Chapter 2
Decoupling

If it is very easy to substitute other factors for natural resources, then there is in principle no "problem". The world can, in effect, get along without natural resources.

– Robert Solow (1974, p. 11)

Robert Solow's above statement was part of a wider response from neoclassical economists to the release of Donella and Dennis Meadow's *The Limits to Growth* (1972). According to simulations created by Meadows and colleagues, indefinite future growth was unlikely, if not impossible. Rather, their model showed robust tendencies toward inevitable collapse (from both resource depletion and pollution accumulation). The *Limits* report, coupled with the onset of the 1973 oil crisis, led to heightened concern over resource depletion. Neoclassical economists, in turn, responded by insisting that input substitution, along with continued technological progress, would ensure that growth could continue indefinitely.

This indefinite growth argument rests on the assumption that economic output can become *decoupled* from resource inputs. Over the 40 years since the *Limits* debate began, resource decoupling has become a major policy objective of many governments and international agencies. For instance, the European Union insists that "breaking the linkages between economic growth and resource use" should be a key policy objective (CEC 2002). The Organisation for Economic Co-operation and Development (OECD) has placed similar emphasis on decoupling, stating that decoupling indicators are "valuable tools for determining whether countries are on track towards sustainable development" (2003, p. 13).

This chapter investigates the empirical evidence for decoupling. While the trends in the energy intensity of US real gross domestic product (GDP) seem to support the neoclassical decoupling assumption, further investigation reveals that this issue is mired by fundamental epistemological difficulties. I argue that both the evidence *for* and the concept *of* decoupling are *artifacts*. I attempt to demonstrate that the evidence for decoupling is a methodological *artifact* that results from the use of monetary value to measure the quantity of output. Furthermore, I argue that the very notion of "economic output"—and hence the notion of "decoupling"—is a conceptual artifact that results from the misapplication of linear thinking onto a complex, nonlinear system. I offer the alternative hypothesis that monetary value,

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rather than representing the quantity of output, functions as a *feedback* mechanism that controls the flow of energy through the economy. I provide evidence that supports this hypothesis, and discuss the implications of this paradigm shift for a biophysical growth theory.

2.1 Natural Resources in Neoclassical Growth Theory

David Stern observes that "there is an inbuilt bias in mainstream production and growth theory to down-play the role of resources in the economy" (2004, p. 38). The reader may have noticed, from Chap. 1, that natural resources are completely absent from the Solow–Swan model, including its production function. Herman Daly (as previously stated) notes that "since the production function is often explained as a technical recipe, we might say that Solow's recipe calls for making a cake with only the cook and his kitchen" (1997, p, 261). Joseph Stiglitz (1974) rectifies this shortcoming by introducing a modified production function with natural resources R:

$$Y = AL^{\beta}K^{\alpha}R^{\lambda} \tag{2.1}$$

Before proceeding to the implications of this modified production function, it is worth discussing why, in practice, it is almost never used. Neoclassical growth theory is embedded in a larger neoclassical framework in which factor incomes are assumed to be proportional to each factor's marginal productivity. The result is that the exponents in the production function represent both a factor's share of national income and its *relative importance to overall production*.

This condition automatically discounts the importance of natural resources, since the income of natural resource owners (λ) represents an exceedingly small portion of total income. For instance, the value of total primary fossil fuel consumption constituted an average of only 3 % of US GDP over the last 60 years, meaning that when adding energy to a neoclassical production function, the energy input must be raised to the exponent 0.03, rendering it almost inconsequential.[1] Thus, maintaining compatibility with neoclassical distribution theory guarantees that resources will remain theoretically unimportant in neoclassical growth theory.

For the moment, however, we leave this difficulty behind and focus on Stiglitz's modified production function (Eq. 2.1). This model presents two possible methods for decoupling output (Y) from resource input (R): either labor (L) and capital (K) inputs may be substituted for natural resources, or technological progress (A) may shift the entire production function, allowing more output per unit of input. Since there are no inherent limits (in neoclassical theory) to either substitution or

[1] Value of fossil fuel production from Enersy Information Administratio (EIA), Annual Energy Review, Table 3.2. Value of fossil fuel imports from ibid, Table 3.7. Nominal GDP from BEA Table 1.1.5.

technological progress, there are no inherent limits to resource decoupling. This constitutes the following implicit assumption:

Decoupling Assumption:
The quantity of economic output can become decoupled from energy inputs.

2.2 Measuring Decoupling

In order to test the decoupling assumption, we must first calculate output Y. Recall that output, in the Solow–Swan model, is conceived as a *single* commodity. In the real world, many different commodities are produced, meaning some sort of aggregation is necessary. This requires that we add together the quantity (Q) of all the commodities that are produced. Using summation notation, this becomes:

$$Y = Q_1 + Q_2 + Q_3 + ... = \sum Q_i \tag{2.2}$$

However, this sum is meaningless without some common unit of measure. Economists typically choose unit-price (P) for such measurement purposes. Thus, the quantity of production is now measured in terms of total value (Y_n), which is calculated using the quantity-price product of each individual commodity and summed across the spectrum of all commodities:

$$Y_n = Q_1 P_1 + Q_2 P_2 + ... = \sum Q_i \times P_i \tag{2.3}$$

Equation 2.3 is the formula for nominal GDP. A problem, however, is that a change in output can arise from both a change in quantity Q or a change in unit-price P. Since we are only interested in the former, we must adjust for *pure price change* (i.e., inflation) by dividing nominal GDP by some index of the average price of all commodities ($\bar{P}$). This gives us Eq. 2.4—the general formula for real GDP:

$$Y_r = \frac{1}{\bar{P}} \sum Q_i \times P_i \tag{2.4}$$

Real GDP has come to be *the* output metric used by economists. Decoupling, which is defined as an increase in output per unit of natural resource input, is typically measured in terms of the ratio of resource input R, to real GDP output Y_r:

$$\text{Resource Intensity of GDP} = \frac{R}{Y_r} \tag{2.5}$$

Since we are only concerned with energy decoupling, we replace the generalized resource term R with the more specific primary energy consumption term E, giving us the primary energy intensity of GDP:

$$\text{Primary Energy Intensity of GDP} = \frac{E}{Y_r} \tag{2.6}$$

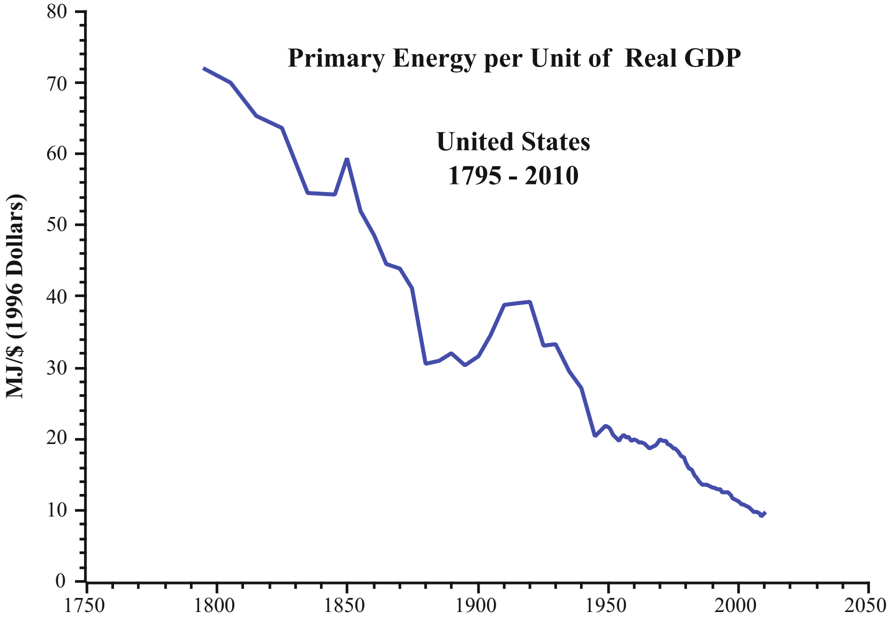

Fig. 2.1 Primary energy intensity of gross domestic product (GDP). (Sources:Primary energy consumption data from EIA Annual Energy Review 2011, Table 1.3 (1949–2011) & Table E1 (1795–1945). Real GDP data from HSUS Table Ca9 (1795–2000) & BEA Table 1.1.6 (2001–2010))

Figure 2.1 shows how this metric has changed over the last two centuries of the US history. While data prior to 1900 should be regarded as a rough estimate, there is clearly a long-term downward trend. It would seem, then, that decoupling is a very reasonable assumption, and we have no reason to suspect that it will not continue into the indefinite future.

