Human Activity, Energy & Money in the United States

Connecting the Biophysical Economy with its Pecuniary Image

Blair Fix

A thesis submitted to the Faculty of Environmental Studies in partial
fulfillment of the requirements for the degree of Master in
Environmental Studies, York University, Toronto, Ontario, Canada.
September 18, 2013

Abstract

There is no consensus, in political economy, about the exact relationship between the biophysical and the pecuniary spheres. This paper enters into the debate by asking the following question: how can a biophysical approach to political economy be used to gain insight into the complex interrelationship between the biophysical sphere of economic activity and its monetary image? After reviewing and critiquing land, labour, utlitarian, and energy theories of value, this paper abandons the search for a direct, causal connection (between the biophysical and the pecuniary) in favor of an impredicative, co-evolutionary approach. Using a synthesis of the work of Giampietro & Mayumi and Nitzan & Bichler, an empirical investigation is conducted that looks for linkages between monetary indicators, the inter-sectoral movement of human activity, and increases in energy consumption. Although the findings are complex, dynamic linkages between the biophysical and pecuniary spheres are consistently found.

Acknowledgments

I would like to thank my wife, Emily, for her love and support,
and my parents, Grace and Garry, for their proof reading prowess.

I would also like to thank Mark Thomas, Ellie Perkins, and Peter Victor
for their helpful comments and suggestions, and for
agreeing to oversee such an unorthodox thesis.

Foreword

The stated goal of my area of concentration is to synthesize political economy with biophysical analysis. This thesis is where the majority of such a synthesis has been carried out. In particular, this thesis helps to satisfy the following components of my area of concentration:

Component 1.2: 19th, 20th & 21st Century Economic History
Learning Objectives: Understand the economic history of the last two centuries and place it within the context of biophysical theory. A central question to ask is: are economic phenomena purely a result of the internal dynamics of capitalism, or a result of external biophysical "forcing".

Component 2.1: Social Metabolism
Learning Objectives: The study of social metabolism studies flows of matter and energy though the human-system, and relates these flows to social phenomena. My objective is to understand and use this pre-analytic vision while conducting research and creating new theory.

Component 2.2: Energetics
Learning Objectives: Gain enough of an understanding of the role of energy in human society (both past and present) to discern between social scientific theory that is compatible with the principles of energetics, and social theory that is incompatible.

Component 2.3: Theoretical Tools for Analyzing Energy Metabolism
Learning Objectives: Apply useful work growth theory and the MuSIASEM approach in a quantitative, empirical manner through my own research.

Table of Contents

List of Figures

Acronyms & Symbols

AG	Agriculture & Forestry Sector
B	Exergy
BM	Building & Manufacturing Sector
BOP	Balance of Payments
DISS	Dissipative Cycle
η	Efficiency
EEI	Economic Energy Intensity
EM	Energy & Mining Sector
EMB	Exosomatic Metabolic Balance
EMR	Exosomatic Metabolic Rate
EROI	Energy Return on (Energy) Investment
EP	Energy Production
ET	Energy Throughput
FF	Fossil Fuels
FTE	Full-Time Equivalent
GDP	Gross Domestic Product
HA	Human Activity
HH	Household Sector
HYP	Hypercycle
I	Income
i	Income per capita
IUT	Involuntary Unpaid Time
K	Market Capitalization
k	Market Capitalization per Worker
M	Mining Sector
N	Nominal
NP	Net Power
NAICS	North American Industry Classification System
Π	Aggregate Profit
π	Profit per Worker
GP	Gross Power
P	Aggregate Price
p	Unit Price
PE	Primary Energy
PS	Primary & Secondary Sector
PT	Paid Time
R	Real
SG	Services & Government
TET	Total Energy Throughput
THA	Total Human Activity
U	Useful Work
u	Useful Work per capita
UT	Unpaid Time
UL	Unskilled Labour
VA	Value-Added
va	Value-Added per worker (or per hour)
VUT	Voluntary Unpaid Time
w	Hourly Wage or Annual Salary
Y	Real value of output

$\hat{u}$	Growth Rate (of u)

Energy

EJ	Exajoule	10^{18} Joules
GJ	Gigajoule	10^{19} Joules
MJ	Megajoule	10^{6} Joules
kWh	kilowatt hour	3.6×10^{6} Joules
W	Watts	

Data Sources:

AER	Annual Energy Review (from Energy Information Administration)
AEO	EIA Annual Energy Outlook (from Energy Information Administration)
EIA	US Energy Information Administration
BEA	US Bureau of Economic Analysis
BLS	US Bureau of Labor Statistics
HSUS	Historical Statistics of the United States

Preface

I believe firmly that science is a normative pursuit. Before any experiment is conducted or any empirical investigate undertaken, a question must be asked. It is this first step of the scientific process that is irrevocably normative. Our world views determine what questions we *ask*, what questions we *do not ask*, and what questions we are not capable of *conceiving.*

My own ethos, which I call the *peak world view*, can be summarized succinctly in the following two statements:

1. The modern era is historically *anomalous* in terms of the scale of matter and ***energy*** controlled by humans;
2. This vast biophysical throughput is temporary and will not last.

These core beliefs have deeply influenced the questions that I ask. From a social scientific perspective, I am interested in the relationship that energy has played in making the present era possible, and the role it will play in shaping the future. Figure 1 shows estimates of world energy consumption from 1820 to the present day. The explosion in energy consumption after the industrial revolution has no parallel in human history. Will this exponential growth continue indefinitely? Answers to this question are deeply controversial and one's response depends firmly on one's world view. My own view is that growth will be a short-lived phenomenon.

The energy explosion shown in Figure 1 has been made possible, for the most part, by fossil fuels. To date, no other energy source controlled by humans possesses both the scale and concentration of fossil fuel energy, and, I believe, none will be found. While I can justify this view with scientific papers and empirical evidence (for instance Heinberg, 2009; D. J. Murphy & Hall, 2011), in the end it is simply an axiomatic statement central to my belief system.

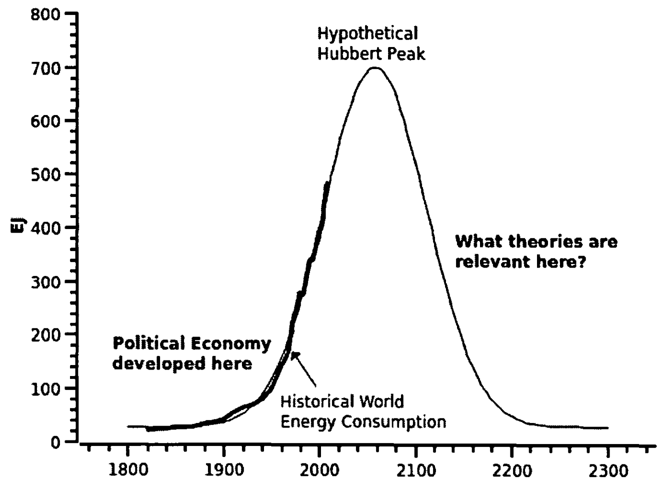

Figure 1: Peak Energy & Political Economy

Sources: This chart is modeled after Murphy & Hall (2010). Historical world energy consumption data for1820-1960 comes from Smil (2010) . This is merged with BP Statistical Review of Energy (2012) data for 1965-2011.

The peak world view, if followed to its logical conclusion, has major ramifications for social scientific theory. Firstly, if we maintain that no meaningful substitutes for fossil fuel exist, it follows that world energy consumption will eventually peak and decline as fossil fuels are exhausted. This trajectory is often referred to as a "Hubbert Peak" after M.K. Hubbert, the US geophysicist who first theorized and predicted the phenomenon that we now call "peak oil". A hypothetical Hubbert curve for world energy consumption is shown in Figure 1. It is meant as an illustration of the peak principle, rather than a prediction of the future – the date and height of the peak are unimportant (for the present argument).

A clear distinction exists between pre-peak and post-peak eras; the former is dominated by growth, the latter by contraction. An important question to ask is – will social scientific theories that were developed during the growth era (ie: most political economic theory) be relevant during the post-peak era? If not, what theories should replace them?

This thesis is a response to the above questions. My goal is to begin rethinking how we view ***monetary value*** and how we understand its function in society. This is not a new topic of investigation; indeed, attempts to theorize monetary value date back more than two millenia (in the Western canon) to Aristotle (Graeber, 2010), and theories of value have been one of the primary concerns of political economy. However, I think that investigating monetary value from a peak world view leads to the formulation of unusual questions … questions that are not often asked (or conceived of) by political economists.

This thesis is primarily concerned with the demographic transitions and energy throughput growth that occurred in the United States during the 20th century[1]. I am interested in how changes in the ***price structure of society*** made these great transformations possible. This line of inquiry is not particularly interesting, I think, unless one is convinced that these demographic and metabolic trends will not continue indefinitely. How will price structures function on the downside of the Hubbert curve? This is a question that is impossible to answer, but my hope is that understanding the past might shed some light on possibilities for the future.

---

[1] While I am ultimately interested in this issue at the global level, data is predominantly available at the national level. I have chosen to use data from the United States both because it is the largest "sample" and because US statistical agencies typically offer data over a much longer time period than offered by other national agencies.

1. Introduction: The Biophysical Human-System & its Pecuniary Image

> *There cannot, in short, be intrinsically a more insignificant thing, in the economy of society, than money; except in the character of a contrivance for sparing time and labour. It is a machine for doing quickly and commodiously, what would be done, though less quickly and commodiously, without it: and like many other kinds of machinery, it only exerts a distinct and independent influence of its own when it gets out of order.*
>
> - John Stuart Mill (1848, Chapter 7.8)

> *Under the price system, men have come to the conviction that money-values are more real and substantial than any of the material facts in this transitory world. So much so that the final purpose of any businesslike undertaking is always a sale, by which the seller comes in for the price of his goods; and when a person has sold his goods, and so becomes in effect a creditor by that much, he is said to have 'realized' his wealth, or to have 'realized' his holdings. In the business world the price of things is a more substantial fact than the things themselves.*
>
> - Thorstein Veblen (1923, pp. 88–89)

The above passages from Mill and Veblen illustrate two very different views about the role of ***money*** in society. These different views can be attributed to an unresolved controversy over how the ***biophysical*** and ***pecuniary spheres*** relate to one another. Mill argues that money (the *pecuniary* sphere) is just a convenient but ultimately "insignificant" facilitator for the distribution and consumption of *real* goods and services (the biophysical sphere). It is these *real* phenomena that he deems important. Veblen, on the other hand, argues that **prices** are often seen as more significant than the "material" realm. These contradictory views demonstrate the fact that there is no consensus, in political economy, over the exact relationship between the ***real*** and the ***nominal,*** the *biophysical* and the *pecuniary*. This paper enters into the debate by asking the following question: how can a biophysical approach to political economy be used to gain insight into the complex interrelationship between the biophysical sphere and its ***monetary image***[2]?

What is *Real*?

There is a long-held belief, within political economy, that prices, while important, are a convenient fiction. Marx (1867) famously referred to money as a *fetish*: an idolized veneer that actually serves to mask a more fundamental reality. But what is this underlying reality, and how, exactly, does it connect to prices[3]? Answering this question has proved surprisingly difficult. In the 18th century, the physiocrats proposed that land was the origin of monetary value. Later, the classical economists of the 18th and 19th centuries held that human labour time could be used to explain prices. The 20th century was dominated by the neoclassical view that ***value*** came from the marginal utility gained by a purchase, and that prices came were formed by the iteration of supply

---

[2] "Monetary image" refers to the metaphysical realm of all objects, institutions, or ideas that have a *price*. The monetary image refers not to the objects, institutions, or ideas themselves, but to their representation as an abstract monetary quantification.

[3] I use "prices" synonymously with "relative price". A monetary quantification has no absolute meaning by itself; rather, it must be compared to other prices to have meaning.

and demand. Finally, in the latter half of the 20th century, biophysical scholars proposed that value might be explained by the ***embodied energy*** of a commodity. To the present day, there remains no consensus on whether or not there is a *real* quantity that underlies prices.

This paper argues that there is no biophysical quantity that can "explain" prices. Rather, I argue for a co-evolutionary view of the biophysical and pecuniary. I propose treating prices as a signaling mechanism that both affects and is affected by the ***metabolic pattern of society*** (Figure 2). Thus, I do not propose a new theory of value as much as I propose a new way of *investigating* value.

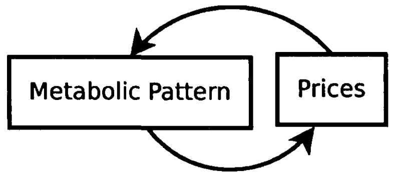

Figure 2: Metabolic Pattern & Price Impredicativity Loop

Because this paper is primarily about the development of a new epistemology for the study of monetary value[4], I focus on *breadth* of application rather than *depth*. My goal is to use the framework that I develop to relate as many biophysical and pecuniary trends as possible within the time and space limitations of a Masters Thesis. That being said, I impose the following constraints on my research:

1. The geographic scope is limited to the United States;
2. The biophysical scope is limited to energy and human activity data.

The layout of the paper is as follows: in Chapter 2 I review and critique land, labour, utility, and energy theories of value. In Chapter 3, I review existing literature in search of an empirical methodology for connecting the biophysical and pecuniary spheres. In Chapter 4, I outline my methodological framework. In Chapter 5, I examine the relationship between human activity and pecuniary data. In Chapter 6, I investigate the relationship between pecuniary data and energy consumption at the *national* level, while in Chapter 7, I look for links at the *sectoral* level. In Chapter 8 I synthesize the results and offer thoughts on their meaning.

In many cases, the empirical results raise more questions than answers. As such, I treat this paper not as the presentation of a finished theory, but as a glimpse into the possibilities of a new political economic research agenda.

---

[4] I take "monetary value" to mean exchange value, and I use it synonymously with "price".

2. Theories of Value

Political economists have been attempting to explain prices for centuries, and numerous theories of value have been proposed. Here I review four notable approaches: land, labour, utility, and energy theories of value. While it is not often framed this way, each of these theories of value, I argue, attempts to show that it is the biophysical sphere that "explains" prices. Each theory proposes a fundamental ***unit*** – a ***universal quantifier*** of the biophysical sphere – that can then be mapped onto prices. However, this search for a fundamental unit comes up short in every instance. Indeed, the universal units used in land, labour, utility, and energy theories of value *cannot be shown to exist*. This poses a fundamental epistemological problem. If something cannot be measured, it cannot be used to "explain" prices!

In the following sections, I offer critiques of these theories, and also discuss the reasons why they were appealing at the time of their creation. I then briefly review theories of "non-value", more commonly called theories of unequal exchange.

2.1 The Physiocrats & Land

In Greek, the word *physiocracy* means the "rule of nature" ("Physiocrat," 2013). The 18th century French intellectuals, aptly known as the *physiocrats*, held that the origin of all wealth lay in agriculture. They viewed agriculture as the producer of a surplus upon which the rest of society survived. Biophysically, I think the physiocrats were essentially correct: in agrarian societies, almost all energy is derived from the sun and made available to humanity through photosynthetic biomass.

However, this in no way implies that monetary value must be tied to agriculture. To be fair, the physiocrats wrote philosophically – they made no attempts to "explain" prices in any rigorous manner. They were more interested in critiquing the emerging mercantilist world view that posited trade as a "creator" of value. However, if we are to take their theory seriously, we must be able show that the amount of land embodied in a commodity explains its relative price. The problem, of course, is that we need a *universal unit* that can somehow *quantify* the innumerable *qualities* of different types of land.

However, the decision to adopt any particular unit depends on the ***narrative*** assumed by the analyst. Giampietro and Mayumi (2009) use the example of apples and oranges. For instance, if we adopt the narrative that apples and oranges are to be consumed by humans for energy, we can logically compare them in terms of caloric content. However, if our narrative instead involves the transportation of apples and oranges in a cargo train, comparison in terms of mass becomes relevant and caloric content becomes irrelevant.

The same is true of land. If the narrative adopted is that land is to be used for growing corn, we may logically compare the corn productivity of different land areas. However, this comparison will become meaningless if, instead, we adopt the narrative that the same land is to be used for oil production. For any given narrative, there exists a logical, *rigorous* way of quantitatively comparing different types of land. However, quantitative results derived from different narratives *cannot* be meaningfully compared. Thus, in order to show that embodied land equates with relative price, we must choose the *correct* narrative from the infinite set of all possible narratives. In my mind, this seems a logical impossibility.

While there are serious epistemological issues with a land theory of value, it is easy to see why it would appeal to those arguing for a deeper connection to agriculture. However, the rise of the mercantilist European empires meant that European nations could displace their agrarian load onto other regions, essentially giving the illusion that agriculture was no longer important (Hornborg, 2011). Given this load displacement, agriculture seemed less important and land theories of value became marginalized.

2.2 Classical Theorists & Labour

As the European empires expanded, European cities became nodes of a vast trade network. Raw materials flowed in, and workers, concentrated in great factories, transformed these materials into finished products. Writing during this period, the classical economists such as Adam Smith (1863) and David Ricardo (1891) started to treat labour as the source of ***value***[5]. It was Karl Marx (1867), however, who first formulated the labour theory of value in a logically consistent manner. According to Marx, the "socially necessary abstract labour" embodied in a commodity could be used to explain its long-term price.

As with land, the ability to link embodied labour to price is predicated on the ability to reduce the innumerable *qualities* of different types of human activity into a single *quantity*. Marx proposed "socially necessary abstract labour" as his universal quantifier, which could then be used to convert the labour time of a CEO to that of an engineer or janitor:

$$1\, CEO\, hr = 1.5\, engineer\ hrs = 5\, janitor\ hrs = 10\, socially\ necessary\ abstract\ hrs \qquad (1)$$

Crucially, abstract labour is *not* the work of any *real* person – it is an abstract archetype of the most basic form of human labour. Yet, precisely because it is an archetype, it can neither be shown to exist nor be measured (Nitzan & Bichler, 2009). Again, we fall victim to the same epistemological problem – there is no single *objective* way to convert the labour time of one worker into the labour time of another.

If we are willing to disregard this problem, there remain fundamental issues associated with the notion of "embodied" labour. It simply has no meaning without a boundary definition – yet the choice of boundary definition depends on the narrative adopted by the analyst (see section 2.4 for a more rigorous explanation of this problem).

