale oil boom, made possible by new extraction technology, has increased US oil production significantly. But, Figure 1.6 shows that increased US production is due to so-called "tight" oil (which includes shale oil), that has lower $EROI_{soc}$ than crude oil. Furthermore, today's "tight" oil is more expensive to produce than the crude of yesteryear. Consequently, oil prices must remain high for shale oil production to remain financially feasible into the foreseeable future. Unfortunately, Section 1.4.1 indicates that high energy prices can lead to high energy cost share in the economy and recessionary pressures.

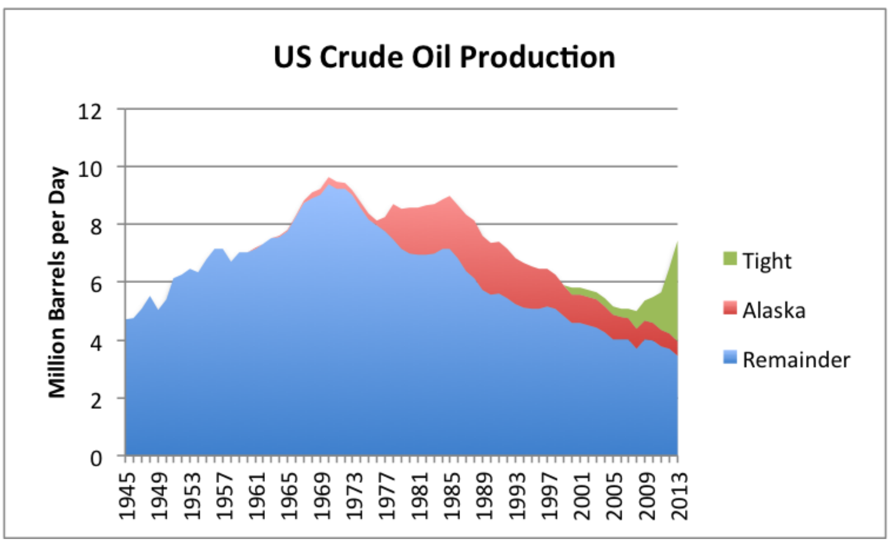

Fig. 1.6 US oil production. `http://ourfiniteworld.com/2014/07/23/world-oil-production-at-3312014-where-are-we-headed/` **** Becky–can you obtain this data and plot it similarly? ****

The fact that shortages of crude oil provide incentives for technological advancements that bring new production online (e.g., shale oil) appears, at first glace, to be a good thing. However, energy substitutions are beneficial to society in the long run only when the $EROI_{soc}$ of the substitute is equal to or higher than the original. Thus, the benefits of shale oil are modest, at best, when the high financial and energy costs of production are considered.

That said, a transition to new sources of energy will be a feature of the economy in the age of resource depletion. But, there is evidence of limits to energy substitution at the macroeconomic level. Pelli, in a study of 21 countries found that clean[11] and dirty[12] inputs to electricity production are complementary (as opposed to substitutable).[22] His conclusion is dire:

> On the one hand, according to the model, if we keep producing electricity using dirty inputs, we head toward an environmental disaster. On the other hand, looking at the empirical results, it seems impossible to stop producing electricity with polluting resources. The policy implication of this paper thus, seems to be that we need more important subsidies to research, as fast as possible, and high carbon taxes combined with a complete halt of the growth rate of the production of electricity. In this way, according to the model, we may be able to avoid an environmental disaster.[22, p. 25]

In a meta-analysis of 15 papers that studied the economic evidence for macro-substitutability among factors of production (materials, capital, labor, and energy), de Wit et. al. [23] found that the elasticity of substitution was below unity for all combinations of factors of production. Furthermore, they argue that,

> [because all of the] results show elasticity of substitution below unity, none of the factor inputs are perfectly substitutable and all tend toward complementarity in varying degrees. Such results suggest that transitions from one production or consumption structure to another can be disruptive and that the transitions need to be modeled dynamically to the extent possible.[23, p. 8]

The challenges of energy substitutions are highlighted when examining the financial situation of oil producers. Figure 1.7 shows that despite the recent increase in oil production and continued high prices, the free cash flow of independent oil producers is negative. It remains to be seen how independent producers can continue advancing production without free cash flow to cover capital expenditures. One possible cure is higher oil prices. But, again, we saw in Section 1.4.1 that high energy cost share provides recessionary pressure.