Typical investigations of decoupling go no further than this; however, there are a few complicating factors that should be investigated. The first concerns how (or "where") we measure energy consumption. Figure 2.2 shows an example of this issue by tracing the path of energy used by a car. Energy enters the system as a primary energy resource (crude oil). This is then transformed into gasoline, then thermal energy in the car engine, and then finally the kinetic energy of the car. At each stage of the process, energy is wasted, meaning very little of the primary energy is transformed into useful work.

We can relate primary energy inputs (E) to useful work output (U) by means of the efficiency (η) of the energy conversion process:

$$U = \eta E \tag{2.7}$$

A major difficulty arises when we move from a single process to the economy as a whole. How do we account for the efficiency of the myriad of different conversion processes that occur? Giampietro et al. (2013) argue that measuring useful work at the

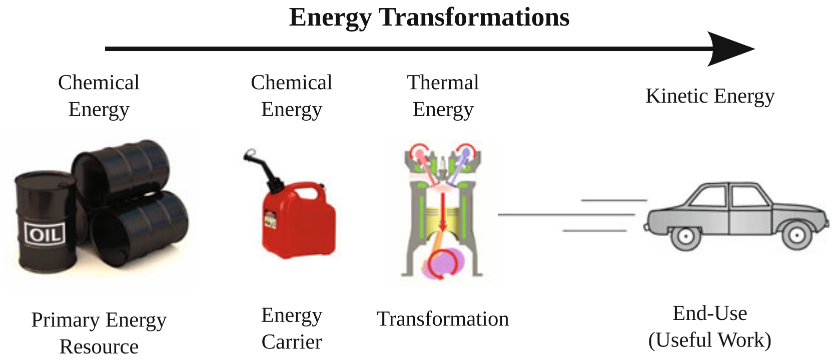

Fig. 2.2 "Where" to measure energy?

level of the entire economy is impossible. Ayres and Warr (2009), on the other hand, argue that useful work can be estimated by means of a conceptual simplification. Ayres and Warr group end-use energy into the following five categories: electricity, heat (low, mid, high), mechanical drive, light, and muscle work. They then calculate the average efficiency of the processes within each category, and then aggregate the results to get an estimate for the useful work done by the entire economy.

Using Ayres and Warr's data, we can conceive of an alternative decoupling index which now uses useful work (U) instead of primary energy:

$$\text{Useful Work Intensity of GDP} = \frac{U}{Y_r} \tag{2.8}$$

The time-series for the useful work intensity of real GDP (Fig. 2.3) looks nothing like the primary energy time-series (Fig. 2.1). While there is significant change in the useful work intensity of GDP, there is little evidence of long-term decoupling. This important result indicates that the majority of historical *primary* energy decoupling has been the result of efficiency increases in energy conversion processes.

This increase in efficiency is what neoclassical economists would call *embodied* technological progress, as opposed to the *disembodied* form (A) used in the Solow–Swan model (Sakellaris and Wilson 2004). Most importantly, this embodied form of technological progress has *inherent limits* stipulated by the laws of thermodynamics. While 100 % efficiency is the ultimate limit (forbidden by the second law of thermodynamics), the maximum theoretical efficiency for many energy conversion processes (such as heat engines) is much less. For instance the Carnot Limit for the internal combustion engine is a mere 37 %, with current car engines having efficiencies of about 20 % (Chandler 2010). Thus, a future doubling of engine efficiency is out of the question. It appears that primary energy decoupling has mainly been the result of increases in energy conversion efficiency. Since there are strict limits on the efficiency of such conversion (for example, coal conversion to electricity appears to be nearly unchanged at 40 % for decades), we must concede that decoupling cannot continue indefinitely.

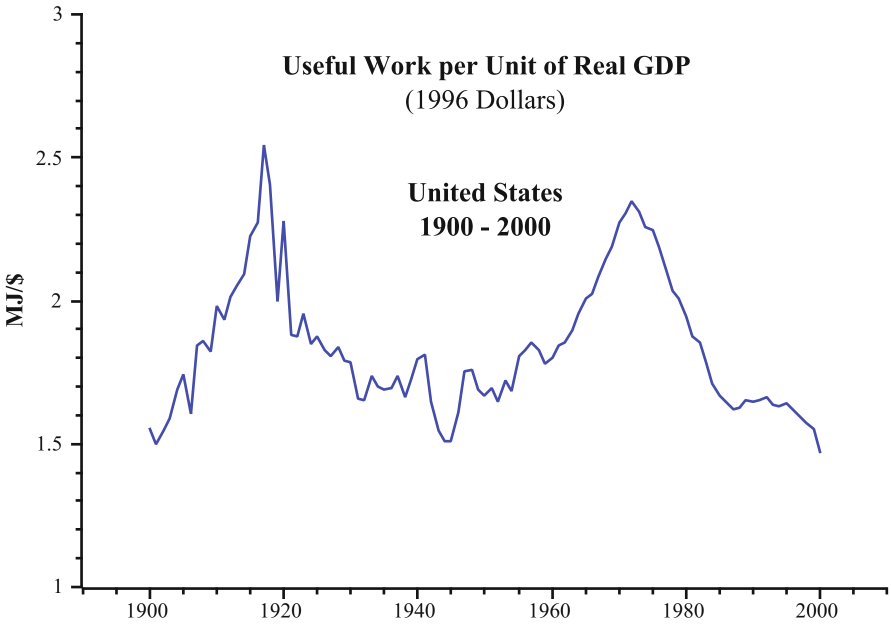

Fig. 2.3 Useful work intensity of GDP. (Sources: Useful work data from Benjamin Warr REXS Database. Real GDP data from HSUS Table Ca9)

2.3 Problems with Real GDP

Before we continue with the investigation of decoupling, it is important to discuss some of the difficulties with using monetary value to estimate an index of output. There are three basic problems:

1. Changes in relative prices mean that the basic unit of measure (price) is not well defined.
2. Measures of quality change contain inherently subjective elements. Moreover, current quality change methodology may be circularly dependent on neoclassical theory.
3. In an economy dominated by services, it is not clear that an "output" can be objectively defined.

We begin with the problem of changes in relative price. The transmutation from the *value* of output (nominal GDP) to the *quantity* of output (real GDP) relies on the existence of an index capable of accurately and *objectively* quantifying the average change in prices. But unless price changes are completely homogeneous, the actual calculation of such an index is intrinsically subjective.

One might think that an average price is unambiguous. One simply adds the prices of all commodities together and divides by the number of commodities. But this is an *unweighted* average. If we were to compute the average price this way, we effectively

Table 2.1 Output using explicit average price

Year	Quantity A	Quantity B	Price A ($)	Price B ($)	Price index	Output ($)
1	100	500	20	10	1.0	7000
2	200	500	40	20	2.0	9000
3	200	500	80	40	4.0	9000
4	200	500	160	20	3.7	11,308

state that the change in price of a single unique commodity (i.e., a rare piece of art) is as important as the same change in price of a *billion* uniform commodities (i.e., pencils). What we want is a weighted average that reflects the fact that some prices are more important than others. But herein lies the crux: there are numerous ways that such an average might be weighted.

In order to demonstrate this issue, we must return to the theoretical underpinnings of real GDP. Equation 2.4 showed (in abstract form) the methodology used to calculate real GDP. To make things more concrete, let us apply this formula to a simple economy with two commodities (A & B). Real output (Y_r) becomes the quantity-price product of these two commodities, divided by an index of their average price:

$$Y_r = \frac{Q_A P_A + Q_B P_B}{\bar{P}} \tag{2.9}$$

Table 2.1 shows sample calculations for output (Y_r), using imagined numbers. Here we use an *explicit* average price, calculated by weighting the price of a commodity by its respective quantity in the first year. Notice that we have a change in the quantity of commodity A only between year 1 and 2. During all other years, the quantity of each commodity remains unchanged. Additionally, price change is homogeneous for the first three years: all prices double annually. However, in year 4 we introduce a divergent price change: the price of A doubles while the price of B is halved. The result of this divergent price change is an *increase* in the measure of output without *any* underlying change in the quantities of either commodity.