While a labour theory of value may have been appealing when work was still primarily done by hand, the rise of massive fossil fuel powered machines meant that ***capital***, rather than labour, seemed increasingly productive. The neoclassical school asserted that both *were* indeed productive, and that both had a role in producing value. This approach developed into an all-encompassing theory that remains dominant today. And yet, as I show below, at the center of the neoclassical approach remain epistemological difficulties similar to both land and labour theories of value.

---

[5] Smith saw the labour theory of value as only applicable to primitive societies (Whitaker, 1904).

2.3 Neoclassical Theory & Utility

Neoclassical value theory is unique among those reviewed here in that it is not usually regarded as biophysical; rather, neoclassical theory asserts that prices are the outcome of the "subjective" desires of individual consumers (in conjunction with the cost-based supply conditions of producers). The price of a commodity derives not from any qualities embodied within it, but from the qualitative effect its consumption has on the buyer. Ultimately, I argue, neoclassical theory still attempts to find an underlying *real* predictor of prices. It simply shifts the search for a universal quantifier from the *exosomatic* to the *endosomatic* – from outside the human body to inside it. Rather than land or labour, ***utility*** – a unit of human desire or want – becomes the universal quantity for making the incommensurable commensurable.

Utilitarianism first appeared as normative theory of ethics within the writings of classical political economists John Stuart Mill and Jeremy Bentham. Bentham famously asserted that rational governing decisions should be based on utility maximization: " the greatest happiness of the greatest number" (Bentham, 1891). Utility, then, was an invisible unit of pleasure (or pain) resulting from some action. During the late 19th century, William Stanley Jevons (1879), Carl Menger (1871), and Leon Walras (1896) independently formulated theories of value based on *marginal utility*: the incremental utility derived from consuming the "last small increment" of a commodity (Hunt, 2011). This "marginal revolution" formed the backbone of modern day neoclassical economics.

The relationship between utility and price is, I think, more subtle than that proposed between land/labour and price. Classical economists such as Marx and Ricardo generally regarded short term price fluctuations as the result of supply and demand (Hunt, 2011). However, they sought some underlying *real* quantity to explain the long term average. Neoclassical theory, however, focused on explaining these forces of supply and demand. Utility functions, they claimed, could then be used to create demand curves, while marginal cost curves could be used to create supply curves. The intersection of these two curves at market equilibrium then explained the price of a commodity.

A problem with this approach is that utility functions cannot be measured directly[6]. This led many economists to abandon the notion of ***cardinal utility*** in favour of ***ordinal utility***, which uses a ranking of preferences to derive the utility function. Again, however, the problem of measurement arises. Samuelson (1938) proposed abandoning utility entirely and instead allowing consumers to empirically reveal their preferences. However, Wong (1978) argues convincingly that revealed preference theory amounts to a restatement of ordinal utility theory. Both theories remain empirically untestable as there is no way of determining the finite set of goods forgone in favour of the one actually purchased. It would seem that the concept of utility, so central to neoclassical theory, remains tautological. Joan Robinson (1962, p. 47) puts this predicament succinctly: "Utility is a metaphysical concept of impregnable circularity; utility is the quality in commodities that makes individuals want to buy them, and the fact that individuals want to buy commodities shows that they have utility".

---

[6] Layard (2003) argues that MRI scans can be used to derive cardinal levels of happiness, and that this might be used to maximize the "sum total of human well-being" (ibid, p. 3). However, the use of MRIs to derive a single, cardinal scale for human well-being seems eerily similar to arguments that IQ tests can be used to derive a single, cardinal level of intelligence – an ability that has been thoroughly critiqued by proponents of multiple intelligences theory (Gardner, 1985). The corollary, in political economy, to multiple forms of intelligence might be Max-Neef's matrix of human needs (Max-Neef, Elizalde, & Hopenhayn, 1992),which is irreducible to a single number.

A further complication with neoclassical theory is that it relies on the notion of market ***equilibrium***. Price is explained as being arrived at by successive iterations of supply and demand. An equilibrium price is reached when supply equals demand. However, the notion of equilibrium makes little sense in the case of a living system. From a thermodynamic standpoint, all living systems are in a permanent state of ***disequilibrium*** (Kondepudi & Prigogine, 1998). Even if we accept that an equilibrium is eventually reached, how do we know when it occurs? How can we distinguish an equilibrium price from a disequilibrium price? Nitzan and Bichler (2009) argue that there is no objective criteria for doing so.

While a thorough critique of neoclassical theory could fill many volumes, here I have focused on the most fundamental axiom of the theory – that consumers' desires can be quantified and transformed into a utility function. However, there remains no empirical method for constructing such curves. Neoclassical theory is subject to the same critique as land and labour theories of value: the universal unit proposed to quantify the *real* world (in this case, desires within the human brain) cannot be shown to exist. However, this has not stopped neoclassical theory from dominating political economic thinking of the 20th century. As many critical political economists have noted, this neoclassical dominance has more to do with its ideological function than its scientific truth (Hunt, 2011; McNally, 2010; Nitzan & Bichler, 2009).

2.4 The Biophysical School & Energy

Energy theories of value have gone through at least two waves of popularity, the first during the Technocratic movement of the 1930s and the second after the oil crises of the 1970s. The oil crises, in particular, led to a large outflow of scholarly work on the role of energy in society. Here I focus on the school of thought stemming from Howard T. Odum's (1988) notion of energy memory, or ***emergy***. This concept is now often referred to as ***embodied energy*** and is defined as the sum of all the energy used during the production of a commodity.

Robert Costanza (1980) tested the linkage between embodied energy and monetary value, and his results showed a high degree of correlation. More recently, King and Hall (2011) linked historical prices of oil and gas with e***nergy return on investment*** (EROI)[7]. The empirical success of these studies seems to lend credibility to an energy theory of value; however, critical appraisal of the techniques used casts doubt on the validity of such a theory.

While the concept of embodied energy is intuitive and has become popular in mainstream culture (for instance: Berners-Lee, 2010), it is plagued by fundamental epistemological issues that often go unrecognized. The most serious issue, known as the ***truncation problem***, arises from the "unavoidable arbitrariness of boundary definition[s] in relation to space and time when dealing with complex systems operating simultaneously on multiple scales" (Giampietro, Mayumi, & Sorman, 2012, p. 39).

The truncation problem was famously explained by Chapman (1974). He asks the simple question: what is the energy required to produce a loaf of bread? We might start our calculation by counting the energy used by the baker's oven. However, we then notice that energy was required to *make* the oven. Furthermore, energy was required to construct the *factory* that made the oven. We could then account for the energy used to build the *infrastructure* required to build the oven factory. Giampietro, Mayumi, & Sorman state that the boundary of an embodied energy calculation can inevitably be expanded to include *all of society*. But why stop there? We could include the energy embodied in the super nova explosion responsible for synthesizing most Earthly metals. In

---

[7] EROI is defined as the ratio of energy *output* per unit of energy *input* when harvesting a particular energy source.

fact, there is no conceivable end to the expansion of time and space around which one can trace energy tied to the eventual baking of our loaf of bread[8]!

Embodied energy literature often refers to this problem as truncation *error* (Dixit, Fernández-Solís, Lavy, & Culp, 2010; Lenzen, 2000; Lenzen & Dey, 2000). One way of calculating embodied energy is through process analysis, whereby the energy used in all "upstream" processes is traced backwards. It has long been recognized that the cut off point for tracing upstream processes is arbitrary. In order to avoid such truncation *error,* input-output analysis has been proposed as a possible solution. However, if we accept Giampietro, Mayumi and Sorman's argument, the notion of truncation *error* has no meaning. An "error" implies deviance from a value that is "correct"; however, a holistic understanding of the truncation *problem* implies that the boundary choice is always *subjective*, hence there is no *correct* calculation of embodied energy from which to judge an "error". While input-output analysis undoubtedly expands the boundaries compared to process analysis, it is by no means "complete", since the boundaries of time and space can be enlarged indefinitely. The truncation problem *cannot* be solved; as Giampietro et al. write, it is an "epistemological predicament associated with purposive quantitative analysis" (2006, p. 307) However, given a *well defined* boundary definition, embodied energy *can* be rigorously calculated, but the pre-analytic boundary choice will always be a subjective decision made by the analyst[9].

This leaves an embodied energy theory of value on shaky footing. At the *very* least, it implies that only embodied energy calculations that use *exactly* the same boundary definitions can be compared to one another, and hence, to prices. However, the relative price of two commodities at the time and place of a market exchange exists as a *singular* ratio. It is quite conceivable that the ratio of embodied energy between these two commodities could vary significantly depending on the subjective choice of boundaries used by the analyst. This poses a fundamental problem for an embodied energy theory of value, since there is no objective way for choosing the "correct" calculation.

However, if one is willing to disregard these epistemological issues, we still have the empirical successes of Costanza and King & Hall to explain. Let us start with Costanza's findings. His 1980 paper investigates the correlation between the embodied energy of 92 different sectors of the United States ***economy*** and the *dollar value of their total output* (in the year 1967). While the results are impressive, I argue that relating prices to embodied energy at the *sectoral* level in no way shows that *unit* price and *unit* embodied energy are actually related.

My arguments here are based on Nitzan and Bichler's elegant critique of similar methodologies used to test the labour theory of value at the sectoral level (Cockshot, Shimshon, & Nitzan, 2010). The central problem is that the sectors being tested are not the same *size*. We can demonstrate the problems of this approach by creating a hypothetical economy consisting of 20 sectors (Figure 3). Each sector produces one type of commodity. The left hand graph displays the unit price (p) vs. the unit embodied energy (e) for the particular commodity produced by each sector. These are *randomly generated numbers* with no correlation to one another. Thus, at the unit level, an *energy theory of value fails completely.*

However, each sector has a different total output (Q). In this model, the output of each successive sector is 1.5 times the last, and Q_1 is equal to one:

---

[8] The truncation problem also occurs when trying to calculate the *land* or *labour* embodied within a commodity. Embodied land/labour simply has no meaning without specifying the boundary definitions.

[9] Giampietro et al. (2011, 2012) propose using a *grammar* as means for making these subjective pre-analytical decisions as open as possible (see section 4.1).

$$Q_1=1, \quad Q_{n+1}=1.5Q_n \tag{2}$$

The total embodied energy of each sector (E) and the total price (P[10]) are defined as unit embodied energy (e) and unit price (p) multiplied by output (Q):

$$E=Qe \;\; \& \;\; P=Qp \tag{3}$$

Despite no correlation at the unit level, *total* embodied energy and *total* price show excellent correlation (Figure 4, right)! How can an energy theory of value that fails at the unit level succeed at the sectoral level? It turns out that the *sectoral* correlation is due to the perfect correlation between *output* (Q) and *itself*, with randomly introduced "noise" – e and p:

$$\frac{P}{E}=\frac{Qp}{Qe} \tag{4}$$

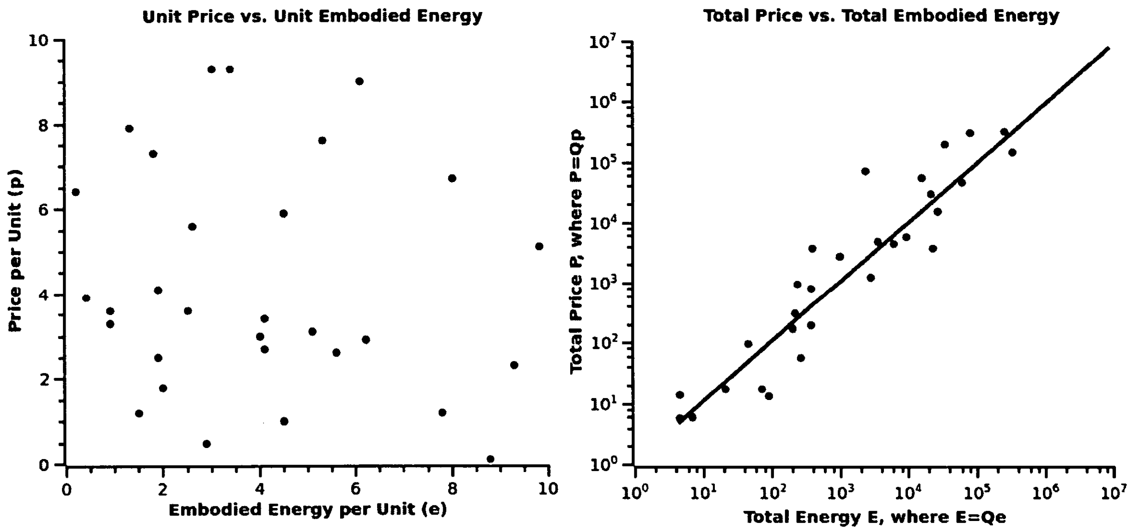

Figure 3: Spurious correlation between total value & embodied energy

Notes: A hypothetical model of 40 different sized sectors. Embodied energy per unit (e) and price per unit (p) are randomly generated numbers between 0 & 10. Quantity per sector (Q) is generated as follows: $Q_1=1$, $Q_2=1.5Q_1$, $Q_3=1.5Q_2$, etc. Modeled after Nitzan & Bichler's critique of empirical tests of the labour theory of value: http://bnarchives.yorku.ca/308/04/20101200_cockshott_nitzan_bichler_testing_the_ltv_spurious_correlation.xls

If one accepts this argument, it follows that Costanza's results need not support an energy theory of value at the level of singular commodities.

Unlike Costanza, King and Hall only seek to connect energy with the price of oil & gas. Rather than use embodied energy, King and Hall use the EROI of US oil & gas. Again, the empirical results are striking – lower EROI seems to predict higher prices. However, the above epistemological critiques of embodied energy apply equally well to EROI. This is because EROI calculations typically account not only for the *direct* energy consumed by the energy sector, but also for the *indirect* consumption *embodied* in capital goods. Again, the truncation problem rears its ugly head. If different boundary definitions were used, would King and Hall's results be reproduced? As no other attempts have been made, this question must go unanswered.

Another problem with King and Hall's approach is that conclusions drawn from a limited geographic

---

[10] Costanza's term for total price is "DOUT", meaning dollar value of total output.

coverage (the US only) are contradictory when broadened to a global scale. Let us use the example of the 1970s oil price spike as thought experiment. During the oil embargo of 1973, the global price of oil increased dramatically and abruptly, caused by an OPEC decision to *strategically* limit production. As the embargo proceeded, US oil and gas EROI decreased drastically, confirming King and Hall's thesis of inverse correlation between EROI and price.

This can be understood as follows: the OPEC embargo suddenly meant that the US was more dependent on its own domestic oil and gas reserves, leading to a drastic increase in drilling. Because EROI is *inversely* related to drilling intensity (Guilford, Hall, O'Connor, & Cleveland, 2011), this *increase* in drilling intensity led to a *decline* in EROI – all under a regime of higher oil prices.

However, can the same results be expected for oil and gas EROI within OPEC nations? While no EROI data currently exists for OPEC nations, I argue that it is unlikely that they experienced an *increase* in drilling intensity – strategic limitation in production, if anything, would have led to a *decrease* in drilling intensity. Thus, it is probable that OPEC EROI would have remained unchanged (or perhaps increased) *despite* rising prices.

EROI, it would seem, succumbs to the same fundamental epistemological issues as our other theories of value – it fails to function as a universal quantifier. As I will discuss later, energy is absolutely central to the functioning of the human system. However, just because something is *important* need not imply that it has anything to do with "causing" prices.

2.5 Theories of Value: Conclusions

All theories of value are essentially a narrative about how value is created. If we assert that a theory of value should be quantitative, then this narrative must propose a unit (or units) that can be used to predict price. The exactitude with which a unit can be defined sets the basis for the exactitude of quantitative comparison. For neoclassical and Marxist theory, the units of utility and socially necessary labour time remain difficult to define. For an energy theory of value, the unit (Joules) is well defined, but the construct of embodied energy has no meaning without specified boundaries – the choice of which is fundamentally subjective.

In many ways, land, labour, utility, and energy theories of value rely on what I call a *universal quantifier*. While a *unit* allows quantitative comparison within the confines of a *specific* narrative, a *universal quantifier* (or *universal unit*) is capable of meaningful comparison *across all possible narratives*. For instance, we might compare the labour of two people based on any number of narratives: educational attainment, muscle power, intelligence, efficiency, etc. For each narrative, we might be able to specify a relevant unit. However, Marx's socially necessary abstract labour supplies no narrative but is supposedly universal in its application, making it a (non-existent) universal quantifier. Similar arguments can be made for both utility and embodied land and energy.

If we abandon these theories, the connection between the biophysical and the pecuniary spheres (if it exists) is as elusive as ever. In the next chapter, I review literature that has informed my thinking about how best to conduct an empirical investigation of the connection between monetary value and biophysical phenomena.

3. The Biophysical & the Pecuniary: Existing Scholarship

In this chapter, I review modern literature that grapples with prices and their relationship to the material world. I trace four major scholastic lineages that have influenced my thinking:

1. Ecological world-systems analysis;
2. Power approaches to political economy;
3. Production function approaches
4. Social Metabolism

3.1 Ecological Approaches to World-systems Analysis

World-systems analysis can perhaps best be described as a heterodox outgrowth of Marxian political economy. First articulated by Wallerstein (1976), world-systems analysis challenges the assumption, in the social sciences, that the nation-state should be the basic unit of analysis. Instead, Wallerstein proposed increasing the geographic scale of analysis to a ***world-system*** of interlocking socioeconomic territories. Building on dependency theorists such as Prebisch (1950), Singer (1950), and Frank & Press (1966), Wallerstein's basic premise was that the capitalist world-system was characterized by a hierarchical relationship between core and peripheral regions. He postulated that an "axial" division of labour existed between the core and the periphery, and that the former extracted ***surplus*** from the latter. World-systems theory has since grown into an expansive framework for understanding capitalist history.

World-systems theorists have proposed that the process of ***unequal exchange*** is one of the key mechanisms for facilitating this flow of surplus. In many ways, the most famous articulation of this concept, by Amin (1977) and Emmanuel & Bettelheim (1972), revolves around the *failure* of the labour theory of value on the international scale. Because of differentials in the price of labour between regions, it was realized that items of equal monetary value might not be equal in terms of labour content. For Amin and Emmanuel, we might say that core-periphery dynamics produced a *distortion* in the labour theory of value that allowed core regions to import more embodied labour than they exported.