All of this comes about simply because it is more physically "difficult," and, as a consequence, more financially expensive to extract oil today than it was 10, 20, 30, and 100 years ago. It is more difficult to obtain oil today because we have depleted the stocks of easy-to-obtain crude oil from the biosphere. And, the remaining stocks are either lower quality (e.g., shale) or further away (e.g., deeper offshore).

Without going into detail, we state without discussion that similar dynamics will apply to any non-renewable material or energy stock in the biosphere for which substitution is difficult. Using oil as our example, we observe that stocks of natural capital, especially energy resources, have significant economic implications. Both the

[11] Nuclear, conventional hydroelectric power, wood and waste biomass, geothermal, solar/photovoltaic, and wind

[12] Coal, petroleum, natural gas, and other gasses

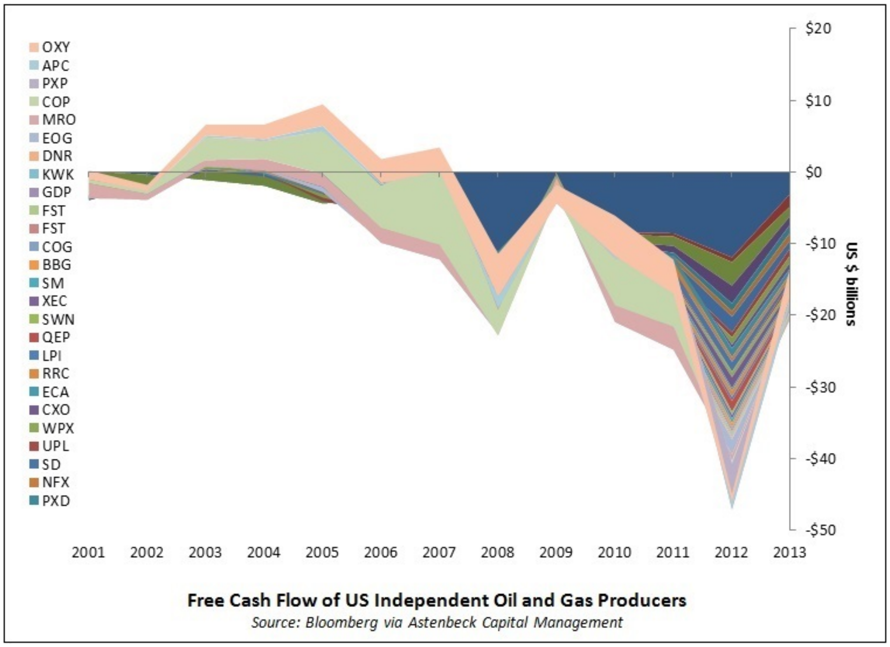

Fig. 1.7 Oil company free cash flow. `http://blogs.platts.com/2014/07/30/peak-oil-forecasts/` **** Becky–can you obtain this data and plot it similarly? ****

declining *quantity* and the diminishing *quality* of remaining non-renewable biosphere stocks are contributing to the slowdown of growth in mature economies discussed in Section 1.1.

Stocks of another sort also play a role in the slowdown of growth experienced by mature economies, because they are important drivers of material and energy consumption. In the next section, we turn our attention away from the biosphere toward the economy and its stock of capital.

1.4.3 Stall is related to capital stock

Capital is extremely valuable and, in most cases, essential to production processes: machines reduce per-unit costs of production; buildings provide space to work and protection for capital; roads provide networks for vehicular transport of raw materials, finished goods, and capital itself; and computers enhance the efficiency of workers and enable technological breakththroughs. There are several types of capital flows to and from its stock in the economy. We use the term "emplacement" to denote a flow of capital into the economy, for example when a new machine is put into service, when a new building is constructed, or when a new road is opened. "Depreciation" is normal wear-and-tear experienced by capital, a type of outflow of capital from the economy. Financial depreciation involves the write-off of a percentage of the value of capital. Physical depreciation involves wear and tear of parts within or sections of the capital. Financial depreciation usually occurs faster than physical depreciation. "Maintenance" is servicing of capital to overcome the effects of physical depreciation. "Disposal" is the physical outflow of capital from the economy to the biosphere upon removal from service. Capital "formation" is the rate of net addition to capital stock in the economy, the difference between inflows and outflows during a time interval. Traditionally, stocks and flows of capital are measured by currency units, $ and $/year, respectively. However, we argue later (Section 8.2) that a physical basis for capital accounting is also warranted.