Alternatively, we can calculate the average price *implicitly* (which is how it is most often calculated). To do this, we first calculate the nominal value of output, and then divide this by the value of output with constant prices. But, in order to do this, we must choose a base year from which to hold prices constant. For instance, the formula for the average price with a year 1 base would be:

$$\bar{P}_{yr_1} = \frac{Q_A P_A + Q_B P_B}{Q_A(\$20) + Q_B(\$10)} \tag{2.10}$$

The decision about which base year to use is completely subjective, yet it is nontrivial. It can have major effects on our measure of output. For instance, the results for both a year 1 base (Yr_1) and a year 4 base (Yr_4) are shown in Table 2.2. While the erroneous output change between year 3 and year 4 has been corrected, we now have a time-series *discrepancy* associated with the use of different base years. There are no objective grounds for deciding which series is correct. Our measure of output is simply ambiguous.

Table 2.2 Output using implicit average price

Year	**Nominal value** ($)	**Price index** (Yr_1)	**Price index** (Yr_4)	**Output** (Yr_1) ($)	**Output**(Yr_4) ($)
1	7000	1.0	1.0	7000	7000
2	18,000	2.0	1.6	9000	11, 340
3	36,000	4.0	3.2	9000	11, 340
4	42,000	4.7	3.7	9000	11, 340

As demonstrated by these examples, an average price (and any measure of output derived from it) is uniquely defined *only* when price change is *homogeneous*. In the case where the relative price change between commodities is *heterogeneous*, any calculation of the average price will be but one of many that are possible. Additionally, the degree to which such calculations may diverge is a function of the degree to which relative prices diverge.

The way to understand this phenomenon is to realize that prices constitute our basic *unit* of measurement. By definition, the most important attribute of a unit is its *uniformity*. When prices change uniformly over time there is no problem—we simply dilate (or compress) our unit accordingly. However, if price change is *not* uniform for all commodities, we have a fundamental problem: our unit is *no longer well-defined*. In principle, there is no way to escape this dilemma. Without a well-defined unit, objective measurement is impossible. In such a case, many different values of real GDP can be defined, each backed by a different method of calculating the average price. At most, one can subjectively argue for the value of real GDP that is "best". However, this subjectivity means that we are no longer measuring what output *is*, but rather, what we think it *should be*.

Thus, it is important to investigate price change in the real world. If price change is relatively homogeneous, the preceding theoretical hurdle can be dismissed as unimportant. On the other hand, if price change is *divergent*, then we must seriously question the objectivity of real GDP. Figure 2.4 shows historical US price changes for a select group of consumer price index (CPI) commodities. Although this is by no means a representative sample, it does serve to illustrate the enormous degree to which actual prices have diverged over the twentieth century.

To give a sense of the scale of this divergence and to quantify the ambiguity in our unit, we can calculate the relative standard deviation of these prices.[2] Initially zero in 1935 (the base year), by 2010, the relative standard deviation in the prices of these ten commodities was 91 %. This indicates that over the course of 75 years, the normal *divergence* from the average price was almost as large as the average itself.

It is important to remember that this is not a measurement *error*—the result of the imprecision of a measuring device. In order to state such an error, one must have a stable unit. For instance, we can state that a thermometer measures the temperature as 20.2 °C with a measurement error of ±0.5 °C. But notice that the error estimate

[2] Relative standard deviation is defined as the standard deviation divided by the data mean and multiplied by 100 %.

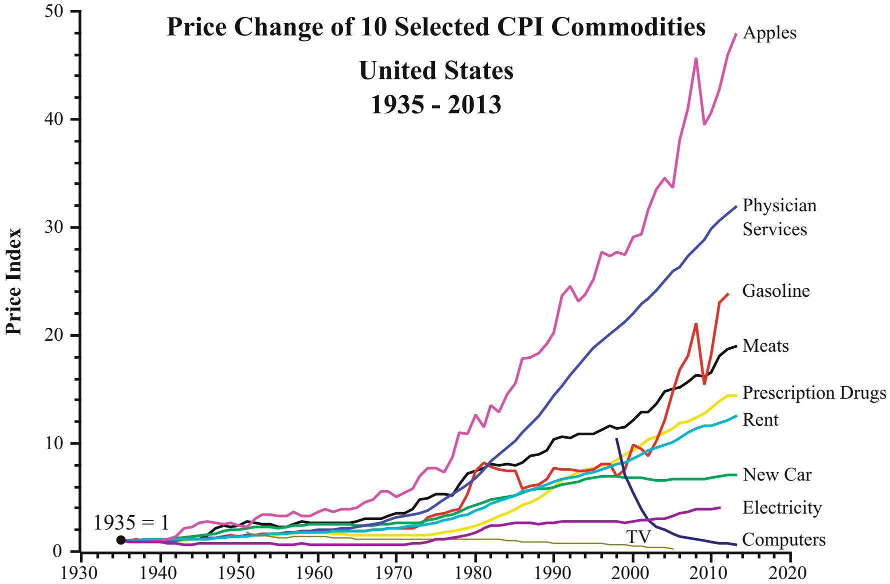

Fig. 2.4 Diverging prices. (Source: BLS Consumer Price Index, all urban consumers. Commodities added after 1935 are indexed to the unweighted average price for the year in which they are introduced)

is expressed in the same units as the measurement itself. Thus, to even *state* this error requires that we agree on the definition of our basic unit (the degree Celsius is precisely defined as 1/100th of the temperature range between the freezing and boiling point of water at sea level). Unlike measurement error, what Figure 2.4 shows is a *fundamental* and *irreducible* uncertainty in our *basic unit*.

This can be put in perspective by comparing the problem to units of length. Historically, people measured small lengths in units of body parts (i.e., actual "feet" and "hands"). Imagine a similar unit called the "man", defined simply as the height of the man doing the measuring. This unit is not very well defined, since height varies considerably among men. However, in contrast to the 90 % deviation in relative prices calculated above, the relative standard deviation in the height of adult males is only about 4 % (Smith et al. 2000). This indicates that, as inaccurate as a unit of length called a "man" would be, it is still *20 times more accurate* than the unit on which real GDP is based. One is tempted to imagine how many bridges would remain standing if engineers based their calculations on such a poorly defined unit.

Since the choice of base year effectively "defines" the unit of measure, rebasing (changing the base year) can lead to spectacular changes in real GDP. For instance, Nigeria recently changed from a 1990 to a 2010 base year. The result was that its GDP nearly doubled (Blas and Wallis 2014). A similar doubling of Ghana's GDP occurred in 2010 when it changed its base year from 1993 to 2006. Base year revisions in Botswana, Kenya, Tanzania, and Zambia have also led to large changes in GDP (Jerven 2012; 2014).

In response to this difficulty, the US Bureau of Economic Analysis (BEA) has changed how it calculates real GDP. It has moved from the base year method to a "chain-weighted" approach that uses an average of multiple, moving base years (Steindel 1995). The hope is that this will "correct" the errors introduced by divergent prices. My contention, however, is that this misses the point. From an epistemological standpoint, the validity of a unit of measurement hinges on it being well-defined over time and space. Since prices (our basic unit) change in nonuniform ways, they fail this basic condition. The chain-weighting approach attempts to "solve" a problem that is unsolvable.

The BEA makes the claim that a chain-weighted average price is "better" than a non-chain-weighted one. However, such a claim is untestable: because we are dealing with the ambiguity of the basic unit, there are no objective criteria on which to determine what is "better" or "worse". The only objective way to determine if a scientific measurement is "better" is if it is more accurate (i.e., has smaller error). But as discussed above, to determine such an error paradoxically requires a well-defined unit of measurement. The basic instability in the unit of price cannot be altered by our methodological choice of how to compute the average price; instead it is an inalterable function of *history*.