Thus, the original articulation of unequal exchange was quite narrow in that it solely focused on labour time. This was to be broadened by the anthropologist Stephen Bunker (2007; 1985) in his case study of unequal energy flows out of the Amazon basin. Building on Bunker, anthropologist Alf Hornborg (1992, 2001, 2011) articulated a major restatement of unequal exchange theory by untangling it from what he calls "normative theories of value" (Hornborg, 2003, p. 5). For Hornborg, land, labour, and energy theories of value reflect how their respective theorists think value *ought to be formed*, rather than how it is *actually* formed. Hornborg sees neoclassical value theory as essentially correct – that value is "subjective"; however, Hornborg contests utilitarian theory's assertion that all exchange is mutually beneficial. For Hornborg, unequal exchange occurs because monetary value is *unrelated* to the biophysical qualities of the commodities being exchange.

Hornborg treats monetary value as "merely a surface phenomenon, an ideology of reciprocity beyond which we can discern highly asymmetric flows of resources" (2011, p. 2). Thus, Hornborg sees unequal exchange as a means for ***environmental load displacement*** – a way for the powerful to appropriate resources from the weak under the veil of reciprocity. It is the task of the critical analyst to measure these asymmetrical resource flows in order to better understand how lasting disparities in wealth are maintained.

Hornborg's conception of unequal exchange represents a clear break from land, labour, and energy theories of value for two reasons. Firstly, he sees unequal exchange as *pervasive*, rather than an unusual breakdown in an otherwise robust theory of value. Secondly, he insists on *multidimensional* (rather than unidimensional) analysis. For Hornborg, an exchange may be unequal in terms of ***exergy***, embodied labour, and embodied land.

In recent years, there has been an outpouring of research that follows Hornborg's line of inquiry into the biophysical asymmetries of world trade. For instance, Podobnik (2002) looks at unequal flows of energy between less-developed and developed countries. Giljum and Eisenmenger (2004), Giljum and Hubacek (2001), and Russi et al. (2008) investigate material flows by measuring the physical trade balance of numerous countries. Muradian et al. (2002) investigate embodied pollution in North/South trade, while Rice (2007) investigates the ecological footprint surplus/deficit of core and peripheral countries.

The above research agenda – what is often called *ecologically unequal exchange* – has been very successful in demonstrating that core-periphery trade that is equal in monetary terms can be shown to be unequal in biophysical terms. Building on the work of Hornborg and the empirical researchers cited above, in this paper, I *completely abandon* the idea that monetary value should equate to some embodied biophysical quantity. Furthermore, I accept Hornborg's assertion that monetary value often functions to conceal asymmetrical resource flows. However, in this paper, I do not use the empirical methodology of the ecologically unequal exchange school.

My first reason for not using this approach is that it relies heavily on geographically specific data – isolating two regions and investigating biophysical flow across their boundaries. In this paper, I am more concerned with biophysical *changes over time* (and their relationship with changes in the pecuniary sphere) than I am with biophysical flows through space. My second reason for not using this approach is that it continues to use concepts such as "embodied land" and "embodied pollution" in its analysis. Following Giampietro, Mayumi and Sorman (2011, 2012), I believe that the *truncation problem* poses a fundamental challenge to such measurement; therefore, I do not pursue it here. Thirdly, my goal in this paper is to look for *connections* (rather than divergence) between the biophysical and pecuniary spheres.

Lastly, and perhaps most fundamentally, if we wish to investigate unequal resource flows, it is unclear why monetary value must be referenced at all. In my mind, the asymmetry of international biophysical flows has been clearly demonstrated by the above researchers. The more interesting question, then, is what process creates the prices that then facilitate such unequal flows? World-systems scholar Christopher Chase-Dunn (1998) develops the notion of "power block formation" as a mechanism for creating and maintaining global disparities. While Chase-Dunn's analysis is primarily directed at state formation, his incorporation of power is important. Indeed, notions of *social power* are conspicuously absent from all theories of value discussed so far. In the next section, I review literature that has put social power at its epicenter.

3.2 Power Approaches to Political Economy

Utilitarian and labour theories of value usually assume that prices are the outcome of competitive markets, meaning no single buyer or seller can single-handedly influence the price of a commodity[11]. From the standpoint of such theories, concentrated social ***power distorts*** the price of commodities away from what they *ought* to be in a competitive environment. Yet the rise of large corporations poses serious problems for theories

---

[11] Energy theories of value (to the author's knowledge) have not engaged in this discussion.

based on competitive markets. Indeed, evidence suggests that the production of most commodities now occurs under conditions of oligopoly (Korten, 2001). Given this reality, a small group of scholars has attempted to place social power at the center of their theories. I call this body of work the *power approach to political economy*.

Perhaps the first scholar to place concentrated corporate power at the center of his analysis was Thorstein Veblen (1923). Both Marxist and neoclassicist theories centered around *production* (although the latter also focused heavily on exchange). Writing during the era of the Robber Barons, Veblen's approach was to view capitalism as a system of top down *control*, rather than a system of production. Indeed, for Veblen, production was a holistic process conducted jointly by humanity. Veblen used the term *industry* to refer to this process – the cumulative state of knowledge, skills, and technology inherited from previous generations of humanity. Industry operated on the principles of workmanship and creativity – the natural inclination of humanity to engage in meaningful activity. For Veblen, capitalism meant the ***business*** control of ***industry***. Veblen's *business* represented the *ownership* structure of society. Its ability to turn a profit, according to Veblen, rested on its power to strategically ***sabotage*** industry.

Veblen's key insight was to place the investigation of profit (and by extension, all monetary value) squarely on *private property* – the legalized right of *exclusion*. That is, for something to have a price, its owner must be able to prevent free access to it. This *power* to exclude ranges from very little, under competitive conditions, to enormous, under monopolistic conditions. Thus, under the oligopolistic conditions prevailing in the 20th century, business had immense power to restrict production for its own benefit.

Writing later in the 20th century, the Monopoly School (Baran & Sweezy, 1966) re-articulated Marxist theory to attempt to rectify it with the rise of corporate oligopolies. For Baran and Sweezy, concentrated power distorted prices such that the labour theory of value could no longer be used to explain them. At the same time, empirical work by Hall and Hitch (1939) placed doubt on the neoclassic theory of the profit maximizing firm. Hall and Hitch showed that firms did not attempt to maximize profit, as neoclassical theory posited. Instead, it appeared that corporate managers simply applied a markup to their costs based on accepted rules of thumb. Large firms, it seemed, were price setters, not price takers.

Kalecki (1971) postulated that the ability of a firm to increase its markup was a function of the "degree of monopoly". Building on this theme, Nitzan and Bichler (2009) propose that the ability to raise markup is a consequence of power, and that this power can be measured through *differential **capitalization***. For Nitzan and Bichler, prices are seen as an outcome of power – and (financial) capital is taken as a symbolic, quantitative manifestation of this power.

The implications of a *power theory of value* (Nitzan & Bichler, 2006, p. 4) are that prices have little, if anything, to do with the biophysical qualities of the objects being priced. Perhaps the greatest strength of such a theory is that it is capable of investigating the price of *legal structures* for which it is difficult (if not impossible) to conceive of a biophysical counterpart. Indeed, what is the biophysical manifestation of a corporate patent, a government bond, a collateralized debt obligation, or the market capitalization of a Fortune 500 corporation? If the *price structure of society* represents the metaphysical realm of all objects, institutions, and ideas that have a price, a compelling argument could be made that actual biophysical commodities represent a very small subset of this structure.

From this power school of political economy, I take three things. Firstly, I recognize that an investigation of the price structure of society is implicitly an investigation of its power structure. Secondly, I widen my conceptualization of price well beyond biophysical commodities to include legal structures. Thirdly, I adopt the

differential methodology proposed by Nitzan & Bichler (see Ch. 4.2).

The implication of Nitzan and Bichler's theory is the complete severing of the pecuniary and biophysical spheres. However, we can reconstruct this connection if we view prices as the symbolic medium of social power and that it is this social power that mediates biophysical flows. Unfortunately, due to time constraints, the investigation of social power that is explicit in the work of Nitzan and Bichler must remain implicit (for the most part) in this paper. Thus, I investigate the connection between prices and biophysical flows, but leave the more difficult task of tying this to social power to a later date.

3.3 Production Function Approaches

Within the neoclassical tradition, production functions have been the most popular way of relating biophysical inputs to monetary value. The production function approach has been adopted by ecological economists such as Ayres and Warr (2009) and Victor (2008). A ***production function*** is similar to recipe or chemical formula in that it is a mathematical mapping of inputs onto outputs; however, unlike a formula for a chemical process, where both inputs and outputs are measured in biophysical terms, a production function relates biophysical inputs to the *monetary value* of output. Thus, the implicit assumption behind all production functions is that the (real) monetary value of a finished product can be attributed to the value-creating qualities of the factors of production[12].

For the classical economists, the factors of production were considered to be land, labour, and capital. The neoclassisists shortened this to just labour and capital. It was not until the 20th century that sufficient statistical data existed to begin relating these inputs to the value of output. The most popular functional form – the Cobb-Douglas function – was developed and statistically tested by Cobb and Douglas (1928):

$$Y = AL^{\beta} K^{\alpha} \tag{5}$$

Here L denotes labour input, K denotes capital input, A is "total factor productivity", Y is the real value of output, and α and β are empirically determined constants assumed to sum to 1. Solow (1956) showed that traditional inputs of labour and capital were incapable of explaining much of the actual growth in real GDP. While he viewed this residual as indicative of technical progress, it remained exogenous to his production function.

Ayres and Warr (2009) attempt to explain this residual by adding an additional factor of production that they call ***useful work*** (U), defined as the product of ***exergy*** (B) input and the average efficiency of all energy converters (η) (see Ch. 6 for more detail):

$$U = \eta B \tag{6}$$

They then choose a LINEX production function of the following form:

$$Y = AU \exp\left(\alpha \frac{L}{U} - \beta \frac{(U+L)}{K}\right) \tag{7}$$

We can see from their functional form that useful work inputs are weighted much more heavily than either capital or labour. Indeed, as I discuss in section 6.3, useful work alone is capable of "explaining" real GDP growth up to the 1970s.

Production functions appear to give a rigorous, quantitative methodology for relating biophysical inputs to the resulting value of outputs. Indeed, in the case of the Ayres-Warr model, the result is incredibly accurate. If

---

[12] A similar assumption underlies the technique of hedonic regression. See p. 22.

we accept this model, it would appear that the relationship between biophysical inputs and real GDP has been settled once and for all.

However, despite the empirical success of the Ayres-Warr model, there remain serious epistemological issues surrounding the use of production functions. Georgescu-Roegen (1979) and Daly (1997) critique the Solow growth model for implying that factors of production are perfectly substitutable and for making no reference to the fact that production requires natural resources. Physicist Tim Garrett (2011a, 2011b) critiques neoclassical production functions for the use of multiple "tunable" coefficients, rather than a single empirically determined coefficient.

Mayumi, Giampietro, & Ramos-Martin critique Cobb-Douglas functions as being part of a "curve fitting fetishism in economics" (2012, p. 26). Looking at equation 5, we see that if α and β are any other numbers besides 0 and 1, dimensional quantities (labour and capital) will be raised to non-integer exponents, leading to nonsensical results. Mayumi et al. argue that the linear view of production implicit in all production functions is incompatible with the fact that economies are complex, self-referential systems. That is, they argue that an "economy not only produces goods and services, but more importantly, produces the processes required for producing and consuming goods and services" (2012, p. 30). This is similar to Veblen's view of industry as a holistic process inherited from previous generations. From a Veblenian framework, the notion of "factors of production" has no meaning.

There also remains the practical (and theoretical) problem of being able to *aggregate* the various factors of production so that they may be inputed into the production function. While labour and energy can be aggregated in units that are well agreed upon (hrs and joules, respectively), the aggregation of capital is fraught with difficulty. This is because capital is aggregated in terms of monetary value. Robinson (1953) argues that neoclassical methodologies for determining the value of capital rely inherently on circular logic. Indeed, Nitzan and Bichler (2009) devote much of their book to documenting the problems with both neoclassical and Marxist theories of capital. If we cannot determine the value of capital (or agree on what capital *is*), we cannot use it in a production function.

A further problem is that the decision about which inputs to include in a production function is entirely subjective. For instance, in order to improve the accuracy of previous efforts, Warr and Ayres (2012) further subdivide capital into "traditional capital" and "information and communication technology capital". Yet, there is no reason that more inputs could not be used.

Ultimately, I argue that the use of production functions is an outgrowth of neoclassical value theory. Production functions place the source of value in the qualities of the factors of production and their ability to produce goods and services from which consumers can derive utility. However, if we argue that value is an outcome of social power (as do Nitzan and Bichler), it is unclear how it can be "produced" at all.

In this paper I do not use production functions; however, there are certain aspects of Ayres and Warr's work that I retain. Garrett (2011a, 2011a) proposes treating the ***human-system*** as a heat engine that does work on itself in order to maintain/grow its structure. In this purely thermodynamic treatment of the human-system, we might use Ayres and Warr's useful work not as an *input* to the production of value, but as a fundamental *self-reflexive output* of the system – that is, the human-system produces useful work in order to "do" this useful work on itself. Thus, I retain Ayres and Warr's estimation of useful work, but I do not use it in a production function.

3.4 Social Metabolism

Recently, a body of literature has emerged that operates under the banner of *social metabolism*. Drawing on insights from systems-ecology, industrial ecology, and complexity theory, the study of social metabolism attempts to empirically examine the interaction between biophysical and social phenomena in a non-reductionist way. Here I focus on the work of Kozo Mayumi and Mario Giampietro, whose work can perhaps best be described as a continuation of the flow-fund model developed by Georgescu-Roegen (1971) and mapping of ecosystem energy flows developed by Howard Odum (1983).

Complex systems represent a unique challenge to quantitative analysis because they are non-linear, contain innumerable ***feedback*** loops, and are characterized by multiple hierarchical nested components. While the typical approach to empirical analysis in economics is to reduce a problem to a single scale and a single metric of analysis, the approach adopted by Mayumi and Giampietro is to conduct analysis at multiple scales using multiple metrics.

Mayumi and Giampietro characterized their work as part of a new post-normal science that undertakes quantitative analysis for informed policy decision-making rather than the search for "truth". Their approach relies on parallel, non-equivalent descriptions of the same phenomena as seen from different scales and different metrics. Giampietro and Mayumi call this the MuSIASEM approach (Multi-Scale Integrated Assessment of Societal and Ecosystem Services). This methodology was first articulated in Giampietro & Mayumi (2000) and then fully developed in Giampietro, Mayumi & Sorman (2011; 2012). Borzoni writes that:

> *MuSIASEM makes it possible to simultaneously analyze how flows of energy, money and material are generated and exchanged among the different scales that make up a given societal organization which, in turn, is embedded in a larger ecosystem. Practical applications of MuSIASEM are mainly parallel economic and biophysical historical analyses of trajectories of development of specific regions or countries.* (2011a, p. 5)

This MuSIASEM approach has recently been applied to a wide range of empirical case studies, both at the national scale and at the local scale (Borzoni, 2011b; D'Alisa, Cattaneo, & Gamboa, 2009; Diaz Maurin, 2012; Fiorito, 2013; Lobo Aleu & Baeza, 2009; Pastore, Giampietro, & Mayumi, 2000; Ramos-Martín, Cañellas-Boltà, Giampietro, & Gamboa, 2009; Ramos-Martin, Giampietro, & Mayumi, 2007; Recalde & Ramos-Martin, 2012; Siciliano, Crociata, & Turvani, 2012).

The bulk of the theoretical content of the MuSIASEM approach can be seen as an epistemological statement about how data for complex socioeconomic systems should be organized. Its essential strength, in my view, is that it does not reduce analysis to the level of singular metrics such as economic energy intensity (GDP per unit of energy) or EROI.

However, while Giampietro, Mayumi, and Sormon outline a robust approach for the treatment of energy and human activity data, their treatment of monetary data is more simplistic. Indeed, Giorgos Kallis aptly critiques the MuSIASEM approach for having "very little to say about relative prices" (2012, p. 96). However, since the MuSIASEM approach is not a prescribed methodology, but rather, an open ***grammar***, there is no reason that a more robust approach to the study of prices cannot be incorporated into the MuSIASEM approach. Indeed, this is what I attempt throughout this paper.

3.5 A Synthesis of Nitzan & Bichler and Giampietro & Mayumi

This paper is built on a synthesis of two approaches that are, in many ways, diametric opposites. On the one hand, Nitzan and Bichler's work fully severs the link between monetary value and the biophysical sphere in order to develop a theory of value based on social power. On the other hand, Giampietro and Mayumi develop a biophysically based analytical framework that connects the biophysical with the pecuniary sphere, but says little about relative prices and nothing about social power. The synthesis that I adopt uses Nitzan and Bichler's method for studying relative prices and Giampietro and Mayumi's method of biophysical categorization. The goal of this synthesis is to gain insight into the following thesis question:

> How can a biophysical approach to economics be used to gain insight into the complex interrelationship between the biophysical sphere of economic activity and its monetary image?
>
> More specifically:
>
> 1. What types of pecuniary signals (if any) are related to the movement of human activity?
> 2. What types of pecuniary signals (if any) are related to changes in energy throughput?

In the next chapter, I outline more exactly the ideas and methodologies that I have borrowed from Nitzan & Bichler and Giampietro & Mayumi for conducting my empirical study. My approach is to treat prices as a *definition* – an agreed-upon[13] social convention. My hope is that this can help us shift the analytical focus away from ***causation*** towards *co-evolution.*

Using the empirical approach laid out in Chapter 4, Chapter 5 investigates ways that pecuniary signals (in the form of value-added, profit and wages) can be related to the movement of human activity. Chapters 6 focuses on how changes in energy throughput at the *national* level can be related to changes in the pecuniary sphere, while Chapter 7 looks at ways that pecuniary signals can be related to changes in *sectoral* energy throughput.

---

[13] "Agreed" is perhaps not the best word, since I implicitly adopt Nitzan and Bichler's view that prices are the outcome of a power struggle.