It is important to note that it takes materials and energy to manufacture and emplace capital at its point of use. Furthermore, once emplaced, capital consumes energy to process raw materials into intermediate and finished products and for its maintenance. The energy required to manufacture and emplace capital (including all upstream processes) is called *embodied* energy. In addition to capital, energy is embodied in all manufactured materials and products.[13] The ratio of energy embodied in products to their price is the energy *intensity* of output (ε, in units of J/$).[14] Both embodied energy and energy intensity are key metrics for understanding the economy. To first order, energy embodied in capital provides an estimate of the energy needed for replacement. The distribution of energy intensity across products and sectors provides a picture of energy demands caused by consumption.

Most capital (especially machines) is considerably more expensive than the individual products it makes. So, it takes significant financial resources (relative to sales) to purchase and emplace capital. Capital is so beneficial (i.e., productive in the economic sense), that firms pursue and obtain debt financing to cover large capital expenses. In the case of public goods like roads, bridges, and utilities, governments pursue debt financing via municipal bonds. The long-term financial obligations associated with capital financing mean that the capital is expected to be in service for at least the repayment period of the debt, usually much longer.

The long-term commitment to capital and production means that emplacement of capital is a bond, a claim on future raw material and energy *consumption*. And, it is an assurance of raw material and energy *extraction* from the biosphere for many years to come. Furthermore, extant productive capital stock can't be fed just any material or energy; capital is designed to work with only certain types of materials and energy. An auto body panel stamping machine is designed to form steel, perhaps even a specific grade or alloy of steel; feeding plastic won't do. The machine likely runs on electricity; feeding gasoline won't do.

Thus, the stock of capital in the economy is an important driver of not only the rate but also the type of material and energy flows from the biosphere. The emplacement of productive capital "locks in" demand for specific types of materials and energy into the forseeable future. As such, long-term commitments associated with emplaced capital provide limits to the rate at which society can effect transitions to different

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[13] See Chapter 5 for more details on embodied energy.

[14] See Chapter 7 for more details on energy intensity.

raw materials and energy sources. Again, we observe tight coupling between the economy and the biosphere!

Given the discussion in Section 1.4.2 regarding the economic dynamics of biophysical limits to raw material and energy extraction, we see that expansion of an economy's capital stock may increase GDP in the short run, but it also "locks in" future material and energy demands from the biosphere. These "locked in" demands bring the economy closer to the biophysical extraction limits that will eventually lead to economic slowdown.

Paradoxically, and contrasting with mainstream policy prescriptions, expansion of the stock of capital in the economy can contribute to the slowdown of economic growth.

1.5 Consumption-driven solutions are unsustainable

Biophysical limits to economic growth are becoming a binding constraint, thus increases in manufactured capital stock can ultimately lead to economic slow down. The cost benefit analysis related to capital stock investment decisions not only includes the opportunity cost of the next best alternative investment in manufactured capital, but also the net present value of all future demands on natural capital. Those costs need to be considered as part of the analysis at the firm, industry, and economy levels.

In Section 1.4.3 above, we noted that existing policy designed to combat economic slowdown in mature economies is focused on increasing many material, energy, and financial flow rates in the economy. Set against the backdrop of Section 1.4, we see that consumption-driven policies are ineffective, because of biophysical limits that constrain the scale of the economy. Unfortunately, biophysical limits are not included in the mainstream economic thinking and modeling that informs policy decisions.[15]

Three factors, in combination, are vitally important but nearly-always ignored: (1) the economy is tightly coupled to the biosphere, (2) there are physical and technological limits to the rate at which materials and energy can be extracted from the biosphere, and (3) today's emplacement of capital locks in tomorrow's material and energy demands for both operation and maintenance of that capital.

In short, the economic analyses that support consumption-driven policies are incomplete. Consumption-driven economic growth is unsustainable.