A further problem, when moving from neoclassical theory to the real world, is that the former posits a single, *unchanging* commodity. In reality, the *qualities* of a commodity can change immensely with time (think of the difference between a 1980s computer and a modern laptop). In price index methodology, a *quality* change is taken to be the same thing as a *quantity* change. Jonathan Nitzan explains:

> [S]uppose Ford Motors produced 100,000 Mustang cars at a unit price of $ 10,000 in 1975 and manufactured 150,000 units at a price of 14,000 per car in 1985. If we can presume that the Mustang of 1975 was identical to the one produced in 1985, we can, without ever defining what a Mustang is, conclude that there was a 50 percent increase in quantity and a 40 percent rise in price. On the other hand, if we acknowledge that the two models are different, such a direct comparison has little meaning and we must now both define the 'commodity' and describe how it changes over time.
>
> The two Mustang models may vary in aspects of production—such as the technology with which they were manufactured, the labour involved in their assembly, and their material composition. They could also vary in their so-called 'consumption attributes'—such as weight, size, power, shape, speed, comfort, colour, fuel efficiency, noise and chemical pollution. Under such circumstances, we must somehow denominate all such 'quality' differences in universal, quantitative terms and adjust our computations accordingly.
>
> For instance, if because of such changes, a 1985 model contained twice as much 'automobile quality' as the 1975 model, we would have a 200 percent rise in quantity produced and a 30 percent decrease—not increase—in unit price! On the other hand, if quality was found to be 50 percent lower in the 1985 model than in the 1975 one, we would end up with a 180 percent rise in price and a 25 percent reduction in quantity! (1992, p. 156)

Thus, the objective quantification of output hinges on the objective quantification of qualitative change. Note that the scale of such adjustments is not trivial. For instance, Fig. 2.4 shows massive deflation in the price of computers. While actual unit prices have declined slightly over the last 30 years, the majority of this deflation is a result of the Bureau of Labor Statistic (BLS)'s quality change adjustment. The BLS looks at variety of computer attributes (processor speed, hard drive capacity, ram, operating system, etc.) and attempts to measure how these attributes have improved over time. It then combines the changes in each attribute (which involves deciding the relative importance of each attribute) to arrive at an index for the overall change in "quality" of the computer. This "quality" then has an inverse effect on the price index: if the "quality" of a computer doubles, the price index is halved.

While quality adjustment is an essential element in the construction of a price index, there are numerous conceptual difficulties associated with such adjustments (UN 1977, Nitzan 1992). For instance, in order to quantify the changing nature of a commodity, one must first subdivide the commodity into relevant "attributes". But how do we *objectively* decide those attributes that are relevant and those that are irrelevant? Furthermore, once we have reduced a commodity to its constituent attributes, how do we decide their relative importance? The most popular method is called "hedonic quality adjustment". The BLS (2010) summarizes the process as follows:

> In price index methodology, hedonic quality adjustment has come to mean the practice of decomposing an item into its constituent characteristics, obtaining estimates of *the value of the utility* derived from each characteristic, and using those value estimates to adjust prices when the quality of a good changes. (emphasis added)

All quantitative comparisons require a unit of measurement. Here we see that the BLS is attempting to measure the attributes of a commodity in units of *utility*. This is problematic for two reasons. First, utility is a hypothetical psychic flux that cannot be directly measured, making it unsuitable as a basic unit. Because utility cannot be observed, Nitzan (1992) argues that hedonic quality measurements are unfalsifiable. Secondly, utility is a fundamental tenet of neoclassical theory. By locating "quality" in a commodity's ability to give utility, statistical agencies are explicitly adopting a neoclassical theory of value (i.e., that value comes from utility). Nitzan writes: "Both the idea that quality can be measured (objectively or not) and the methods developed for that purpose are closely tied with the neoclassical paradigm. The evidence supporting these conclusions seems overwhelming" (1992, pp. 175–176).

This possible circularity between neoclassical theory and the estimation of real GDP represents a fundamental problem for the empirical researcher. It is a cardinal sin to test a theory using data that is circularly dependent on the theory being tested. As such, if we want to conduct a truly independent test of neoclassical growth theory, we may need to look for alternative metrics. Furthermore, we should not discount the fact that the national accounts are created by and for governments. Since governments are under immense pressure to show that the economy is growing, we should not be so naive as to treat official real GDP estimates as a "disinterested" measurement.

The last problem with real GDP is that while the notion of a "quantity of output" is intuitive when applied to the production of *goods*, it becomes less intuitive (even nonsensical) when applied to certain *services*. For instance, how do we objectively define the output quantity of education, healthcare, the performing arts, or of finance? Imagine an economy that initially consists of only farmers, but gradually changes its composition to consist of only financiers. In dollar terms, the economy will grow, because financiers earn more money than farmers (in economic jargon, they "add

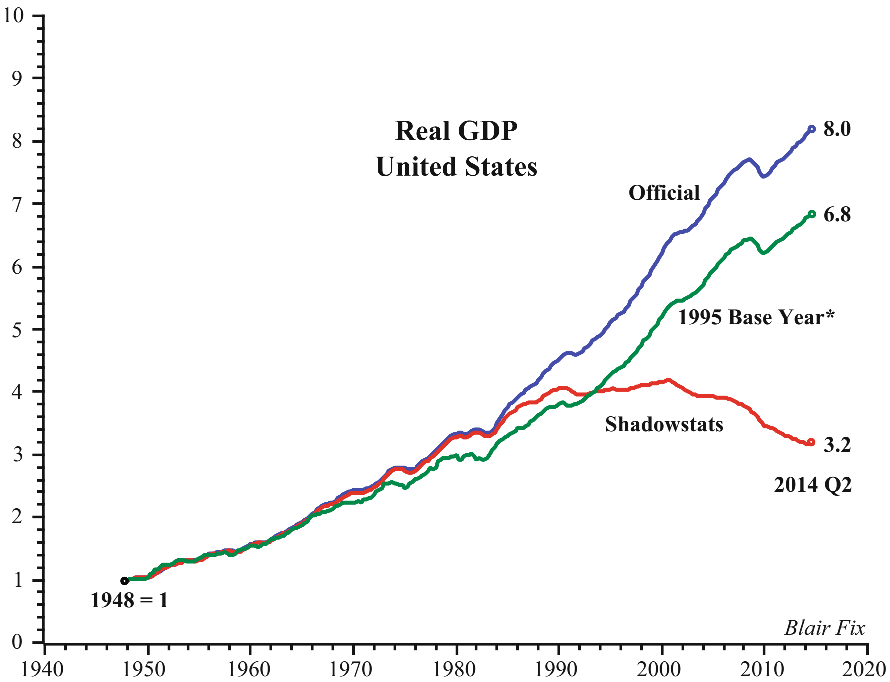

Fig. 2.5 Divergence between official and alternative real GDP estimates. (Source: Official real GDP from BEA Table 1.1.6. "Shadowstats" GDP from John Williams' Shadow Government Statistics (shadowstats.com). 'Vintage' 1995 base year GDP from Federal Reserve Bank of Philadelphia (ROUTPUT95Q1). Note that this data ends in 1995, but I have projected it forward (for comparison purposes) using official growth rates)

more value"). Yet in physical terms, the economy will shrink, because financiers do not produce anything tangible.

The enormous structural shift toward services means that this thought experiment is now playing out in reality: services have been a major source of US GDP growth in the last few decades, yet they have no clear physical dimension. Statisticians avoid the problem of measuring service "output" by simply *defining* the output of such services as equivalent to their market value, and then deflating this value using a price index from another sector that is more amenable to measurement (Sherwood 1994; Griliches 1992). Putting aside all of the measurement problems discussed above, the fact that the majority of people in the USA are now employed in services means that the very notion of a "quantity of output" is becoming increasingly fuzzy. If we cannot objectively define what output *is*, we cannot objectively measure it.

At this point, if one accepts my argument that the estimation of real GDP is inherently subjective, one might still object that the scale of the problem is not that large. Indeed, when stated only in theoretical form, it is difficult to grasp the degree to which different estimates of real GDP might diverge (when different methodological choices are used). This difficulty can be remedied by contrasting official and unofficial estimates of real GDP. Figure 2.5 plots the official real GDP estimate against estimates from John Williams' Shadow Government Statistics website and a "vintage" estimate using a 1995 base year (curiously the year that the BEA abandoned the fixed base year method). The discrepancy between upper and lower estimates is a whopping 250 %. Again, it must be stressed that there are no objective criteria to choose between these three estimates.

The basic theoretical edifice of "decoupling" rests upon both a well-defined resource input, and a well-defined output. My contention, however, is that the lack of a stable unit makes it *impossible* to objectively define a quantity of output. This puts the whole notion of decoupling into a measurement limbo.

2.4 Decoupling: Fact or Artifact?

For the remainder of the chapter, I investigate the hypothesis that the evidence for decoupling is a methodological *artifact* that arises from the use of monetary value to measure output. As demonstrated below, when the price of energy is used to deflate nominal GDP (rather than the GDP deflator), evidence for decoupling almost entirely disappears. I hypothesize that monetary value, rather than represent the quantity of output, functions as a feedback device for controlling the flow of resources. Further investigation suggests that this feedback is not random; rather, it is fundamentally related to the biophysical labor productivity of the mining sector.