4. Towards a Co-Evolutionary View of the Pecuniary & the Biophysical

> *The transference of culture in time can, in large measure, be described as the conservation of sign systems serving as a control on behavior.*
>
> - Ivanov & Bradbury (1978, p. 200)

Prices, I argue, play a fundamental role in influencing our collective behavior – meaning they affect the *future.* By introducing time into our analysis, I assert that it is possible to link the pecuniary and the biophysical spheres as they *co-evolve*. What I propose, therefore, is not so much a theory of value as a theory about how to *investigate* value. I begin by proposing that we treat prices in a similar manner as we might treat a linguistic *definition.*

A linguistic definition allows a word to be mapped onto an object (or idea). For instance, Figure 4 shows the mapping of the word "shirt". Why is this definition true? Interestingly, Ferdinand de Saussure, one of the founding fathers of ***semiotics***, famously postulated that the relationship between a sign and its meaning (its *definition*) is completely arbitrary (Drimmer, 2007). It is merely agreed upon by social convention, the disintegration of which renders a definition meaningless. The more interesting relationship, then, is not the symbolic mapping at any given time, but the evolution of this mapping *over* time, at its relationship to societal structure. For instance, by tracing and placing within a historical context the co-evolution of the word "shirt" (its etymology) and the physical garment, we might gain a better understanding of how the word became associated with the material object.

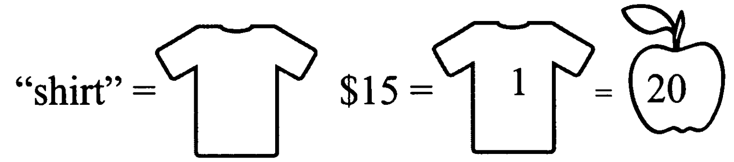

Figure 4: Semantic Relationships

I argue that prices can also be treated as (rapidly changing) definitions, but ones that allow an *abstract quantity* to be mapped onto an object (or idea). For instance, Figure 4 shows the mapping of a price onto a shirt and the relationship between a commodified shirt and a commodified apple. Again, we might ask – why is this mapping true? In Chapters 2 and 3, we looked at different ways that scholars have proposed for answering this question. While I am partial to Nitzan and Bichler's power theory of value, for most of this paper, I avoid the "why" question in favour of a "how" question; that is, I attempt to investigate how prices and the material world co-evolve. Whenever possible, I attempt to place this investigation within a historical context.

Because of the universality of prices (all commodified objects are universally commensurable), it makes little sense to study the co-evolution of biophysical qualities and pecuniary quantities at the level of a few commodities. Instead, I propose studying the *price structure of society*[14], here defined as the metaphysical realm of all objects, institutions, or ideas that have a monetary *price*. The price structure of society refers not to the objects, institutions, or ideas themselves, but to their representation as an abstract monetary quantification. Because I am not proposing a theory of value, but a theory of how to *investigate* value, a co-evolutionary view of the biophysical and pecuniary spheres should be empirically, rather than theoretically, guided.

---

[14] Used synonymously with *pecuniary sphere* and *monetary image.*

In order to conduct such an empirical study, I have selected two very distinct empirical methodologies. For the categorization and quantification of the biophysical sphere, I draw heavily on Giampietro, Mayumi, and Sorman's "MuSIASEM" approach. For pecuniary data, I use Nitzan & Bichler's "differential" analysis. These methodologies are very different from those typically used by economists. By synthesizing them, it is my hope to create an unorthodox empirical methodology that is suitable for investigating unorthodox questions.

4.1 The MuSIASEM Approach

Giampietro, Mayumi, and Sorman's MuSIASEM approach stands for "multi-scale integrated analysis of societal and ecosystem metabolism". While discussing the details of their methodology surpasses the scope of this paper (see Giampietro et al. 2011, 2012 for a detailed explanation), here I outline the aspects of the MuSIASEM approach that are most relevant to my own work.

In my mind, there are two essential components to the MuSIASEM approach: 1) a complex taxonomy for classifying the biophysical sphere, and; 2) an in-depth epistemological treatise justifying/explaining this taxonomy. My work here draws mostly on their taxonomy; however, I make use of three specific elements of their epistemology: the concepts of *autopoiesis*, *impredicativity*, and *grammar*.

Autopoiesis literally means "self-creation". The term has become popular in biology because living systems constantly reproduce their own structure. In contrast, an ***allopoietic*** system – for instance, a computer factory – produces things *other* than itself. The act of self-creation is problematic to the traditional scientific process that based on ***cause*** and ***effect***. ***Autopoietic*** systems are, by their nature, ***impredicative*** – they are self-referential. Giampietro explain why this is problematic:

> *The epistemological predicament of impredicativity is difficult to reconcile with quantitative science since it conflicts profoundly with the simplifications inherent in reductionism. In fact, impredicativity is closely related to the familiar paradox of "chicken-egg logic" that challenges the unidirectional explanation of causality: one needs to assume the pre-existence of a chicken to explain the existence of an egg, but at the same time one needs to assume the pre-existence of the egg to explain the existence of a chicken.* (2011, p. 159)

Lastly, Giampietro et al. introduce the concept of a ***grammar*** as an alternative to a scientific ***model***. A scientific model is a theoretical argument based on a set of logical postulates. These postulates imply a set of pre-analytic decisions that *remain fixed in time*. Thus, a scientific model does not evolve – it is either accepted or rejected. In contrast, Giampietro et al. propose a *grammar* that allows pre-analytic decisions to remain dynamic and subject to feedback. Their concept of a grammar can be seen as a response to neoclassical economic models that bury pre-analytic decisions under mountains of mathematical "formalism nonsense" (ibid, 2011, p. 132).

When applied to a complex system, Giampietro et al. argue that the pre-analytic decisions used in a grammar should answer the following questions:

1. What is the system?
2. What does the system do?
3. How does the system do it?

Below, I outline my own responses to these three questions.

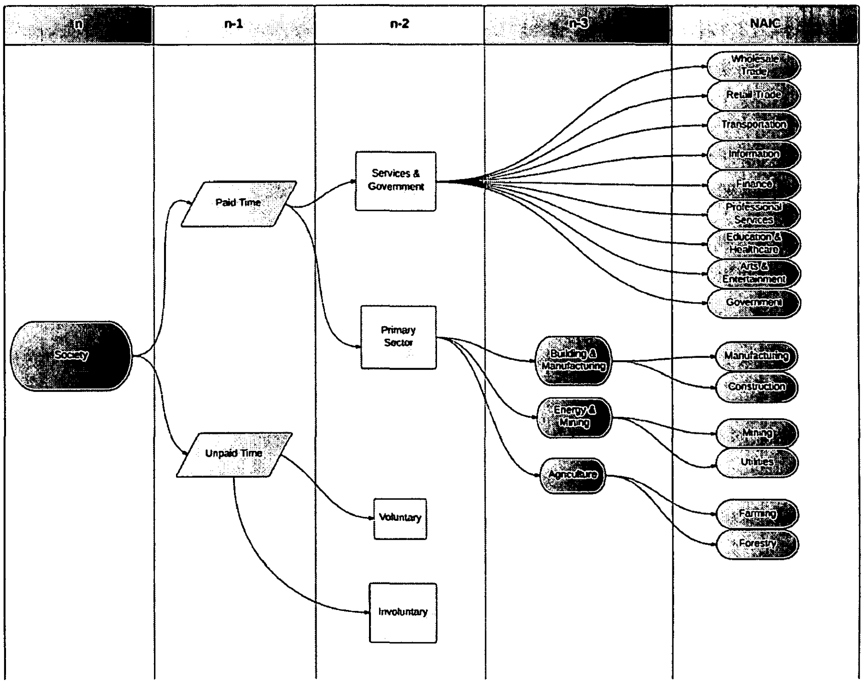

Figure 5: MuSIASEM Taxonomy of Human Activity
Adapted from Giampietro, Mayumi, and Sorman (2011)

4.1.1 What is the system?

Following Giampietro et al., I define the human-system in terms of the different types of ***human activity*** that occur within it. Figure 5 shows a variation of a taxonomy created by Giampietro, Mayumi, and Sorman (2011) for this purpose. Here, I apply it specifically to the United States. The simultaneous use of multiple scales allows for a non-reductionist approach to categorization. From left to right, the taxonomy moves from the "whole" towards consecutively more specific sub-sections.

At the level *n*, society is viewed as an undifferentiated whole. Moving to *n*-1, we differentiate between activity that is paid and activity that is unpaid. While unpaid activity can be further differentiated, this paper is concerned with the pecuniary sphere and, therefore, restricts analysis mostly to paid activity only. Moving to *n*-2, paid activity is further differentiated into the Services & Government sector (SG) and the Primary & Secondary Sector (PS). At the level *n*-3, the PS sector is differentiated into Building & Manufacturing (BM), Energy & Mining (EM), and Agriculture (AG).

Statistical data for the US is generally categorized according to the North American Industry Classification System (NAICS). In Figure 5, the right hand column shows how NAICS categories fit into the MuSIASEM taxonomy.

This taxonomy is the most fundamental aspect of my epistemology. All the concepts and empirical data that I investigate in this paper rely upon the differentiation of the human-system into hierarchically linked ***domains***[15] of human activity.

4.1.2 What does the system do?

All autopoietic systems reproduce themselves, so in a sense, this is what the human-system "does". However, in order to garner useful analysis, one must focus on specific aspects of this reproduction. Here, I am interested in the demographic changes that have occurred since the industrial revolution.

In order to investigate this transition quantitatively, from the MuSIASEM taxonomy I select and rank four human activity *domains* in order of their metabolic *primacy*[16]:

1. **Agriculture**: endosomatic energy and nutrient gathering (for *human* metabolism);
2. **Energy & Mining**: exosomatic energy and raw material gathering (for *social* metabolism);
3. **Building & Manufacturing**: transformation of raw materials into finished product;
4. **Services & Government**: administration, distribution and delivery of final goods and services.

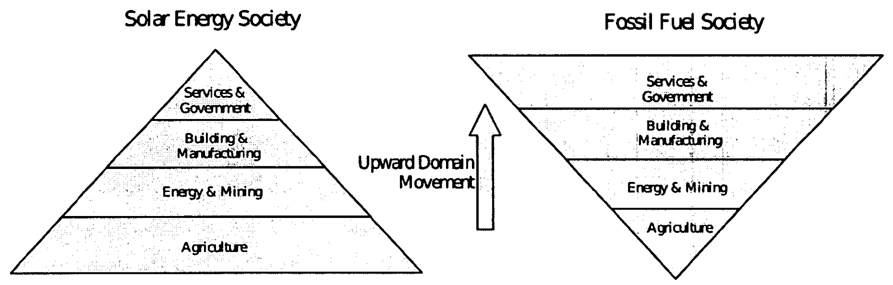

Figure 6: Human activity distribution: solar vs. fossil fuel societies

Having defined these domains, Figure 6 shows how agrarian societies differ from fossil fuel societies. While this is an idealized representation, it is meant to convey the fact that the two societies are *dramatically* different – they are demographic *inversions* of each other. In order for a solar energy society to become a fossil fuel society, it must undergo what I call ***upward domain movement*** – the mass movement of human activity from lower to higher domains.

This demographic inversion, I argue, is one of the defining features of fossil fuel societies. However, it is not a one time transition; rather, it is a *continual process*. Therefore, in this paper I argue that *upward domain movement is what fossil fuel societies do.*

---

[15] I use the word ***domain*** more or less synonymously with the word ***sector***; however, the latter implies a formal division of labour while the former does not. Human activity within an agrarian society (or even a hunter gather society) is still split between multiple activity *domains* even though *sectors* do not exist.

[16] By *primacy*, I simply mean that the material output of lower domains typically becomes the input to higher domains – this is in no way a ranking of *importance*.

4.1.3 How does the system do this?

From a conservation of mass standpoint, it is straightforward to show that upward domain movement requires increases in the labour ***productivity*** of lower domains. If fewer people provide the same (or greater) amount of biophysical output, the output per worker in lower domains must increase. Increases in labour productivity, therefore, *allow* upward domain movement to proceed. The gains in US labour productivity over the last 200 years have been enormous. For example, from 1800 to 1980, the labour productivity of corn producers increased by a factor of 115 (Figure 7).

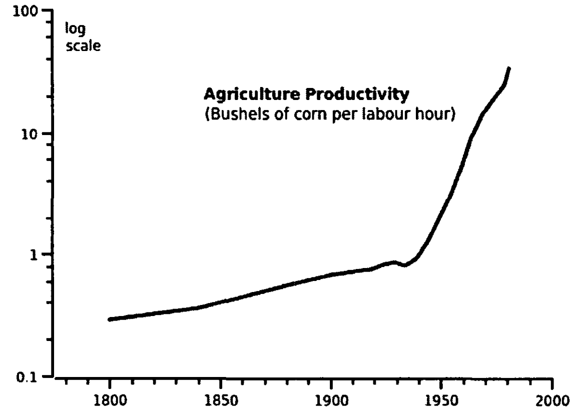

Figure 7: US Agricultural Productivity
Source: Historical Statistics of the United States (Carter et al., 2006),Table Da1144

Increases in labour productivity are often attributed to the increased use of machines. I agree with this attribution; however, we need to go the extra step to ask *why* machines are able to run in the first place. Suffice it to say that all machines require *energy* inputs to function. Biophysical scholars have demonstrated a deep connection between increases in labour productivity and increases in energy throughput (Cleveland, Costanza, Hall, & Kaufmann, 1984). Thus, machines allow the increases in productivity that facilitates upward domain movement; however, the whole process is predicated on increases in energy consumption.

Having answered the three questions posed by Giampietro et al., I can state my pre-analytic vision succinctly: *fossil fuel societies use increases in energy consumption to facilitate upward domain movement.*

4.2 Nitzan & Bichler's Differential Analysis

If fossil fuel societies use increases in energy consumption to facilitate upward domain movement, what mechanism "tells" people to move from one activity domain to another? What mechanism "tells" society to use more energy? My hypothesis is that the price structure of society sends these signals. However, I am *not* testing to see if this is a causal relationship. Rather, I view the price structure of society, upward domain movement, and increases in energy consumption as being linked in an impredicativity-loop.

For analysis of the pecuniary sphere, I make use of Nitzan and Bichler's concept of ***differential*** analysis. Before explaining what it is, I will explain the epistemological problem that it seeks to address – namely, our inability to objectively quantify ***inflation.***

The quantification of inflation relies on the continual comparison of the price structure of society to some underlying *real* quantity (compared to some base year). If prices increase but this real quantity does not, we have *inflation*. On the other hand, if prices increase in tandem with this real quantity, this is *appreciation*. Our ability to measure inflation depends crucially on our ability to objectively quantify the changing qualities of the biophysical world.

While few would deny that prices increase over time, the ability to quantify inflation even at the level of a single commodity remains problematic. Jonathon 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! (Nitzan, 1992, p. 155)

There exist several different methods for quantifying qualitative changes in commodities, perhaps the most rigorous of which is called ***hedonic quality adjustment***. The BLS explains this technique as follows:

> The use of the word "hedonic" to describe this technique stems from the word's Greek origin meaning "of or related to pleasure." Economists approximate pleasure to the idea of *utility* – a measure of relative satisfaction from consumption of goods. 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. ("Frequently Asked Questions about Hedonic Quality Adjustment in the CPI," 2010) [emphasis added]

Thus, this methodology adopts a neoclassical framework based on utility, meaning the most fundamental critique that can be leveled is that utility *cannot* be measured. However, if we disregard this problem, the process of ***hedonic regression*** still relies on a set of deeply subjective pre-analytic decisions. In order to conduct a regression, the analyst must first determine the relevant set of attributes of the commodity being analyzed. The BLS uses the example of men's shirts and lists the relevant attributes as type of fiber and short-sleeve vs. long sleeve. We might add to this the color, the fabric pattern, and the existence/type of a branded logo. Of course, consumer desires are also shaped by fashion. If a celebrity makes a particular style of shirt popular, we need to add a "trendy" attribute to our analysis. The list goes on and on. I argue that the pre-analytic choice of relevant attributes is fundamentally a subjective decision.

Furthermore, the validity of hedonic regression depends on the choice of regression *function*. Should it be exponential, linear, logarithmic? There are no objective criteria for choosing. Interestingly, the BLS uses a logarithmic regression function:

$$\ln p=\beta_0+\beta_1 X_1+\beta_2 X_2+\beta_k X_k+\epsilon \tag{8}$$

Here, the dependent variable, $\ln p$, is the natural log of price, β_k are the coefficient estimates of the relevant quality attributes (X), and ε is the error term. Equation 8 violates a fundamental mathematical rule by placing a dimensional quantity (price in \$) inside a logarithmic function. Mayumi et al. (2012) note that this leads to the absurdity of cubic and higher order "dollars"[17].

Even if we suppose that inflation could be quantified in a completely objective manner, it is not at all clear what the inter-temporal comparison of *real* measures means. Nitzan asks – "how should we interpret the measure of real GNP in 1882 when denominated in '1982 prices'? Most commodities produced in 1882 were simply unavailable in 1982 and hence could not have '1982 prices.'" (1992, p. 176). However, the construction of real GDP time series, for instance, relies upon the implicit assumption that all data within the series can be compared. I argue that from a semiotic point of view, the concept of constant prices makes little sense. The relationship between a sign and its definition is time and place specific.

If we return to the relationship between the word "shirt" and the signified physical garment, we run into problems with inter-temporal comparison. For instance, the word "shirt" comes from the Old English words *scort* or *sceort* ("Shirt," 2013); however, these latter words seemed to refer more to an apron garment than what we recognize as a "shirt". If we attempt to map the garment pictured in Figure 4 to older words, we run into similar problems because the T-shirt design did not exist before the late 19th century ("T-shirt," 2013). If prices are to be treated as purely quantitative semantic relationships, it follows that they only have a meaning at the time and place of a market transaction.

---

[17] Mayumi et al. note that the natural logarithm may be re-written as the following infinite polynomial, where *z* is a positive real number:

$$\ln z=2\left[\left(\frac{z-1}{z+1}\right)+\frac{1}{3}\left(\frac{z-1}{z+1}\right)^3+\ldots+\frac{1}{2m-1}\left(\frac{z-1}{z+1}\right)^{2m-1}+\ldots\right]$$

If a dimensional quantity (\$) is put into the natural logarithm (left side), it implies that it is also put into the polynomial (right side). However, we can see that this will result in cubic and higher order dollars. To maintain dimensional validity, only dimensionless (unit-less) numbers may be inputed into logarithms. Thus, the regression formula used by the BLS is *nonsensical* on a dimensional basis.