Stimulating the economy via consumption-enhancing policies through investments in capital stock can increase economic throughput (GDP) for a time. Unfortunately, such policies also hasten the day when we reach binding biophysical constraints due to resource depletion. Adoption of these policies when society is already encountering resource depletion constraints will result in see-saw economic performance. In fact,

[15] More on the problematic nature of this issue can be found in Section 2.3.

we may have already entered a regime of boom-bust economic dynamics, because of a binding constraint for oil extraction rate as discussed in Section 1.4. In the face of see-saw dynamics, it is difficult to make wise long-term investment or policy decisions, because you're perpetually recovering from the most-recent bust.

In the age of resource depletion, we need to move beyond GDP. These dynamics should cause us to measure and report the material and energy demands that products and capital stock make upon the biosphere. We should know these factors in *physical* as well as financial terms, for constraints of the physical world lead to problems in the economy. These data should be available routinely from a centralized location.

This is the end of an era. In mature economies, consumption-enhancing economic policies can no longer guarantee growth of living standards and well-being. But, the mainstream is blind to what should be done instead. This has to change!

1.6 Change is needed!

The fact that we (as a society) do not include exogenous, biophysical factors in economic decision-making indicates that we do not fully understand how the real economy operates. Society is ignorant of the role that natural and manufactured[16] capital together play in both sustaining today's economy and constraining future economic prospects and choices. At present, markets are virtually the only tool at our disposal to help us understand the characteristics of the real economy. What benefits do markets provide? Markets are extremely efficient allocators of resources. Mainstream economic theory holds that prices are the mechanism by which signals of value are communicated to sellers and buyers: sellers receive information about how goods are valued by consumers, and buyers receive information about the cost of materials accrued by producers.

In the age of resource depletion, are price signals sufficient to indicate shortages, especially of important and difficult-to-substitute resources? It appears that some signals are getting through. Heun and de Wit showed that scarcity (as indicated by low $EROI_{soc}$) correlates with higher oil prices.[20] And, higher prices spur efficiency improvements. **** reference here about higher average fuel economy of autos in the US. ****

However, the market's price mechanism may not be enough. We showed in Section 1.4.1 that the physical importance of scarce and difficult-to-substitute resources (e.g., oil) far exceeds cost share in the economy, suggesting that prices alone cannot provide comprehensive signals of importance to producers and consumers. Consequently, producers and consumers participate in the market with incomplete information. Furthermore, a good must be owned before it can be sold. Thus, prices cannot be set and market value cannot be determined for goods that are not considered "property," such as clean water, clean air, and other "ecosystem services." In addition, today's markets are simply incapable of deciding important issues such as

[16] Manufactured capital presupposes the existance of significant levels of human and social capital.

the optimal scale (size) of the economy relative to the biosphere. (See Section 2.4.4.) Because the allocative efficiency of markets is predicated upon correct and complete information being available to market participants, today's markets are a poor choice for allocative decisions about scarce and difficult-to-substitute resources (such as oil) or non-property goods (such as clean air, clean water, and other ecosystem services).

In the age of resource depletion, the allocative efficiency of markets is attractive. Indeed, life would be better if the markets could shift supply and demand away from binding biophysical constraints when they are encountered. But, lack of information in *today's* markets leads us to argue that they are not up to the task.

What additional information would be helpful? We contend that detailed information about energy, embodied energy, and energy intensity would be a good place to start. We, as a society, routinely account and publish energy flow rates only.[17] We do not, however, routinely update energy *intensity*[18] estimates (ε) and, therefore, we have little idea of where energy is embodied in our capital stock and in the products we consume. Furthermore, when energy intensity (ε) of products is estimated, it does not account for the energy embodied in our stock of capital and is therefore in error.[19]

We suggest that all of this information (economic, material, and energy indicators) should be collated by a single agency and reported from a single location. Doing so will provide convenience and consistency and indicate the interconnectness of the economy and the biosphere to policymakers and researchers.

Until these crucial pieces of information are routinely available in a centralized location, society will be unable to properly frame and conceptualize the "problem" of "stalling" growth. Until this information is available to markets, investment, consumption, and policy decisions will not lead to socially optimal outcomes.

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[18] Estimates of energy intensity are not included in systems of national accounts. And, such work is rarely undertaken by academics.[24, 25]

[19] See Section 8.2 for our suggested remedy.

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