To frame this discussion, we return to evidence for the decoupling of real GDP from useful work. However, rather than look at the *ratio* of useful work to real GDP (as we did in Fig. 2.3), we now look at the respective *growth rates* of each series (i.e., we move from absolute units to percentage rate of change). Figure 2.6 plots the historical growth rates of useful work and real GDP over the last century. When plotted this way, evidence for decoupling will appear as a divergence in the growth rates of the two series, with real GDP growing more quickly than useful work. Note that for most of the period shown, the two series are very similar, meaning there is little evidence of decoupling. However, after 1970, useful work and real GDP growth rates diverge significantly, with real GDP continuing to grow at about 3 % per year, while useful work growth slows significantly. What is behind this decoupling? Does it represent some new form of technological progress, some sort of capital substitution, or the take-off of the "knowledge economy"?

Warr and Ayres (2012) attempt to explain this decoupling by looking at the growth of information and communications technology capital. I pursue a different explanation. Instead, I hypothesize that this divergence is an *artifact* of our measure of output, real GDP. In order to test this hypothesis, we must first adopt a different method for deflating nominal GDP. Recall that the transmutation from nominal to real GDP ($Y_n \Rightarrow Y_r$) is accomplished by means of an average price index ($\bar{P}$) that

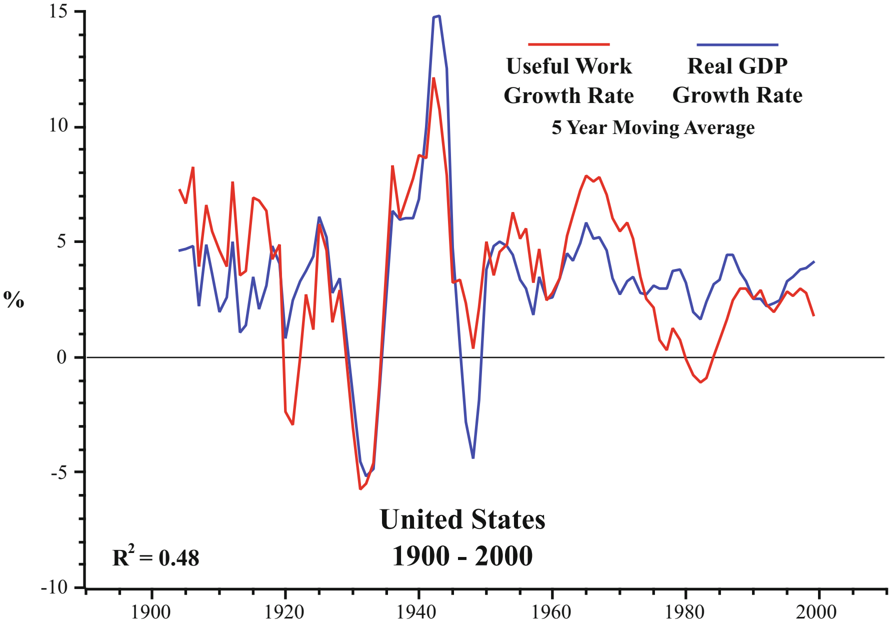

Fig. 2.6 Annual growth rates of real GDP and useful work. (Sources: see Fig. 2.3)

adjusts for inflation:

$$Y_r = \frac{Y_n}{\bar{P}} \tag{2.11}$$

Nearly all of the theoretical difficulties associated with real GDP reside in the construction of the average price index. A simple way around these problems is to avoid the average price concept entirely, and instead deflate nominal GDP by the price of a *single*, *unchanging* commodity. By doing so, however, we are no longer constructing a quantity measure of output; rather, we are constructing what I call a *specific purchasing power* (SPP) index [3]. The specific purchasing power of commodity x is defined as nominal GDP divided by the price of x:

$$SPP_x = \frac{Y_n}{P_x} \tag{2.12}$$

The specific purchasing power of commodity x measures the ability of a nation to *finance* the consumption of this commodity. It is a symbolic measure in the sense that it denotes neither the amount of commodity x that is actually consumed nor the

[3] I use the word *specific* to disambiguate from the more common notion of purchasing power, which typically refers to the ability to consume a basket of goods or services, rather than a single good.

amount that could conceivable be consumed.[4] However, since the ability to finance consumption is a prerequisite to *actual* consumption, this metric should be related to biophysical flows.

In order to avoid the problem of measuring changes in quality, we want to choose a commodity that remains uniform across time. Energy resources are almost completely unique in this regard. While primary energy sources come in many qualitatively different forms, the science of energetics allows us to compare all of them using a single, well-defined unit (the Joule). In this section, I use energy-specific purchasing power to avoid average price problems.

We can use energy-specific purchasing power to see if the post-1970 decoupling shown in Fig. 2.6 is a methodological artifact. However, by abandoning real GDP in favor of specific purchasing power, we are no longer investigating the decoupling of output from resource input; rather, we are looking for evidence supporting the following monetary feedback hypothesis:

> **Monetary Feedback Hypothesis**:
> Monetary value represents a feedback mechanisms for controlling resource flows. As such, the growth of energy inputs should be tightly coupled to the economy's ability to finance their consumption.

We can test this hypothesis by investigating changes in the specific purchasing power of useful work (which is equal to nominal GDP deflated by an index of the price of useful work). An immediate problem is that most forms of useful work have no price. We usually pay for energy in its primary form; once it has been transformed into an end-use application, we almost never pay directly for this work. For instance, we purchase the gasoline used by a car, but *never* the end-use kinetic energy of the car. The only Ayres–Warr category of useful work with a well-defined market price is *electricity*. Deflating nominal GDP by the price of a kilowatt-hour (kWh) of electricity gives *kWh-specific purchasing power*:

$$SPP_{kWh} = \frac{Y_n}{P_{kWh}} \tag{2.13}$$

My contention is that kWh-specific purchasing power represents a rough proxy for the ability of the economy to purchase useful work. We are not used to thinking in these terms, so a comparison to the household level is helpful. One's household income determines what one can consume. If we compare one's income to the price of a pencil, this gives an indication of how many pencils one could consume. By extension, if we compare the value of the entire economy to the price of a pencil, we get an indication of how many pencils the economy could consume. Likewise, by comparing the value of the entire economy to the price of useful work (proxied by

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[4] While an individual could conceivably spend his entire income on a single commodity, it is impossible (and absurd) for a nation to do so. For instance, if the USA spent its entire nominal GDP on fossil fuel energy, its energy consumption would be greater than that for the entire world, and no other goods or services would be generated.

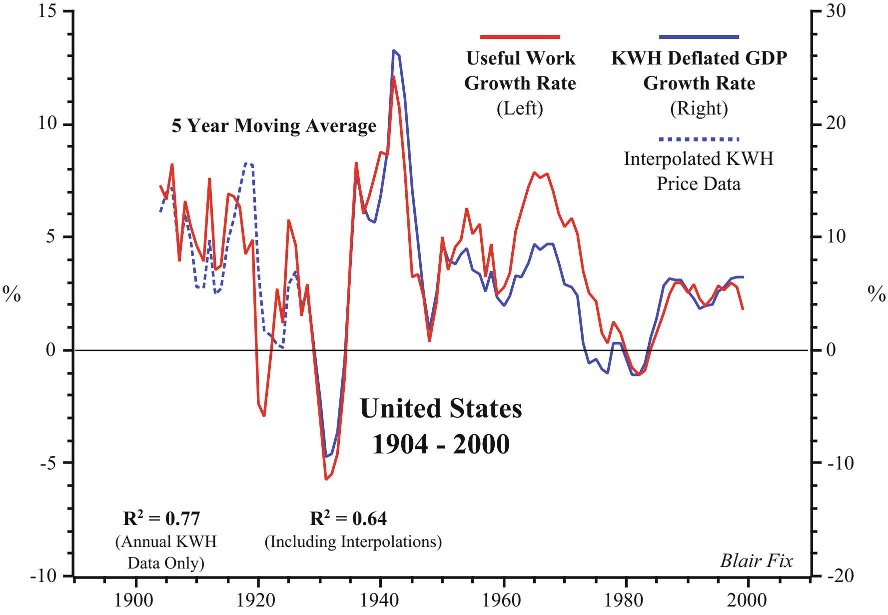

Fig. 2.7 Growth rates of kWh-specific purchasing power and useful work. KWh-specific purchasing power represents a rough estimate of the ability of the economy to finance the consumption of useful work. (Sources: Nominal GDP from HSUS Table Ca10 (1900–1928) and BEA Table 1.1.5 (1929–2000). Price of electricity (1904–2000) from HSUS Table Db234 (average price, all services). Electricity prices for 2001–2011 calculated by weighted average over three end-use sectors: commercial, industrial, and residential. Sectoral prices from EIA Annual Energy Review 2011, Table 8.10; consumption from Table 8.9)

the price of electricity) we get an indication of the economy's ability to finance the consumption of useful work. If the monetary feedback hypthesis is true, the growth rate of kWh-specific purchasing power should be highly coupled to the growth rate of useful work.