Given this assertion, how are we to construct time series of monetary data? Nitzan and Bichler (2009) propose a simple solution that they call *differential* analysis. Prices are treated as *relative* phenomena that are meaningful only when compared to other prices of the same period. Differential analysis means that all pecuniary time series are constructed out of the dimensionless ratio of two prices, rather than deflated by a price index.

I have adopted this methodology wholeheartedly and have used it not only for pecuniary data, but for biophysical data as well. I make use of the semantic categories from the MuSIASEM approach, but I opt to look at the differential growth *between* sectors over time. Using this synthesis of the MuSIASEM approach and differential analysis, in the remaining chapters I investigate the relationship between upward domain movement, increases in energy consumption, and differential changes in the pecuniary sphere.

5. Human Activity

In this chapter, I seek to address the following question: what types of pecuniary signals (if any) are related to the movement of human activity? I specifically attempt to link changes in value-added, profit, and wages to a metric that I call *differential domain growth.* My goal here is to investigate the role that the price structure of society has played in shaping the great demographic transitions of the 20th century.

The layout of this chapter is as follows. In section 5.1 I first discuss the strengths and weaknesses of the human activity data made available from US statistical agencies. I then outline my reasons for choosing the particular data set used in this thesis. In section 5.2 I explain my concept of *differential domain growth* and graphically display its relationship with *absolute domain growth.* In sections 5.3, 5.4, and 5.5, I relate differential per person value-added, differential per person profit, and differential wages (respectively) to differential domain growth. In section 5.6, I summarize results and attempt to offer thoughts on their meaning.

5.1 Data Selection

Despite the fact that US statistical data is among the best in the world (if not *the* best), there are numerous shortcomings with all human activity datasets provided by the US Bureau of Labor Statistics (BLS, 2012) and the US Bureau of Economic Analysis (BEA. 2012).The MuSIASEM taxonomy relies on our ability to accurately categorize human activity into different domains. Thus, decisions about *how* this categorization is to be done are of crucial importance.

The accuracy of any quantification depends upon the exactitude of the unit of categorization. Perhaps the most accurate unit for categorizing human activity might be the "domain-hour", whereby every hour of every person's life is categorized into a particular domain of activity. Alternatively, we might use the "domain-person", whereby every person's life is categorized into a domain based on their "primary" activity[18]. In practice, the BLS and the BEA use the basic unit of the ***establishment***, defined as

> *an economic unit, such as a factory, mine, store, or office that produces goods or services. It generally is at a single location and is engaged predominantly in one type of economic activity. Where a single location encompasses two or more distinct activities, these are treated as separate establishments, if separate payroll records are available, and the various activities are classified under different industry codes.* ("BLS Handbook of Methods," 2009, Chapter 2, p. 1)

The classification of establishments into NAICS codes is done based on their *primary* activity. If an establishment is engaged in more than one activity "the entire employment of the establishment is included under the industry indicated by the principal activity" (ibid, Chapter 2, p. 4). This presents an immediate problem. For instance, using the above methodology, accountants who work at an automobile factory (primary activity – manufacturing) would be statistically represented as manufacturing workers. However, if the same accountants were to be moved to a head office, they would then be statistically represented as service sector workers.

The matter is further complicated once pecuniary measures are introduced. While wage and salary

---

[18] Classification by primary activity could conceivably be done based on BLS Occupational Employment Statistics (OES). However, a problem with this approach is that similar occupations (for instance, management) occur in different sectors. If we classified all management as a service, this would render employment data incompatible with monetary data (ie: profit, value-added) in which management is classified according to the industry status of the company in which they work. Furthermore, the OES does not collect data from self-employed persons ("Occupational Employment Statistics Overview," 2013).

information is collected from *establishments*, other pecuniary data (for instance, profit) is collected from *companies*, which are then categorized into an industry code on the basis of the "principal industry of all their *establishments*" ("Concepts and Methods of the U.S. National Income and Product Accounts," 2012 Ch. 2, p. 21). While an *establishment* is a geographic entity, a ***company*** is a legal entity based fundamentally on *ownership*. Thus, changes in the ownership structure of society will seriously affect this measure.

For instance, if a small insurance company (a *service* firm) is bought by Ford Motor Company (a *manufacturing* firm), suddenly the insurance company's profit will be classified as *manufacturing* even though no underlying change in activity occurred. The BEA admits that "classification of a company may change as a result of shifts in the level of consolidation of entities for which company reports are filed or as a result of mergers and acquisitions. This factor affects company-based estimates much more than establishment-based estimates" (ibid, Ch. 2 p. 21). This makes establishment data more reliable, in my mind. In some instances, when comparing human activity and pecuniary data, I am forced to commit the cardinal sin of combining data collected from *establishments* with data collected from *companies*. While this is not ideal, there are simply no alternative data sources.

Another issue arises around *who* is to be counted. The idea behind MuSIASEM categorization is to count *every* person in each domain. However, most statistical data is geared towards counting only *employees*. Figure 8 shows three potential sources for human activity data. There are problems with each. Series A was created by the author using composite data from the Historical Statistics of the United States (HSUS) and the Bureau of Labor Statistics. Human activity (in hours) was calculated using equation 9:

$$Human\,Activity(hrs) = number\ of\ employees \times hours\ per\ week \times weeks\ per\ year \tag{9}$$

Unfortunately, the *hours per week* data available from the BLS only includes *private* sector workers. This is problematic because the average work week in the *private* service sector has declined significantly over the last 30 years, due to the growth of part-time labor. A similar decline has not occurred in the *public* sector, meaning Series A undercounts SG hours.

Both Series A and B are less than ideal for MuSIASEM analysis because they *exclude* self-employed persons. Series C rectifies this problem by including self-employed individuals[19]. All workers are counted on a *full-time equivalent* basis. According to the BEA:

> *The number of full-time equivalent employees in each industry is the product of the total number of employees and the ratio of average weekly hours per employee for all employees to average weekly hours per employee on full-time schedules.* ("What are full-time equivalent employees?," 2007)

What constitutes full-time employment, it would seem, is not defined by the BEA but by the *employer*. It is quite conceivable that the average work week of a full-time employee could differ from sector to sector, meaning inter-sectoral data is not strictly comparable.

The choice between data sets is entirely subjective. In terms of the PS sector, Series B seems to be an outlier, especially prior to 1970. In terms of the SG sector, Series A and B are virtually indistinguishable, while Series C is significantly higher – likely due to the inclusion of self-employed individuals. Because of the inclusion of self-employed individuals, I have chosen to use Series C for all human activity data (unless

---

[19] In order to convert full-time equivalent data into hours per year, I have multiplied by an average work week of 40 hours and a work year of 52 weeks. While this decision is arbitrary, I am mostly concerned with *differential* measures, so these numbers will disappear when data is compared in ratio form.

otherwise indicated).

Having made this decision and noted the methodological flaws, for the remainder of this paper I simply accept this data as given and treat it as a reasonably accurate representation of the human activity of the United States.

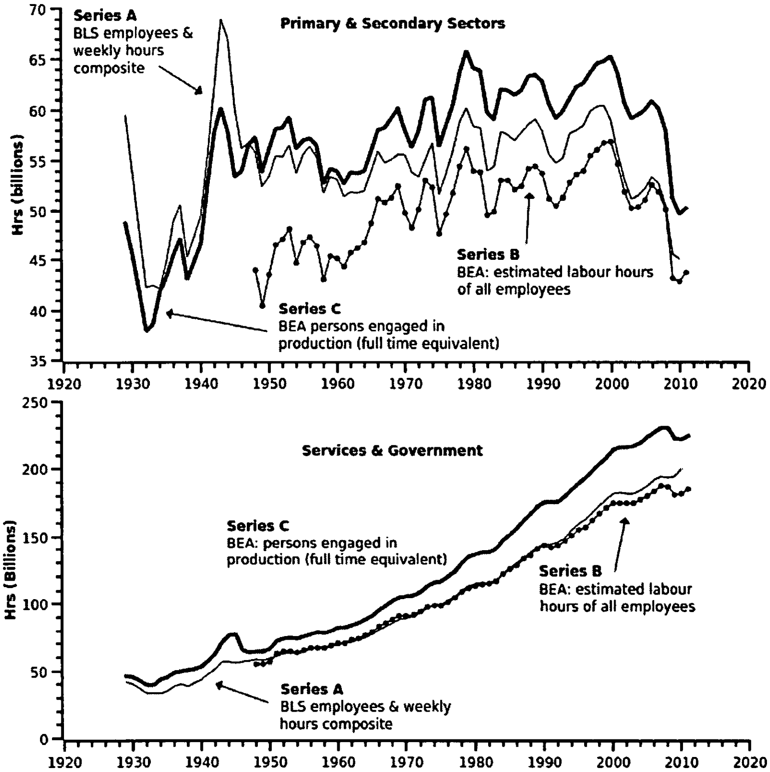

Figure 8: Human Activity Data from Different Sources

Sources:

BLS employee & weekly hours composite data derived from multiple sources:

Non-Farm employees:

1920-1999 from HSUS, Table Ba840-848, *Employees on nonagricultural payrolls, by industry;*
2000-2008: BLS, Employment & Earnings , January 2009 Vol. 56 No. 1, Table B-1;
2009-2010: BLS Current Employment Statistics Online;

Farm: 1920-1990: HSUS, Ba472, *Labor force, employment, and unemployment*;
1991-1999: HSUS, Ba482 *Labor force, employment, and unemployment* ;
2000-2010: BLS Employment status of the civilian noninstitutional population 16 years and over by sex

Average Weekly Hours:

1920-50: HSUS, Table Ba4575. Average weekly hours of workers in private, nonagricultural jobs;
1950-1964: Linear interpolation to BLS data for SG & PS;
1964-2008: BLS Employment & Earnings , January 2009 Vol. 56 No. 1, Table B-2;
2009-2010: BLS Current Employment Statistics Online;

BEA estimated labour hours of full & part-time employees from BEA Income & Employment by Industry, Table 6.9B (1948-87), Table 6.9C (1987-2000), & Table 6.9D (2000-2011). Discontinuities exist between each table – therefore all values are indexed to Table 6.9C.

BEA persons engaged in production (FTE) data from ibid, Table 6.8A (1929-48), Table 6.8B (1948-87), Table 6.8C (1987-2000), & Table 6.8D (2000-2011). All values are indexed to Table 6.8C and multiplied by $40\ \text{hr/week} \times 52.1775\ \text{weeks/year}$.

5.2 Differential & Absolute Domain Growth

In Chapter 4, I defined and ranked the following four domains in terms of their metabolic primacy:

1. Agriculture (AG)
2. Energy & Mining (EM)
3. Building & Manufacturing (BM)
4. Services & Government (SG)

Upward domain movement was defined as the movement of human activity from lower to higher domains. It is this upward domain movement that I wish to quantify and compare with pecuniary data. Because no data exists on the exact flow of people between domains, I propose an alternative measure that I call *differential domain growth,* defined as the *growth rate* of the *ratio* of human activity between any two domains. For instance, for the SG and BM sectors:

$$\text{SG / BM Differential Domain Growth Rate} = \widehat{\left[\frac{HA_{SG}}{HA_{BM}}\right]} \approx \hat{HA}_{SG} - \hat{HA}_{BM} \qquad (10)$$

In equation 10, HA_{SG} denotes SG human activity, HA_{BM} denotes BM human activity, and the hat sign (^) denotes growth rate. Equation 10 also shows that the differential domain growth rate can be approximated by the *difference* in the absolute growth rates of each sector.

I have opted to investigate differential growth between both adjacent and non-adjacent domains[20]. There are six unique combinations of the four domains (Figure 9). In the following sections, I compare all six combinations to pecuniary data. However, by looking only at *differential* growth, we cannot tell which domain is growing *absolutely.* For this reason, I first look at trends in both *differential* and *absolute* domain growth for SG/BM, SG/EM, and SG/AG.

1. SG/BM   2. SG/EM   3. SG/AG   4. BM/EM   5. BM/AG   6. EM/AG

Figure 9: Domain Combinations

Figure 10 shows differential and absolute domain growth rates for the SG and BM sectors. The distance between the absolute growth rate curves approximates the differential growth rate, with the color gray denoting $\hat{HA}_{SG} > \hat{HA}_{BM}$ and striped denoting $\hat{HA}_{SG} < \hat{HA}_{BM}$. The top axis shows how this translates into differential domain growth.

Three interesting trends emerge. Firstly, the differential domain growth rate remained *positive* for almost the entire period shown. The two exceptions were during the Great Depression and immediately after World War II. The fact that the SG sector grew faster than the BM sector for most of the 20th century lends support to the assertion that upward domain movement is a central feature of fossil fuel societies. A second interesting trend is the secular decline in absolute growth rates that occurred after 1990. Note that in 2008, SG absolute growth becomes negative for the first time in half a century.

A third key trend that emerges is the *cyclical* nature of growth. After WWII, both absolute and differential growth rates move in a 10-15 year cycle. However, the *peaks* in differential growth occur not during *peaks* in absolute growth, but during *troughs.* Looking more closely, it appears that it is *contraction* in the BM sector, rather than *growth* in the SG sector, that drives differential growth.

---

[20] Adjacent in terms of their metabolic ranking

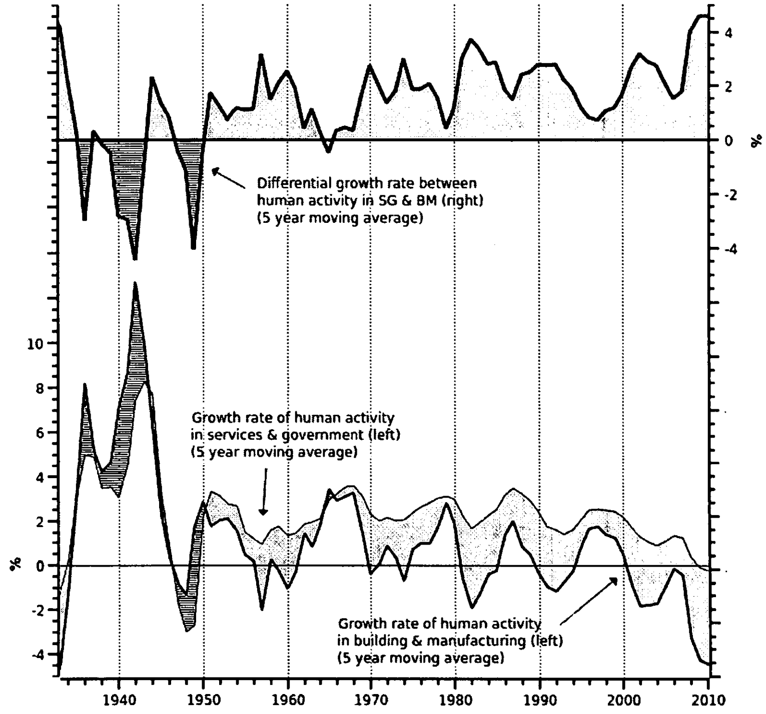

Figure 10: Differential & absolute domain growth: SG/BM
Sources: Human Activity Series C. See Figure 8.

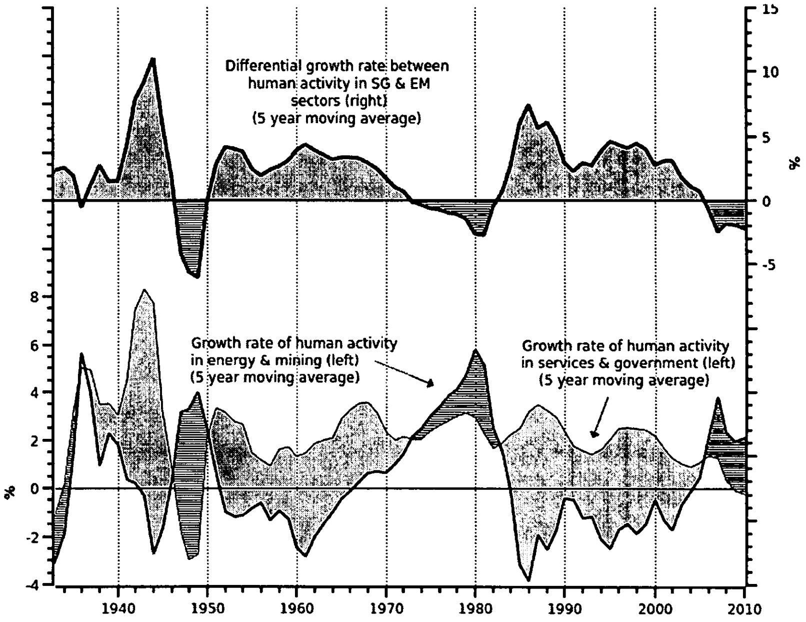

Figure 11: Differential & absolute growth: SG/EM
Sources: Human Activity Series C(see Figure 8)

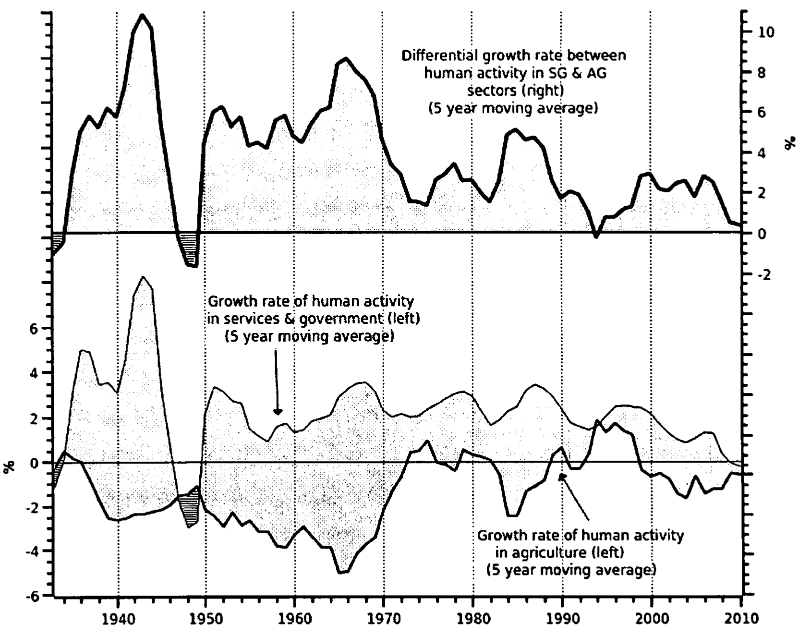

Figure 12: Differential & absolute domain growth: SG/AG
Sources: Human Activity Series C (see Figure 8).

Figure 11 shows both differential and absolute domain growth rates for SG/EM. Again, positive differential domain growth dominates. Interestingly, we do not see short-term cyclical behavior like with SG/BM; rather, we see three long term cycles. Notice that the *troughs* in differential growth occur during *peaks* in EM absolute growth. In fact these three peaks in EM absolute growth and troughs in SG/EM differential growth correspond nicely with the post-WWII demobilization, the 1970s energy crisis, and the Great Recession. It seems that periods of crisis correlate with *growth* in HA_{EM}. This is puzzling from the neoclassical perspective, which treats all job growth as equally positive[21]. In Chapter 6, I will attempt to explain this contradiction in terms of the EM sector's unique position as the sole supplier of exosomatic energy to the entire human-system.

Figure 12 shows SG/AG differential and absolute domain growth. The AG sector does not seem to share cyclical behavior with the SG sector. What is remarkable, however, is the *magnitude* of SG/AG differential growth – it averaged 6% during the post-WWII boom. In terms of AG absolute growth, the mid 1960s seem to mark a turning point. Prior to this time, the trend was one of *accelerating* contraction; however, by the 1970s, the AG sector remains quite stable in terms of size. Lastly, notice that there is a long-term downward trend in the SG/AG differential growth rate. Unless this is reversed, it would seem that the centuries-long trend of AG to SG upward domain movement is nearing its end.

In Figures 10, 11, and12 I have attempted to show how differential domain growth can be used as a proxy for measuring upward domain movement. These figures show that SG differential growth – relative to BM, EM, and AG– has been the dominant trend of the 20th century.

---

[21] If judgment is passed on different types of employment, it is usually on the basis of value-added (for instance: FedDev Ontario, 2012; UK Business & Enterprise Committee, 2009). As we will see in coming sections, the EM sector adds more value per person than any other sector. From a neoclassical perspective, positive $\hat{HA}_{EM}$ should *drive* system growth, not the reverse.

My goal, for the rest of the chapter, is to relate this data to the pecuniary sphere. As I have defined it, the pecuniary sphere is a metaphysical concept that cannot ever be viewed in its entirety. How we analyze it depends on the narrative assumed by the analyst. My approach here is to use three distinct lens: value-added, profit, and wages.

5.3 Differential Value-added per Person

> *The need to create a higher value-added economy is widely taken as a given in public policy debate—but what exactly does this apparent platitude mean?*
> – UK Business & Enterprise Committee (2009)

Although the growth of value-added is often viewed as an end in itself, here my hypothesis is that it is as a signal that affects human behavior. Given this framework, can we show that the growth of value-added is quantitatively related to upward domain movement? The results in this chapter suggest that we can.

I begin by treating each sector as a ***black box*** with two known quantities – value-added and human activity. Equation 11 tells us that the value-added of an entire sector may be thought of as an outcome of both its human activity and its value-added per unit of human activity. If we compare the growth of total value-added to the growth of human activity, we need to make sure that the former is not simply growing as a result of the latter. Thus, I am interested only in value-added per unit of human activity.

$$VA = HA\left(\frac{VA}{HA}\right) \qquad (11)$$

I use lower case letters to distinguish value-added per unit of human activity from total value-added (equation 12). The units of *va* are either \$/person or \$/hour, depending on the source for human activity data.

$$va = \frac{VA}{HA} \qquad (12)$$

As noted in Chapter 4.2, nominal data for value-added is not comparable over time. Rather than convert to *real* measures, I opt to use differential measures. Equation 13 shows the notation for SG/BM *differential value-added per person* (or per hour):

$$SG/BM\ Differential\ va = \frac{va_{SG}}{va_{BM}} \qquad (13)$$

My approach is to compare differential domain growth rates with differential value-added per person. Equation 14 shows my notation for this comparison (for SG and BM sectors):

$$\widehat{\left[\frac{HA_{SG}}{HA_{BM}}\right]} \Leftrightarrow \frac{va_{SG}}{va_{BM}} \qquad (14)$$

From a conventional economic framework, there is no reason to suspect such a connection. My own motivation for doing so is based purely on curiosity. Nonetheless, the results for the SG and BM sectors, shown in Figure 13, are quite interesting.

The top graph uses Series C for human activity, while the bottom uses Series A. Interestingly, the latter shows better correlation prior to the 1970s, while the former shows better correlation from 1970s onwards (I do not know why this is the case). Without an objective method for determining which is more accurate, I simply display both. It is important to note that changing human activity data changes *both* the HA_{SG}/HA_{BM} growth rate *and* va_{SG}/va_{Bm}.

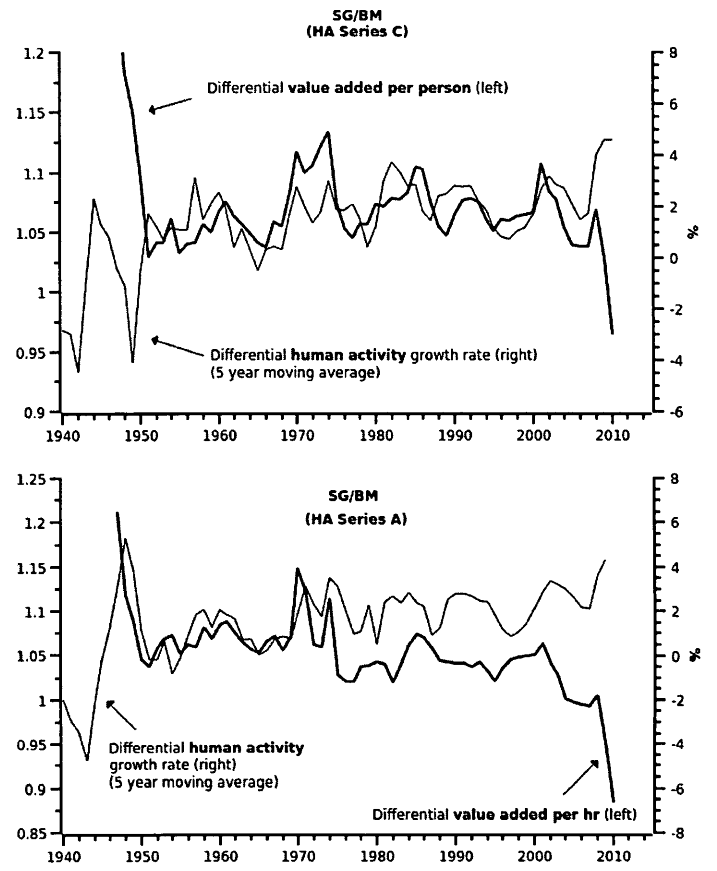

Figure 13: Differential value-added per person & differential domain growth: SG/BM
Sources: For human activity (Series A & C), see Figure 8. Value-added data from BEA GDPbyInd_VA_NAICS_1947-1997 & GDPbyInd_VA_NAICS_1998-2011

This relationship between differential value-added and differential domain growth needs unpacking. We are testing the hypothesis that dynamic changes in the pecuniary sphere (here quantified in terms of value-added) can be connected with upward domain movement. Thus, we are looking for evidence that the two quantities are related *through* time, meaning their time series show visible correlation. This seems to be the case for the SG and BM sectors. Interestingly, it is also the case that SG/BM differential value-added per person is *greater* than one for the entire period until 2008, and meaning the sector experiencing differential domain growth has *higher* per person valued. A striking deviation from this trend occurs after 2008. In historical terms, we know this to be the onset of the "Great Recession"; however, from the "black box" perspective taken here, we cannot deduce the cause of this deviation[22].

Recall from the investigation of SG/BM differential and absolute domain growth (Figure 10) that *peaks* in differential growth correspond to *troughs* in absolute growth. Because of this inverse relationship, in Figure 14 I look for (and find) correlation between SG & BM *absolute* domain growth and BM/SG differential value-added per person:

---

[22] Note that in both the top and bottom graphs in Figure 13, it would appear that va_{SG}/va_{Bm} and HA_{SG}/HA_{BM} experience a "decoupling" after 2008. While this is true to some degree, the 5 year moving average used to smooth both curves seems to accentuate, rather than reduce, this deviation.

$$\hat{HA}_{SG} \Leftrightarrow \frac{va_{BM}}{va_{SG}} \tag{15}$$

$$\hat{HA}_{BM} \Leftrightarrow \frac{va_{BM}}{va_{SG}} \tag{16}$$

Note that the value-added ratio is *intentionally* reversed (from SG/BM to BM/SG) meaning *absolute* domain growth and *differential* domain growth occur under opposite price "regimes". Again, let's unpack this. Absolute domain growth refers to the growth in the number of people doing *paid* work within a given sector. Figure 14 seems to tell us that when the BM sector increases its per person value-added relative to the SG sector, paid activity in the BM sector *grows*, and paid activity in the SG sector *grows faster*. However, the conditions during which jobs are created most *quickly* (higher BM/SG differential value-added per person) are also the conditions during which upward domain movement is the *slowest* (lower SG/BM differential value-added per person). It would seem that maximizing absolute SG and BM job growth is mutually exclusive to achieving upward domain movement. Each occurs under a different price "regime".

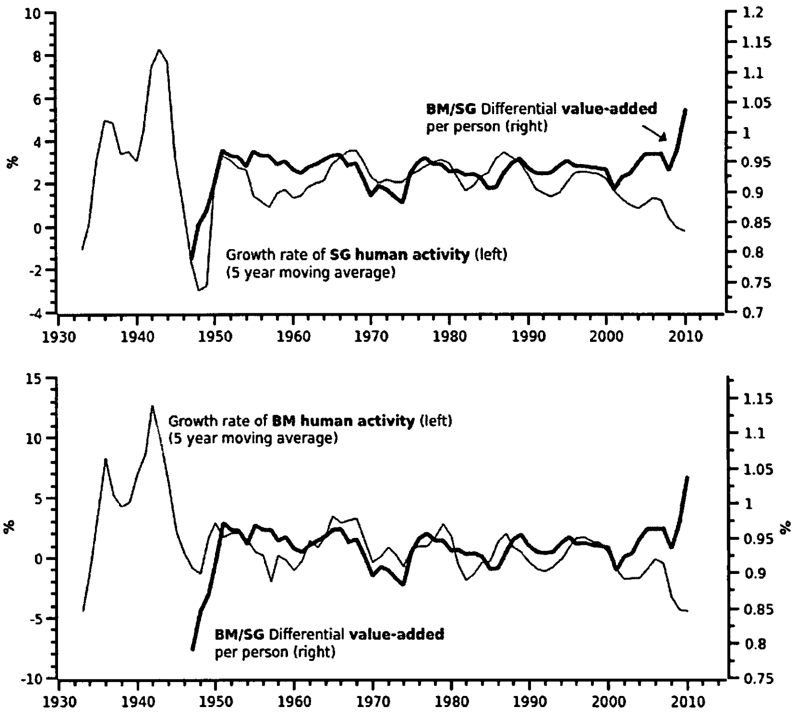

Figure 14: Differential value-added per person & absolute domain growth: BM/SG
Sources: Human activity Series C (see Figure 8). For value-added sources, see Figure 13.

Moving on, Figure 15 shows the remaining SG combinations (SG/EM & SG/AG). SG/Mining is also included for reasons explained below. Starting with SG/EM, two interesting trends arise. Firstly, from Figure 11, we know that SG/EM differential domain growth was positive for most of the period in question, meaning the SG sector grew relative to the EM sector. Contrary to our findings for SG/BM, here the sector experiencing differential domain growth (SG) has *lower* per person value-added (compared to EM). That is, the EM sector "created" less value per person than the SG sector, yet people still moved from the former to the latter.

Furthermore, va_{SG} rapidly declined relative to va_{EM} from 1950 to 1980, but there was no similar decline in differential domain growth. It is only after 1980 that correlation appears between HA_{SG}/HA_{EM} growth and va_{SG}/va_{EM}.

Because of this odd behavior, I have included in Figure 15 a graph of SG/Mining differential domain growth and differential per person value-added. The EM sector is made up of Mining & Utilities, and by removing the latter, a clearer long-term correlation emerges. SG/Mining differential per person value-added is still less than one and declines for much of the period; however, it is much more volatile than SG/EM and this volatility seems to correspond with changes in differential domain growth, especially after 1980. For the present time, it suffices to note that the EM sector displays anomalous properties compared to the behavior of other sectors.

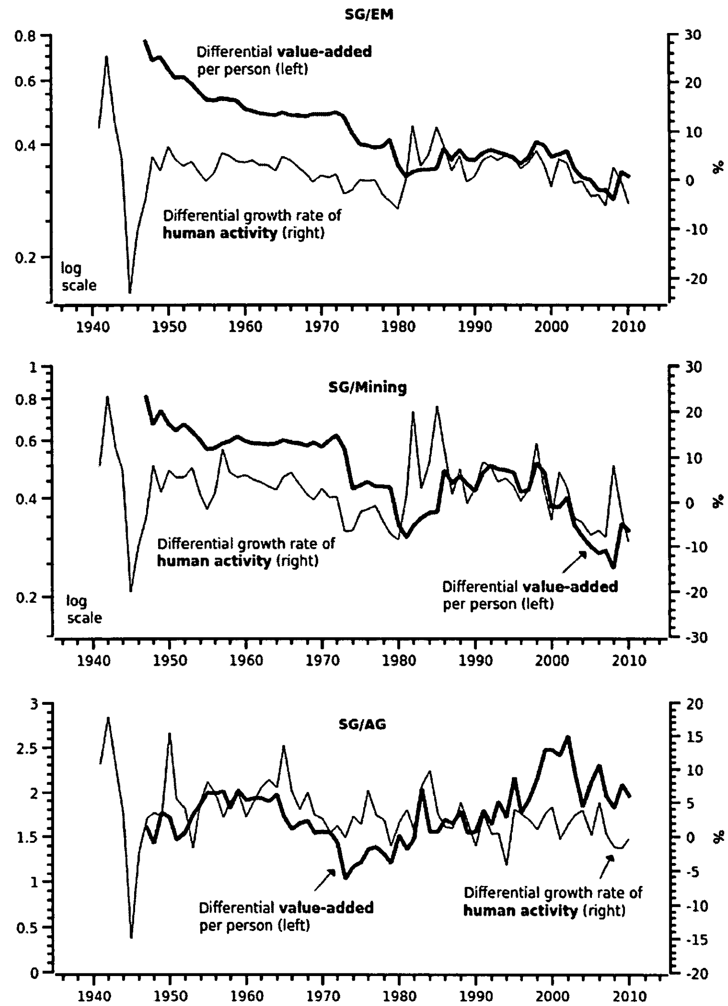

Figure 15: Value-Added & Differential Domain Growth: SG/EM, SG/Mining, SG/AG
Sources: Human activity Series C (see Figure 8). For value-added sources, see Figure 13.

The bottom graph in Figure 15 shows SG/AG differential per person value-added and differential domain growth. At times there is alignment between peaks and troughs; however it is difficult to see any long-term connection between value-added and human activity. Despite this lack of connection, SG per person value-added is *greater* than AG per person value-added, corresponding with AG to SG upward domain movement.

Having finished with SG combinations, in Figure 16 we move on to the 3 remaining combinations of BM, EM, and AG. Because the BM sector shares the same cyclical pattern as the SG sector, it is reasonable to expect that BM/EM and BM/AG behave similarly to SG/EM and SG/AG, respectively. Indeed, this expectation is confirmed by Figure 16. BM/EM per person value-added is less than one and declines precipitously between 1950 and 1980, after which it seems to correlate with BM/EM differential domain growth. BM/AG differential per person value-added is greater than one, corresponding with positive BM/AG differential domain growth. At times there seems to be excellent correlation between va_{BM}/va_{AG} and HA_{BM}/HA_{AG} growth (for instance, between 1960 and 1990). However, there are other periods during which the two time series are clearly unrelated.

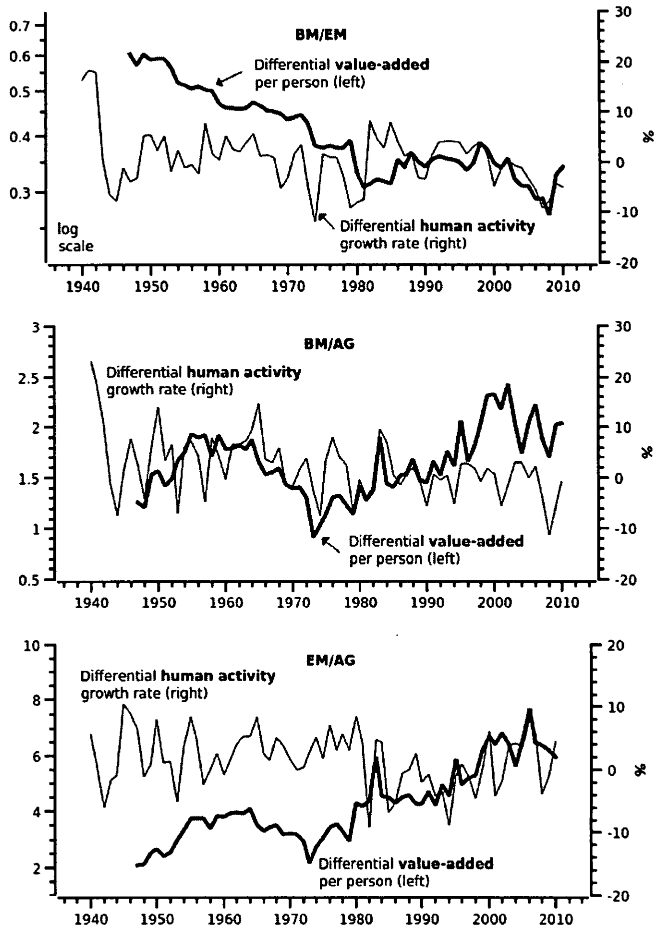

Figure 16: Value-Added & Differential Domain Growth: BM/EM, BM/AG, EM/AG
Sources: Human activity Series C(see Figure 8). For value-added sources, see Figure 13.