When we compare the historical growth rates of kWh-specific purchasing power to those of useful work (Fig. 2.7), an interesting thing happens: the post-1970 decoupling of real GDP from useful work (shown in Fig. 2.6) almost entirely *disappears*. Throughout the entire twentieth century, the growth in the US economy's ability to purchase electricity remained tightly correlated with the growth of useful work. This evidence is consistent with the monetary feedback hypothesis, and it supports the hypothesis that the evidence for decoupling is a measurement *artifact*.

I should be clear that my argument is not that statistical agencies have somehow made a "mistake" in their calculation of output. To the contrary, I hypothesize that the notion of "output" (and therefore, "decoupling") is a *conceptual artifact* that results from the misapplication of linear thinking to a nonlinear system. If we think in biophysical terms, the economy is a complex, nonequilibrium system that uses

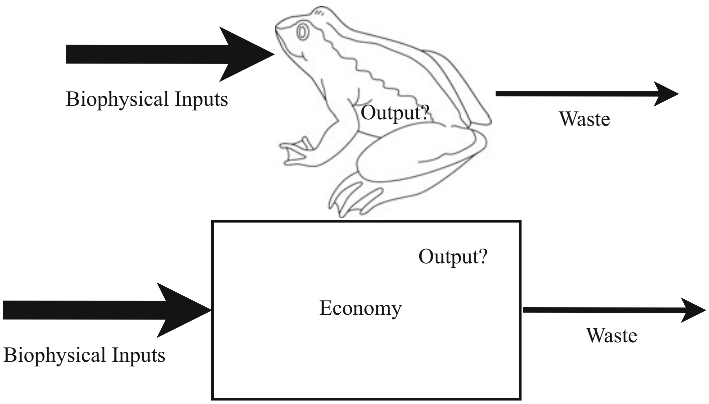

Fig. 2.8 The biophysical flows through a frog and the economy. Where is "output"?

biophysical flows to sustain itself. The only linear output of such a system is its *waste*.

This can be made more clear if we compare an economy to a living organism (in this case, a frog). Both the frog and an economy function by exploiting a flow of biophysical inputs and exuding a flow of biophysical waste outputs (Fig. 2.8). This material flow sustains the internal processes of each system. While the frog has many internal subsystems/organs that might be said to produce an "output" (i.e., the heart has a blood flow output, the lungs an output of oxygen, and the endocrine system an output of hormones), all such outputs are destined to become inputs to other processes. Thus, the internal workings of an organism are intrinsically circular—the frog (as a whole) has no "output" other than its waste.

When we think in these terms, the economy, like the frog, has no output; rather, it has a resource *throughput*. Our mistake comes when we label certain internal processes as "output": This gives the illusion of linearity where none actually exists. All of the outputs of the myriad of internal processes within the economy are destined to become inputs to other processes. Thus, the internal workings of the economy are inherently circular, meaning the notion of a linear output is difficult to justify.

I argue that the notion of "output" (at the level of the entire economy) is a conceptual artifact that arises from the focus on monetary value. That is, we conflate a *sale* (a monetized exchange) with the creation of an *output*. Note that a sale is inherently linear: Money always flows from buyer to seller. Thus by aggregating sales (and calling this output), we create the illusion that the economy is a linear process. However, if we drop the assumption that a sale represents an output, the illusion of linearity disappears: all internal processes become circular and the very notion of output (and hence, decoupling) becomes untenable. At the level of the entire economy, the only linear flow is the stream of biophysical throughput, which ends in the output of waste.

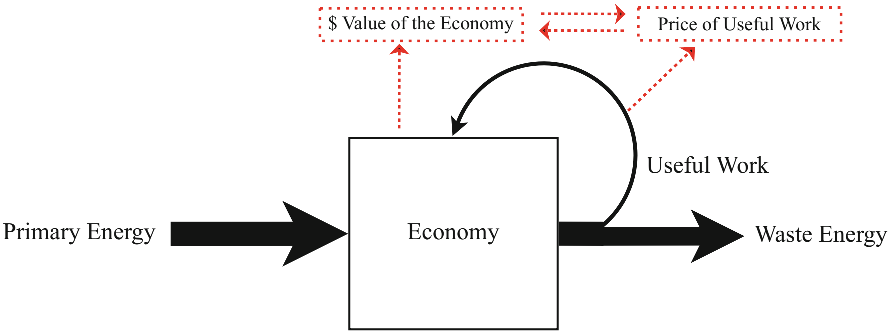

Fig. 2.9 Monetary value as a feedback device for "controlling" biophysical flows

Rather than treat monetary value as an output, I offer the alternative hypothesis that monetary value functions as a feedback device for controlling the flow of biophysical throughput (Meadows 2012). We can frame this paradigm shift by asking the following question: how does the economy "know" to consume more resources? In the animal kingdom, the stimulus to consume resources comes from sensory feedback: animals "know" to consume resources because they "feel" hungry. What is the corollary of this sensory feedback in the economic system? My hypothesis is that monetary value functions as such a feedback mechanism, stimulating or stifling the flow of resources. Figure 2.9 shows a schematic of this process when applied to the flow of useful work.

The exploitation of a resource does not intrinsically require monetary value. However, if an economy becomes monetized (meaning certain human interactions require the exchange of money), then resource exploitation is suddenly restricted by the stock of money (since resources must be "paid for"). The pool of monetary value by which we finance the consumption of resources is perpetually renewed by a process that economists call "adding value". For any given internal process, the sale of the final product always has a greater value than the sum of the inputs. The sum of all such added value is equal to nominal GDP—the value of the entire economy.

As this pool of added value expands relative to the price of a resource, we feel "wealthier". Resources are "cheap" so we consume more of them. If the opposite is true—the value of the economy contracts relative to the price of a resource—we feel "poorer". Resources are "expensive" so we consume fewer of them. Thus, I argue that prices constitute a feedback system that regulates the flow of resources through the economy. This feedback system functions so long as humans agree not to consume resources unless they can be "paid for" (i.e., we agree not to *steal*). The long-term coupling between the growth rate of useful work and kWh-specific purchasing power lends credence to this view.

By thinking in this way, however, we place a heavy emphasis on the price of energy (the price of electricity in this case). Thus, we must ask—where does the price of energy come from? It is rather disconcerting to think that random market fluctuations might cause a change in the price of energy that somehow leads to a change in the entire economy's ability to consume useful work. This would lead us straight back to the neoclassical view that the market is the ultimate arbiter of the economy. The task of biophysical economics should be to show that energy prices are, in fact, not random at all. Instead, they are a reflection of a broader biophysical reality.

Interesting work on the topic of energy prices has been done by King and Hall (2011), who link historical prices of oil and gas to energy return on investment (EROI). Giampietro et al. (2012) stress that the biophysical labor productivity of the energy sector is equally as important as EROI in indicating the quality of the energy production process. Building on Giampietro et al., we can define the biophysical labor productivity of the US mining sector (ρ_M) as the energy content of domestic fossil fuel production (E_{FF}) divided by the number of workers in the mining sector (L_M):

$$\rho_M = \frac{E_{FF}}{L_M} \tag{2.14}$$

As King and Hall have done with EROI, it seems quite reasonable to hypothesize that the price of energy could be somehow linked to mining productivity. Before proceeding, it is helpful to first reflect on what the price of a commodity really means. Most economists would agree that the nominal price of a commodity is meaningless, in and of itself. A price only gains meaning when placed in comparison to the price of *other* commodities. One way of making such a comparison is to relate the price of a *single* commodity to the average price of *all* commodities. This gives us the "real" price of a commodity. However, as discussed in Sect. 2.3, there are numerous problems with average price indexes, so I avoid this approach. A different (very unorthodox) way of contextualizing the price of a single commodity is to compare it to the *total value* of all (new) commodities. Unlike the average price, the total value of all new commodities (nominal GDP) is uniquely defined at a single point in time (sampling errors aside).