Lastly, we come to EM/AG. Recall that both the EM and AG sectors experienced mostly negative absolute domain growth during the time period shown (Figures 11 & 12). Therefore, positive HA_{EM}/HA_{AG} growth means that human activity in the EM sector shrank more slowly than in the AG sector. As with SG/EM and BM/EM, here the EM sector has higher per person value-added than the AG sector. However, despite some short term correlation, the long term trends in HA_{EM}/HA_{AG} and va_{EM}/va_{AG} are not similar.

Recapping our findings, the clearest relationship between differential domain growth and differential per person value-added exists between the SG and BM sectors. For SG/EM and BM/EM, a connection is present but is less clear. For BM/AG there is some supporting evidence of a connection, while for SG/AG and EM/AG, there is very little. Thus, our results are mixed – for some sectors, value-added seems to nicely "explain" upward domain movement, but for others it does not. In the next section, I investigate whether or not sectoral profit can shed more light on this situation.

5.4 Differential Profit per Person

Without any knowledge of *how* value was added or *how* human activity moved, the black box treatment of a domain nonetheless allowed us to empirically connect these two quantities, albeit with varying success. However, if we open the black box, we realize that a sector is *not* a decision-making unit. That is, humans have created different legal entities empowered with the *right* to create or destroy a paid position, but a *sector* is not such an entity. Rather, these entities are, from smallest to largest: the *sole proprietorship* (a self-employed person), the *firm* (or *company/corporation*), and *government*. These *employers*[23] decide whether or not to create a paid position, while *employees* "decide"[24] which paid position they will accept. Our task is to link these decisions with relevant pecuniary data. On the employer side, I choose to look at profit, while on the employee side, I look at wages (Chapter 5.5).

Rather than a *sector* being our black box, let us now apply this metaphor to all the *firms* within a given sector. We know only the total annual profit of these firms and the human activity contained within the sector. Can the two quantities be linked in a similar manner as was done with value-added? As the empirical evidence presented below suggests, I think they can. First, as was done with total value-added, I define per person profit (π) as the total profit (Π) of a sector divided by the human activity (HA) contained within it:

$$\pi = \frac{\Pi}{HA} \tag{17}$$

As with value-added, we only care about *differential* per person profit:

$$\text{SG/BM Differential profit} = \frac{\pi_{SG}}{\pi_{BM}} \tag{18}$$

We then compare differential profit with differential domain growth:

$$\widehat{\left[\frac{HA_{SG}}{HA_{BM}}\right]} \Leftrightarrow \frac{\pi_{SG}}{\pi_{BM}} \tag{19}$$

Figure 17 shows the results of this comparison for SG/BM, SG/EM, and SG/AG. As with value-added, it would seem reasonable that two basic conditions be met: 1) per person profit should be *higher* in the sector experiencing differential *growth* in human activity; 2) short-term and long-term trends in both time series should be clearly correlated. Let us see if empirical evidence supports these expectations.

Starting with SG/BM, there is a *striking* correlation between differential domain growth and differential per person profit. Both the long-term upward trend and the short-term 10-15 year cycles are visible in both time series. Clearly there is a fundamental connection between profit and the decision to create/destroy paid employment. However, two observations should be noted. Firstly, differential per person profit is more volatile than differential domain growth (in Figure 17, a log scale for profit is used to smooth this volatility). Secondly, π_{BM} is *greater* than π_{SG} (since $\pi_{SG}/\pi_{BM}<1$). That is, human activity moves to the sector with *lower* differential profit per person.

Caution should be exercised before reading too much into this result, as it may be partially an artifact of the MuSIASEM taxonomy. While both public and private entities add value, the former do not have *profit*. Therefore, within the SG sector, only private services "generate" profit; however, SG human activity includes both private services and government:

---

[23] In the case of a sole proprietorship, the *employer* and *employee* are the same person.

[24] I put the word "decide" in quotations because for many workers it amounts to a choice between an undesirable job or unemployment.

$$\pi_{SG}=\frac{\Pi_{Services}}{HA_{Services}+HA_{Government}} \tag{20}$$

If government human activity were removed from the calculation, per person profit would be higher[25]. However, I leave government human activity in to maintain methodological consistency between value-added, profit, and wages.

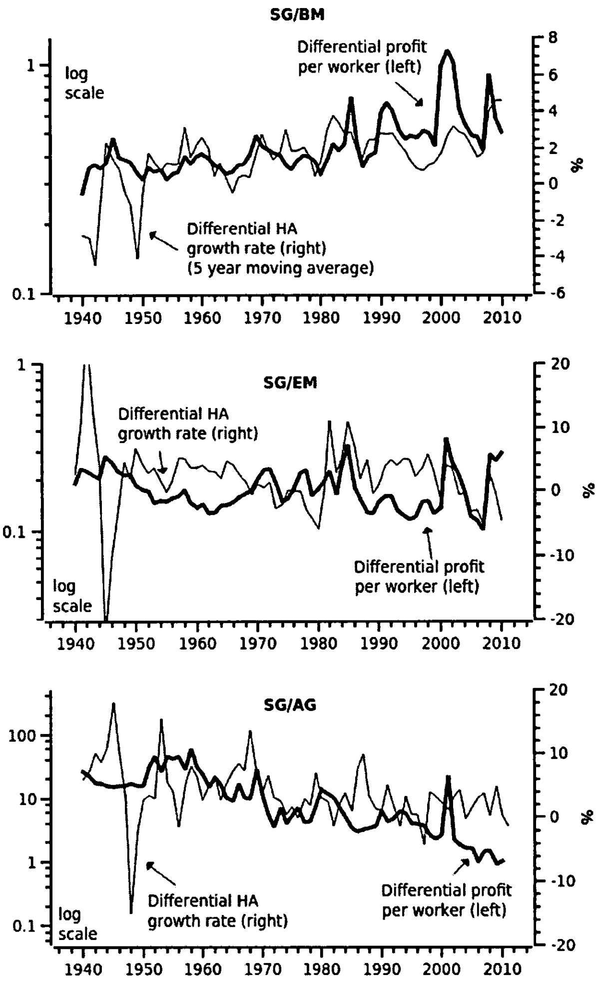

Figure 17: Differential Profit: SG/BM, SG/EM, SG/AG

Sources: Human activity Series C (see Figure 8). Corporate Profits Before Tax by Industry from BEA Income & Employment by Industry, Table 6.17A (1941-47), Table 6.17B (1948-86), Table 6.17C (1987-2000), & Table 6.17D (2000-2011). Table 6.17D is indexed to Table 6.17C. Per person profits calculated by dividing total sectoral profit by sectoral human activity. All profit data is time-shifted back 1 year to improve alignment with human activity data.

---

[25] How much higher? BEA statistics reveal that $HA_{Government}$ has never been more than 30% of HA_{SG}. Thus, removing $HA_{Government}$ would increase SG/BM differential per person profit by 43% at *most*.

Moving on to SG/EM, it is difficult to see any correlation prior to 1970, while after this date the correlation is modest. As with value-added per person, SG per person profit is *much* lower than in the EM sector. Lastly, SG/AG differential per person profit and differential domain growth show very little correlation, other than the long-term downward trend. The log scale masks the magnitude of the decline in differential profit. During the 1950s, π_{SG} was up to 60 times *greater* than π_{AG}; however, by 2009, π_{SG} was *less* than π_{AG}. This corresponds nicely with our observations that by the 21st century, AG to SG upward domain movement had essentially ceased (Figure 12).

Figure 18 shows the remaining domain combinations (BM/EM, BM/AG, EM/AG). Starting with BM/EM, if we look closely, we see that there is quite excellent short-term peak/trough alignment between differential domain growth and differential per person profit. Long-term trends, however, seem unrelated (the downward trend in π_{BM}/π_{EM} is not replicated in $\mathrm{HA}_{\mathrm{BM}}/\mathrm{HA}_{\mathrm{EM}}$ growth). As with π_{SG}/π_{EM}, π_{BM}/π_{EM} is less than one, meaning the higher domain is less profitable, per person. Moving on to BM/AG, we see that the long-term downward trend between π_{BM}/π_{AG} and $\mathrm{HA}_{\mathrm{BM}}/\mathrm{HA}_{\mathrm{AG}}$ is matched, but short-term peaks and troughs are completely unrelated. BM/AG differential per person profit declines from a high of nearly 160 in 1958, to a low of 1.6 in 2009. Similarly, EM/AG differential per person profit declines from a high of nearly 300 in 1954 to a low of 3.5 in 2010. Looking closely, it appears that there is modest peak/trough alignment between π_{EM}/π_{AG} and $\mathrm{HA}_{\mathrm{EM}}/\mathrm{HA}_{\mathrm{AG}}$.

Taken as a whole, all domain combinations (except SG/BM) have experienced declining per person differential profit. Since the 1940, firms in lower domains have become increasingly profitable, per person, relative to higher domains. We can rank average per person profit *growth rates* $(\bar{\bar{\pi}})$ according to expression 21:

$$\bar{\bar{\pi}}_{AG} > \bar{\bar{\pi}}_{EM} > \bar{\bar{\pi}}_{SG} > \bar{\bar{\pi}}_{BM} \tag{21}$$

This is undoubtedly an important trend; however, I leave investigation of its significance to a later date. To summarize our key findings: SG/BM differential per person profit seems to be tightly connected with differential domain growth. For all other combinations the connection is less clear.

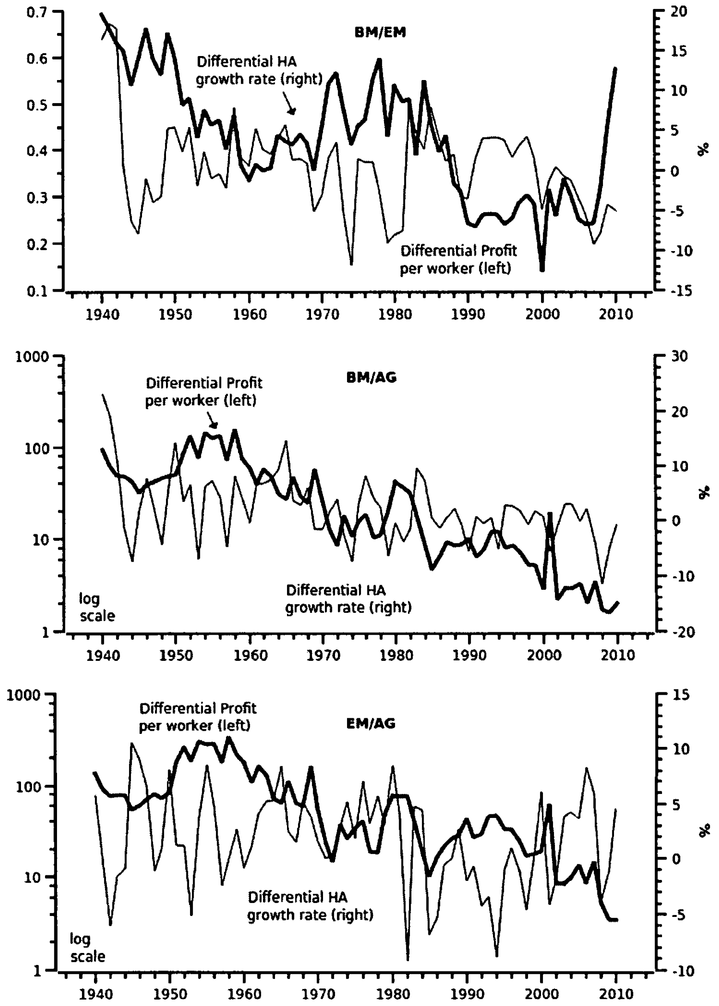

Figure 18: Differential Profit: BM/EM, BM/AG, EM/AG

Sources: For human activity Series C (see Figure 8). For corporate profit sources, see Figure 17.

5.5 Differential Wages

The connection between wages and differential domain growth can be framed as the pecuniary pressure on *employees* to move between sectors. If we make the simplistic assumption that, all other things being equal, workers would rather work in a sector where they can make more money, then we might expect that the sector experiencing differential domain *growth* should have *higher* wages (*if* this assumption is correct and *if* wages play a role in upward domain movement). As with profit and value-added, we are also looking for a clear peak/trough connection between differential domain growth and differential wages. The empirical evidence presented below, however, seems to show that wages are *not* connected to upward domain movement, except in the case of agriculture.

Again, we begin by calculating *differential wages* (22) and then compare this ratio to the differential domain growth rate (23):

$$\text{SG}/\text{BM Differential wages} = \frac{w_{SG}}{w_{BM}} \tag{22}$$

$$\left[\frac{\hat{HA}_{SG}}{HA_{BM}}\right] \Leftrightarrow \frac{w_{SG}}{w_{BM}} \tag{23}$$

Figure 19 shows differential wages and differential domain growth for SG/BM, SG/EM, and SG/AG. Looking at SG/BM, there appears to be very little correlation between $\text{HA}_{\text{SG}}/\text{HA}_{\text{BM}}$ growth and w_{SG}/w_{BM}, other than the long-term upward trend. Surprisingly, SG wages are *less* than BM wages, suggesting that from the perspective of employees, BM to SG upward domain movement was either *involuntary* or wages were not a determining factor. Similarly, SG wages are also *less* than EM wages. EM wages also show very little correlation with SG/EM differential domain growth, other than a long-term downward trend. For SG/BM and SG/EM, it would seem, there is little connection between wages and upward domain movement.

An entirely different picture emerges when looking at SG/AG differential domain growth and differential wages. Firstly, we notice that SG wages are *higher* than AG wages, meaning AG to SG upward domain movement corresponds with a *pay raise* for employees. Secondly, after the mid 1960s, there is decent peak/trough correlation between differential domain growth and differential wages. It would appear that *relative* changes in SG and AG wage rates are connected with the rate of upward domain movement. However, without further investigation, it is unclear why this connection falls apart prior to 1960.

Moving on, Figure 20 shows differential wages and differential domain growth for BM/EM, BM/AG, and EM/AG. Looking at BM/EM, we again see that the higher domain (BM) has lower wages, meaning EM to BM upward domain movement corresponds with a *decrease* in wages. Similarly, BM/EM differential wages show little peak/trough correlation with differential domain growth rates.

Looking at BM/AG, we find that BM wages are *greater* than AG wages, meaning AG to BM upward domain movement corresponds with an *increase* in wages. As with SG/AG, there is decent peak/trough correlation after 1960. Lastly, with respect to EM/AG, we find that EM wages are *greater* than AG wages. After 1980, there is also reasonable peak/trough correlation between differential wages and differential domain growth.

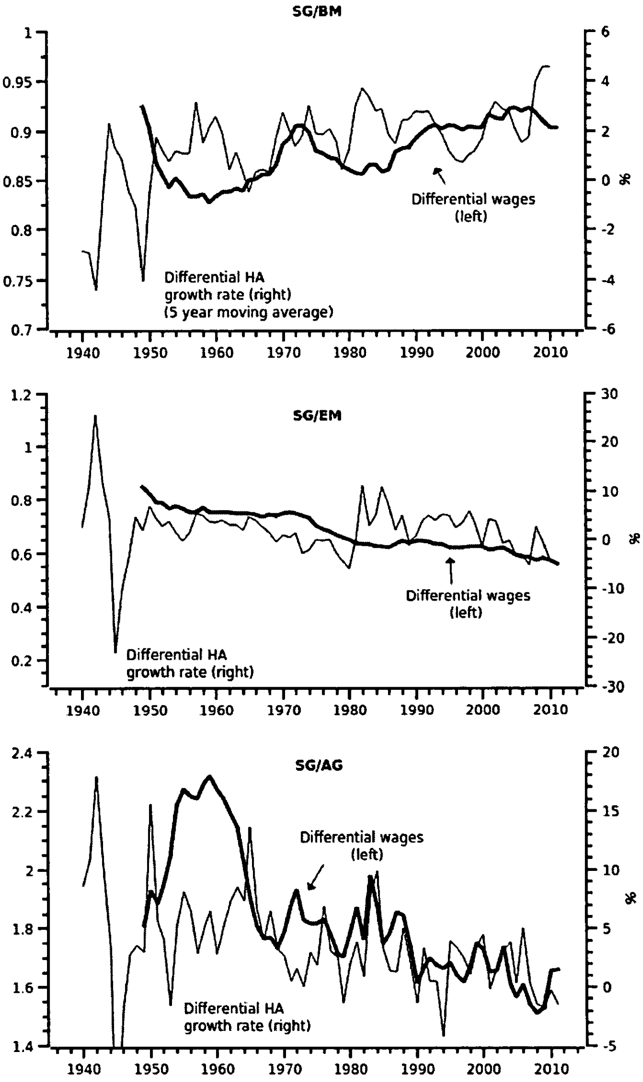

Figure 19: Differential Wages: SG/BM, SG/EM, SG/AG

Sources: For human activity (Series C), see Figure 8. Average sectoral wage calculated by weighting wages times number of FTE employees. FTE employees by industry from BEA Income & Employment by Industry, Table 6.5B (1949-87), Table 6.5C (1988-1997), & Table 6.5D (1998-2011). All data indexed to Table 6.5D. Wages & Salary Accruals per FTE from ibid, Table 6.6B (1949-87), Table 6.6C (1988-1997), & Table 6.6D (1998-2011). All data indexed to Table 6.6D.