Based on this unorthodox approach, we can contextualize the price of energy by comparing it to the value of all new commodities—nominal GDP. Since we are now concerned with the output of the mining sector (fossil fuels), we are interested in the nominal price of one domestically produced Joule of fossil fuel energy (P_J). We calculate this price by dividing the total value of fossil fuel production by the energy content of this fuel. Using the notation developed previously, *joule-specific purchasing power* is defined as the ratio of nominal GDP (Y_n) to the average price of one Joule of fossil fuel:

$$SPP_J = \frac{Y_n}{P_J} \tag{2.15}$$

Figure 2.10 plots joule-specific purchasing power against the biophysical labor productivity of the mining sector. The two series show a striking degree of correlation. Given this high correlation, it seems reasonable to write the following proportionality statement:

$$SPP_J \propto \rho_M \tag{2.16}$$

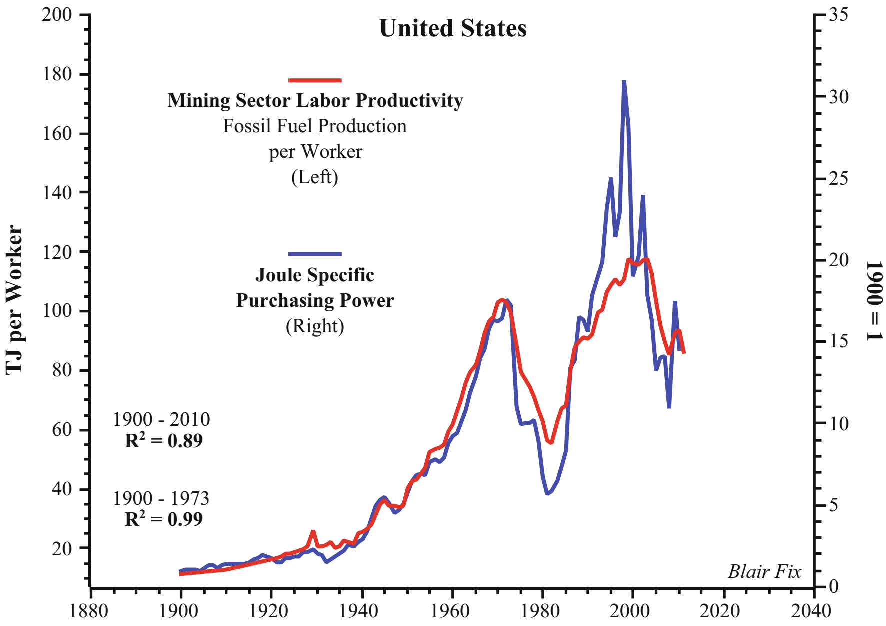

Fig. 2.10 Joule specific purchasing power (the ability of the economy to purchase fossil fuels) and mining sector biophysical labor productivity

Since what we are interested in is the price of fossil fuel, we use the definition of joule-specific purchasing power (Eq. 2.15) to arrive at Eq. 2.17:

$$\frac{Y_n}{P_J} \propto \rho_M \tag{2.17}$$

By rearranging for fossil fuel price, we get Eq. 2.18:

$$P_J \propto \frac{Y_n}{\rho_M} \tag{2.18}$$

This indicates that the nominal price of fossil fuel is a simple function of two variables: nominal GDP and the biophysical productivity of the mining sector. Figure 2.11 plots the left and right sides of Eq. 2.18 as separate time series. The results are robust: the price of fossil fuel can be almost completely accounted for by the ratio of nominal GDP to mining sector productivity (implying that biophysical considerations have a great power in our economy).

Thus, we can conclude that the price of energy is not arbitrary. Rather, when contextualized against the value of the entire economy, the price of energy seems to be fundamentally determined by the biophysical productivity of the mining sector. This is an important result, because it allows us to ultimately ground monetary feedback in what is arguably the most important process of an industrial economy: the exploitation of fossil fuels.

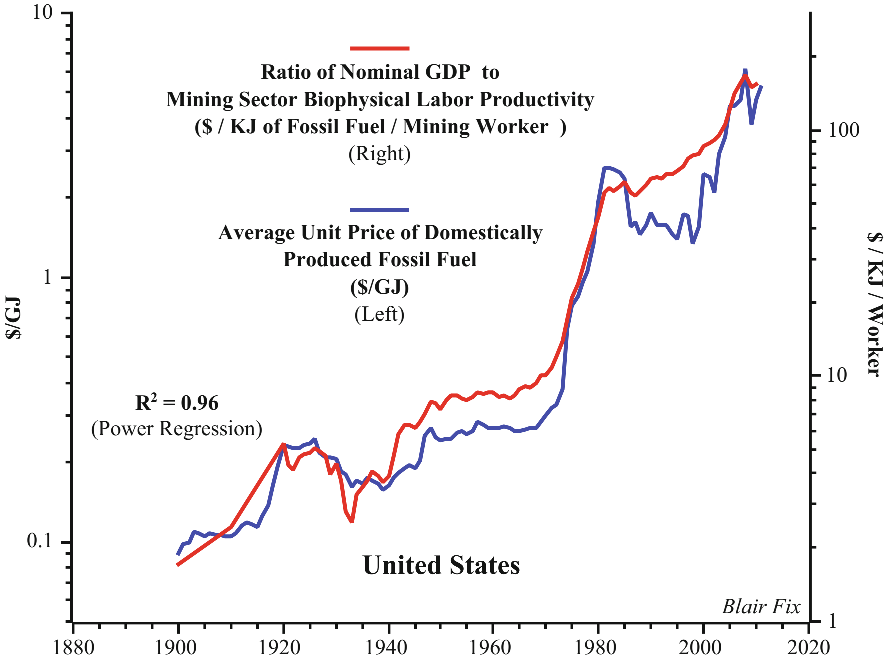

Fig. 2.11 Biophysical underpinnings of the price of fossil fuels. The relation between the nominal price of fossil fuels and the nominal value of the economy is arbitrated by the biophysical labor productivity of the mining sector. (Sources for both figures: Fossil fuel production data from HSUS Table Db155 (1920–1948) & EIA Annual Energy Review 2011, Table Mining sector employment from HSUS Ba819 (1900–1910), HSUS Ba841(1920–1957), & BLS CEU1021000001 (1958–2011). Value of fossil fuel production (1949-2010) from EIA Annual Energy Review Table 3.2. Natural gas price (1930–1949) from EIA Historical Natural Gas Annual 1930 Through 2000, Table 1. Crude oil (1920-1949) from BP Statistical Review of Energy 2011. Anthracite (1920–1949) from HSUS Tables Cc238–240)

To summarize our results, we find that the evidence for decoupling almost completely disappears when nominal GDP is deflated by the price of electricity, rather than by the GDP deflator. Evidence also suggests that the relation between nominal GDP and the price of fossil fuel is arbitrated by the biophysical productivity of the mining sector. I have hypothesized that this implies that evidence for decoupling is a methodological artifact—a result of the decision to measure output in terms of monetary value. The evidence presented here supports the alternative hypothesis that monetary value functions as a feedback device for controlling biophysical throughput.

2.5 Decoupling in Theory and Reality: What Goes Wrong

The neoclassical argument for decoupling is simple and intuitive: either through technological progress or input substitution, the economy can become more *efficient* at transforming natural resources into final output. However, when we attempt to apply this theoretical argument to the real world by *measuring* the decoupling of output from input, we find that the concept of decoupling is plagued by fundamental epistemological problems.

Decoupling metrics are a subset of a larger class of output/input metrics in which the efficiency of a system is defined in terms of its output per unit of input. In my view, all sound efficiency metrics must satisfy three basic requirements: (1) flow consistency, (2) boundary consistency, and (3) unit consistency.

Flow consistency means that we should track the flow of the *same* substance through the system. For instance, when measuring the efficiency of an internal combustion engine, we continuously follow the flow of *energy* through the system. Thus, engine efficiency is defined as the useful energy output per unit of total energy input. If we do not maintain flow consistency, then the notion of efficiency becomes ambiguous. For instance, the efficiency of a computer is not easily defined. If we track energy inputs, we run into the problem that the energetic output of a computer (the work done on the electrons in its circuits) is of little interest to computer users. Instead, computer users care about outputs of processor speed, information storage capacity, and a host of other qualities. Thus, to calculate the "efficiency" of a computer we must break flow consistency and measure output on a different basis than input. By doing so, we forgo the possibility of a single metric for the efficiency of a computer; instead, we get a different efficiency metric for each relevant output that is chosen.

Moving on to *boundary consistency*, Giampietro et al. (2013) note that well-defined system boundaries are a prerequisite for any quantitative analysis. A boundary definition allows us to differentiate between what is "inside" and what is "outside" the system. The consistency of boundary definitions is essential for the calculation of an efficiency metric. For instance, when calculating the efficiency of a car, one must stipulate whether the system includes the *entire* car, or only the passengers *inside* the car. In the former case, the kinetic energy of the car is "inside" the system and counts as an output; however, in the latter case, the kinetic energy of the car is "outside" the system and counts as waste (only the kinetic energy of passengers is counted as useful output). The resulting efficiency metric will be different for each boundary definition. While both calculations are "correct", it is meaningless to compare efficiency metrics that are based on different boundaries definitions. Furthermore, the system boundary used to account for inputs must remain the same as the boundary used to account for outputs. This is easily accomplished in a simple system, but more difficult in a complex system (see below).

Lastly, *unit consistency* is essential for a well-defined efficiency metric (or any calculation, for that matter). If the basic unit of measurement is not well-defined, then quantitative analysis becomes impossible.

Let us now apply these concepts to the neoclassical treatment of decoupling. In abstract form, the idea is seductively simple: the economy grows progressively more efficient at transforming resources into output, and we can measure this efficiency in terms of an output/input ratio. When applied to energy, this becomes the GDP output per unit of energy (or the inverse, the energy intensity of GDP).

However, when we move from theory to the real world, the neoclassical notion of decoupling is beset by fundamental epistemological difficulties. First, we encounter a problem of flow consistency. When following energy inputs, the only way that flow consistency can be maintained is by adopting the Ayres–Warr notion of efficiency, where "output" is measured in energetic terms as useful work (although I would argue that useful work still constitutes an "input"). If we adopt this approach, we find that energy conversion technology has become more efficient, but the growth of this efficiency has strict upper bounds set by the laws of thermodynamics. Thus, the neoclassical notion of perpetual decoupling becomes impossible.

Unlike the Ayres–Warr method, the conventional approach to the measurement of economic efficiency is to abandon the flow of energy after it enters the economy and to instead shift to a notion of "economic output". By doing so, we lose flow consistency. On the input side we track energy flows, but on the output side we track "economic output", which consists partly of biophysical flows (the production of goods), but also of human activity (services). It is far from clear what aggregating such disparate phenomena means. By losing flow consistency, we lose the uniqueness of our measure, since there are many possible ways that "economic output" might be defined. For instance, it might make sense to define all services as *inputs*, thereby counting only the production of goods as output. I have argued that from a biophysical standpoint, the only "output" of the entire economy is its waste. All internal outputs are destined to become inputs to other process. Thus, the very notion of an "economic output" is ill-defined.

We also run into problems with boundary definitions. For instance, when measuring energy inputs, the "economic system" is implicitly defined to include any human activity that involves the use of energy (meaning *all* human activity). However, the conventional approach to measuring outputs relies on a different boundary definition. By measuring "economic output", we are concerned only with the subset of human activity that is *monetized*. Thus, the well-paid banker produces an "output" but the unpaid housewife does not. When we compare "economic output" with energy inputs, we are actually using different boundary definitions of the economic system (monetized human activity vs. all human activity). This inconsistency undermines the validity of our efficiency metric.

Lastly, there is no objective unit on which to measure "economic output". As discussed extensively in Sect. 2.3, real GDP is plagued by a fundamental instability in its basic unit (price), meaning unit consistency is not maintained.

Thus, when moving from neoclassical theory to the real world, our ability to measure decoupling is undermined by serious (and I would argue, insurmountable) epistemological difficulties. The conventional measure of decoupling—the energy intensity of GDP—fails all three conditions for an effective efficiency metric. Thus, any evidence for decoupling that is provided by this metric should be met with appropriate scepticism. As such, I argue that the neoclassical notion of decoupling is untestable.

2.6 Conclusions: Monetary Value as a Feedback

I have proposed that we abandon the conventional approach of using monetary value to measure output. Instead, I argue that we should treat monetary value as a *feedback device* that controls the flow of biophysical throughput. When we undertake this paradigm shift, the evidence for decoupling disappears. Indeed, we find that kWh-deflated GDP is strongly coupled with changes in the flow of useful work. This does not mean, however, that financial constraints are the ultimate arbiters of biophysical flows. Rather, I argue that financial constraints are a manifestation (in feedback form) of more fundamental problems.

In my opinion, there are three ways in which energy inputs (or any other resource input) to the economy may be constrained:

1. *Biophysical scarcity*: Our ability to consume energy depends fundamentally on both the quantity and quality (i.e., EROI) of an energy resource.
2. *Technological capacity*: Exosomatic energy resources cannot be exploited by humanity without the use of technology that transforms this energy into a form usable by humans (useful work).
3. *Social organization/coordination*: In a complex society, the mobilization of an energy throughput requires the coordination of many individuals. If such coordination cannot be mustered, energy throughput will be constrained.

If anything can be garnered from the study of economic history, it is that when the economy bumps up against one or more of the above three constraints, individuals rarely perceive the truth of what is occurring. Instead, such constraints are universally perceived as a *financial* problem.

We can understand this by way of an analogy with the human body. The body is a complex system with many feedback mechanisms, some of which are conscious. Conscious feedback manifests itself as a "feeling". When the body requires more energy, we "feel" hungry. When the immune system is under attack, we "feel" unwell. When the body requires time for recuperation, we "feel" tired. In all cases, the "feeling" is a sensory manifestation of a deeper physiological issue.

In the case of the economy, financial constraints are not a "cause" of economic problems; instead they are a manifestation of a deeper biophysical/social issue. The difference, however, is that in the human sensory system, feedback is *qualitative*. The advantage to this qualitative feedback is that we are able to distinguish between different "feelings", allowing us to respond appropriately. In the case of the economy, monetary feedback is *quantitative*. This has the advantage of being very "precise", but the disadvantage is that different constraints become indistinguishable when expressed in feedback form.

This leads to a peculiar problem—when faced with constraints on the economy, we often "blame the messenger". To confirm this, one need only look at the ubiquitous claims made by politicians that scarcity of *money* is the source of the problem. Yet at the level of humanity as a whole, such claims are nonsensical. Money is a creation of the human imagination. To claim that problems arise from a scarcity of money is equivalent to claiming that the stars in the sky cannot be counted because there are not enough numbers. As Soddy (1926) long ago noted, the creation of money is bound not by the laws of thermodynamics but by the laws of mathematics—hence its creation has no upper bound. Therefore, when we witness a financial constraint (and we witness them all the time) we must insist that this is actually a *barometer* for a more fundamental process that is occurring.

We can use the empirical results of this chapter to elucidate this principle. My contention is that kWh-specific purchasing power represents a rough proxy for our ability to finance the consumption of useful work. An increase in this indicator means that useful work becomes "cheaper". Our response to this signal is to consume more useful work (or to accelerate the growth of this consumption). Alternatively, when kWh-specific purchasing power decreases, useful work becomes "dearer". Our response to this signal is to consume less useful work (or to slow the growth of our consumption).

Yet the great historical changes in useful work growth rates are not "caused" by financial feedback. Such feedback is ultimately an indicator of either a biophysical, technological, or social constraint (or a combination of the three). Our investigation of the productivity of the mining sector can give us further insight. Mining sector biophysical labor productivity is a joint outcome of biophysical, technological, and social constraints. Better technology will act to increase productivity, while declining resource quantity (and quality) will have the opposite effect. Social constraints also play a role. For instance, the 1970s Organization of the Petroleum Exporting Countries (OPEC) embargo prompted a rapid rise in US drilling rates without a corresponding increase in oil production (Guilford 2011). The result was that productivity declined greatly, but recovered once the embargo ended and drilling intensity relaxed.

Empirical evidence shows that the productivity of the mining sector acts as an arbiter between the price of fossil fuels and the nominal value of the economy. Thus, what is manifested as a financial phenomenon (the "cheapness" or "dearness" of fossil fuels) is actually a reflection of a very concrete biophysical reality—our ability to harvest fossil fuels.

In this chapter, we found evidence of a stable and long-term *coupling* between the consumption of energy and the ability of the economy to finance this consumption. This gives strong support for the hypothesis that monetary value functions as a feedback device. This result has important implications for a biophysical growth theory. Given the strong historical evidence, we can expect that future energy constraints will appear as financial constraints. Indeed, this may already be occurring. The strength of a biophysical growth theory will lie in its ability to demonstrate that the ultimate cause of these financial problems has little to do with money and everything to do with biophysical reality.

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