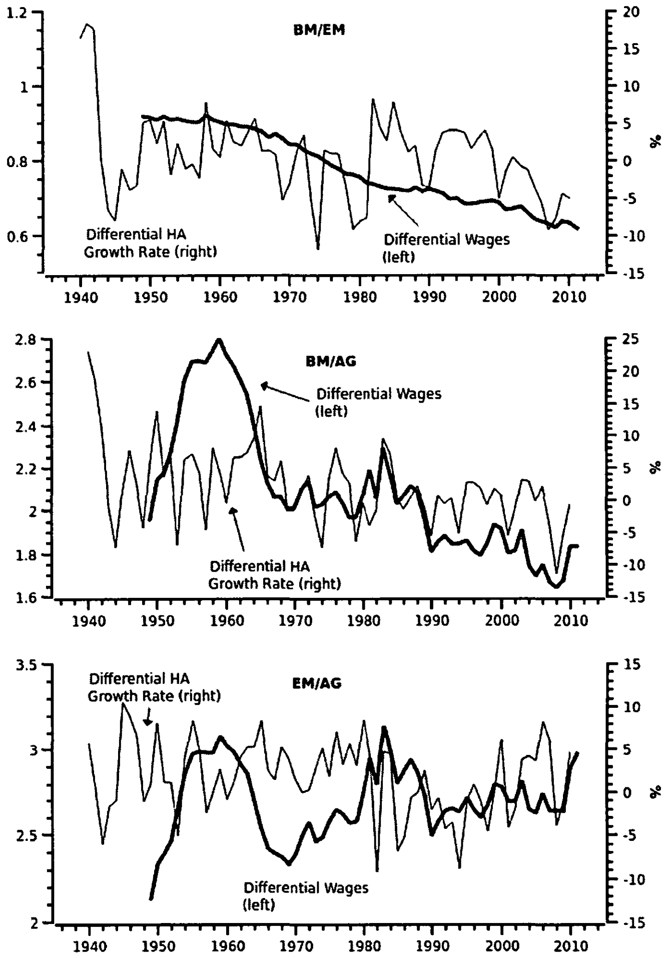

Figure 20: Differential Wages: BM/EM, BM/AG, EM/AG

Sources: For human activity (Series C) see Figure 8. For average sectoral wage sources, see Figure 19.

To summarize, expression 24 ranks the wages of each sector. Below each wage is the metabolic rank of that sector.

$$\begin{array}{cccc} w_{AG} < & w_{SG} < & w_{BM} < & W_{EM} \\ 1 & 4 & 3 & 2 \end{array} \tag{24}$$

It appears that only upward domain movement *away* from Agriculture is associated with an *increase* in wages. For all other sectors, upward domain movement is associated with a *decline* in wages. This is a startling finding – the majority of upward domain movement is not associated with any pecuniary gain for workers! It is hard not to conclude that it is *employers*, rather than *employees*, that dictate the movement of human activity.

5.6 Human Activity: Conclusions

This chapter sought to address the following question: what types of pecuniary signals (if any) are related to the movement of human activity? In order to quantify demographic changes, I calculated the relative growth rate between sectors and I called this metric the *differential domain growth rate*. I then compared differential domain growth to differential per person value-added, profit, and wages. I framed this not as an attempt to show that changes in the pecuniary sphere "caused" the movement of human activity, or vice versa, but as an attempt to see if the two were connected. I drew on Giampetro and Mayumi's notion of the impredicative loop as a way to think about this relationship.

	Value-Added	**Profit**	**Wages**
SG/BM	**0.109**	**0.192**	0.009
SG/EM	0.017	0.000	0.021
SG/AG	0.004	0.026	**0.240**
BM/EM	0.062	0.061	0.090
BM/AG	0.007	0.050	0.196

Figure 21: R-squared values
The largest values in each column are displayed in bold. Correlation is between differential pecuniary metrics shown and the differential domain growth rate.

	Differential Value-Added	**Differential Profit**	**Differential Wages**
Upper Domain Greater than Lower Domain	SG/BM SG/AG BM/AG EM/AG	SG/AG BM/AG EM/AG	SG/AG BM/AG
Peak/Trough Aligns with Differential HA	SG/BM SG/EM BM/EM	SG/BM SG/EM BM/EM	SG/AG BM/AG
Long-Term Trend Aligns with Differential HA	SG/BM	SG/BM SG/AG BM/AG	

Figure 22: Summary of Human Activity Findings

Figures 21 and 22 summarize the results of this empirical investigation. The findings are complex, often counterintuitive, and defy simple conclusions. However, I think that we can safely conclude that there *are* linkages between the movement of human activity and changes in the pecuniary sphere. The relationship is most pronounced for SG/BM differential per person value-added and profit, and for SG/AG differential wages.

What is perhaps most interesting is that the relationship exists on the *per person* level. It is unclear why, for instance, value-added/profit *per person* should be related to the movement of human activity. Firms are usually regarded as being concerned with *total* profit, not profit per person. Indeed, there is little in economic theory to suggest that per person profit at the level of an entire sector should be an indicator of interest. The fact that it is clearly related to demographic changes (in some instances) is a finding that needs further investigation. My own thoughts are that it we might treat this as an emergent phenomenon – one that cannot be predicted from first principles. A study that looks more closely at the hiring practices of large firms might shed light on this situation.

6. Energy

In this chapter, I continue my investigation of the connection between the biophysical and pecuniary spheres by asking the following question: what types of pecuniary signals (if any) are related to changes in energy throughput?

The layout of this chapter is as follows. In section 6.1, I discuss the importance of energy in relation to the laws of thermodynamics, and I outline some of epistemological issues surrounding the quantification of energy throughput. In section 6.2, in order to empirically make the connection between upward domain movement and increases in energy throughput, I show how Ayres and Warr's concept of ***useful work*** can be quantitatively related to the BM/AG differential domain growth rate. In section 6.3, I relate useful work to *kilowatt-hour deflated* GDP, demonstrating that the latter can be thought of as the symbolic pressure to consume useful work. In section 6.4, I calculate a metric that I call the *energy and mining sector's gross power* (following Giampietro et al., 2012). In section 6.5, I relate this metric to *joule-deflated* GDP and *joule-deflated* S&P500. In section 6.6, I relate ***mining gross power*** to differential value-added per person. Lastly, in section 6.7, I relate EM gross power to differential per person capitalization.

In most of the above case studies, there are obvious linkages between changes in the biophysical sphere and changes in the pecuniary sphere. In each instance, I attempt to show how these results can be interpreted using the ideas of Nitzan and Bichler as well as Giampietro and Mayumi. Where applicable, I also discuss how the results relate to (and often contradict) more conventional approaches.

6.1 Quantifying Energy

> *But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.*
> – Arthur Stanley Eddington (2005 [1928], p. 74)

In order to understand why energy is important to human society, we must understand the laws of thermodynamics. The *first law of thermodynamics* is essentially a statement of the law of conservation of energy and matter: energy and matter can neither be created nor destroyed, only transformed. Thus, the human-system *transforms* resources into usable goods and services– it does not *produce*[26] them. The *second law of thermodynamics* describes the tendency for an ***isolated system*** to spontaneously evolve towards a state of ***equilibrium*** – a state of maximum ***entropy.*** Thus, highly ordered (low entropy) states should spontaneously devolve towards low ordered (high entropy) equilibrium.

Life on earth, however, seems to defy this principle – highly improbable states of organized matter continually reproduce themselves, rather than degrade into unorganized matter. Living organisms are what Ilya Prigogine (1984) calls *dissipative structures* – they maintain a state of non-equilibrium by increasing the entropy of their surroundings. Crucially, this state of non-equilibrium can only be maintained by means of constant *energy* throughput. Georgescu Roegen (1971) famously broadened the application of the second law from individual organisms to the human-system as a whole. Thus, the maintenance and growth of the human-system depends crucially on energy – it is the "master resource" (Zencey, 2012).

---

[26] While I recognize that economic "production" is more properly material "transformation", I continue to use the word "production" for ease of reference.

The concept of energy is simple enough; however, it turns out that actually *quantifying* energy flows through society is fraught with epistemological difficulties. While Giampietro, Mayumi and Sorman (2010) devote an entire book to these difficulties, here I focus on their core argument. The energy used by society takes on many forms and undergoes numerous transformations. Depending on the methodology used, energy data can diverge greatly; indeed energy data only has meaning when attached to a semantic category.

Figure 23 illustrates this point. On the bottom, ***primary energy*** sources are pictured. These forms of energy are not usable by humans directly; instead, they must be transformed. Using ***energy conversion*** technologies, primary energy sources are transformed into what Giampietro et al. refer to as ***energy carriers***. These are the fuels and electricity that carry energy to their eventual end-use. Finally, ***end-use energy*** (not pictured) is the final output of usable work. At every stage, energy losses occur, thus we can rank these three categories of energy in terms of scale:

$$\text{Primary Energy Sources} > \text{Energy Carriers} > \text{End Use Energy} \qquad (25)$$

The quantification of energy consumption depends crucially on what type of energy we decide to count. In general, most energy statistics quantify primary energy sources. As we move from primary energy to end-use work, it becomes increasingly difficult to quantify energy flows because we must know the ***efficiency*** of every energy conversion process. While Giampietro et al. regard the quantification of end-use work as impossible, Robert Ayres and Benjamin Warr (2009) have taken up the task and have been, in my opinion, quite successful.

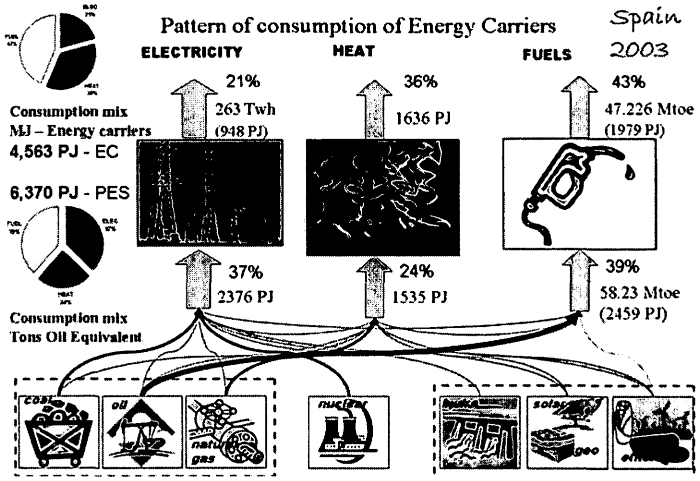

Figure 23: Energy Transformations
Source: Giampietro et al. (2010)

6.2 Useful Work & Upward Domain Movement

The application of end-use work in industrial societies involves a dizzying array of energy converters. I concur with Giampietro et al. that quantifying the efficiency of every process is impossible. Ayres and Warr (2005, 2009) estimate end-use work – which they call ***useful work*** – by conceptually simplifying its diversity. They use only five semantic categories:

1. Electricity
2. Heat (low, mid, high)
3. Mechanical Drive
4. Light
5. Muscle Work

Within each category, the average efficiency of all energy converters is estimated. Notice that electricity is not actually end-use work but, rather, an energy carrier (see Figure 23). Thus, Ayres and Warr calculate the efficiency of electricity generation, but *not* the conversion efficiency of electricity into useful work. The latter, I would argue, is ultimately unquantifiable because electricity is used for such a diversity of applications[27]. These caveats aside, I think that Ayres and Warr's estimate of useful work is invaluable so long as we remember that it is a simplification of reality.

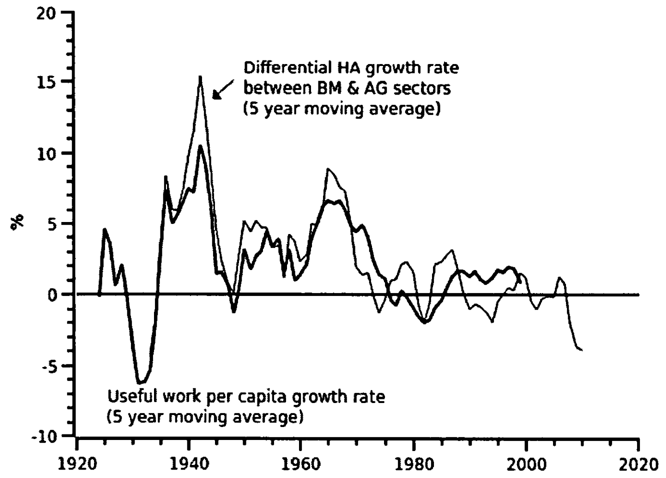

Figure 24: Useful Work & BM/AG differential domain growth
Sources: Data for useful work and US population from Benjamin Warr (2009) REXS Database. For human activity data (Series C) see Figure 8.

I begin my analysis by linking useful work (U) with human activity. I have asserted that upward domain movement *requires* an increase in energy throughput, the purpose of which is to increase the amount of end-use ***work*** done. While I have made theoretical arguments justifying this statement, it would be preferable if it could be quantified empirically. I attempt such a quantification by comparing the growth rate of per capita useful work $(\hat{u})$ with the BM/AG differential domain growth:

---

[27] For many of these applications, the notion of efficiency is problematic. For instance, what is the efficiency of a computer? Efficiency is defined as the work output (in units of *energy*) per unit of *energy* input. For a computer, the output that we care about (processing *speed*) does not carry the same units as the input (electrical *energy*) meaning traditional thermodynamic efficiency is not a useful concept.

$$\hat{u} \Leftrightarrow \left[\frac{\widehat{HA}_{BM}}{HA_{AG}} \right] \tag{26}$$

The results, shown in Figure 24, demonstrate a clear connection between upward domain movement and the growth of useful work (at least until the 1980s). I have specifically used *per capita* useful work because it can be interpreted as the average machine work commanded by *each* human in the human-system. For upward domain movement to proceed, this machine work must increase. I think Figure 24 lends good empirical support for my pre-analytic vision.

One drawback of this aggregate approach is that we cannot tell if all sectors produce useful work at the same rate. As I will show in Chapter 7, lower domains are much more energy intensive than higher domains. However, because no data exists for useful work at the sectoral level, we cannot proceed with this line of inquiry here.

6.3 Useful Work and GDP

Dating back to Solow (1956), neoclassical economists have been trying to explain the growth of real GDP using *production functions*. However, the traditional inputs of capital and labour fail to accurately account for much of the actual growth in real GDP, leaving a large residual in need of explanation. Often called "total factor productivity", this residual is an exogenous component to the neoclassical growth model that represents productivity growth not explained by the accumulation of capital or labour.

In their book, *The Economic Growth Engine*, Ayres and Warr attempt to explain this residual by adding useful work inputs to their production function. In empirical terms, their theory is very successful – they are able to hindcast real GDP with a high degree of accuracy. Here, however, I do not pursue the production function route. Why? Firstly, I have critiqued the validity of *real* measures, thus there is little reason to "explain" *real* GDP. Secondly, a production function implies that monetary value is "produced". This is incompatible with my view that monetary value is arrived at by social convention (and societal power structures).

Instead of the production function route, I continue the methodology advanced in previous chapters. Drawing on the work of Garrett (2011a, 2011b) and Hall et al. (2008), I take a biophysical view of production by framing it as a series of energy transformations. I think of "production" as the purposeful application of useful work by the human-system *onto itself*. This useful work is necessary both to fight entropic decay and to build new structure (if the scale of the system – however defined – is increasing). Figure 25 shows a schematic of this framework.

The same accounting structure used in Figure 25 could be applied to any dissipative structure, at least on a conceptual level. All dissipative structures (ecosystems, organisms, etc.) require the application of energy (work) to maintain a state of thermodynamic *disequilibrium* (Kondepudi & Prigogine, 1998). In terms of biophysical analysis of the human-system, we are interested in the growth of useful work.

However, unlike ecosystems, there is an added layer *within* the human-system, namely monetary accounting. Veblan writes that "the final purpose of any businesslike undertaking is always a sale, by which the seller comes in for the price of his goods" (1923, p. 88). Figure 26 shows my conceptualization of how we can relate this idea to a biophysical view of production. On the biophysical side, useful work is an input to a transformation process controlled by the human-system (matter inputs are ignored here). The final output of this process is a good or service. However, humans use money (not energy) as an accounting tool for business activity. The sale of this good or service represents a pecuniary gain for the entity controlling the transformation process.

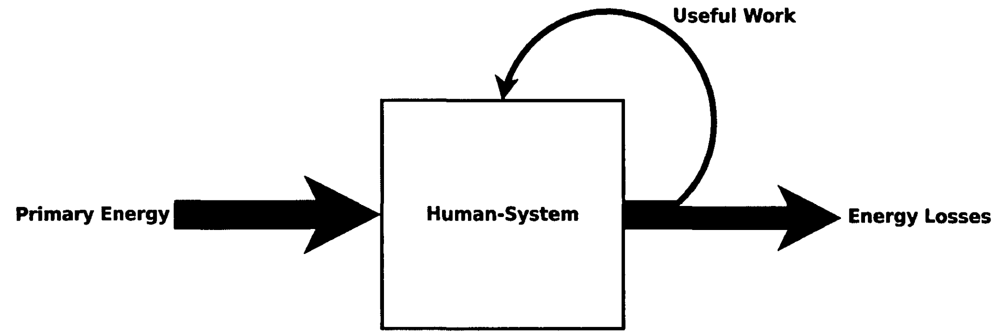

Figure 25: Production viewed as an energy feedback

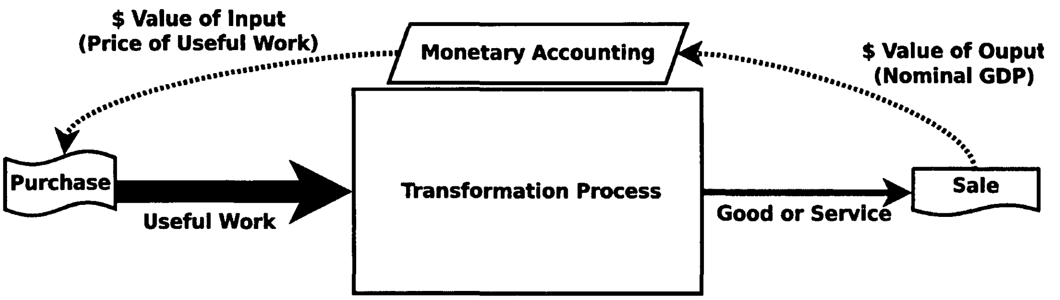

Figure 26: Monetary accounts as feedback mechanism

The ability to continually input useful work (in order to render the transformation process possible) requires the *purchase* of useful work (assuming it is priced). I interpret the ratio between the price of a finished good and the price of useful work inputs as the *symbolic ability to consume useful work.* An increase/decrease in this ratio indicates an increase/decrease in the ability to ***finance*** useful work consumption. If we generalize this process to the human-system as a whole, the value of sales becomes nominal GDP and the value of inputs becomes the value of all useful work.

Unfortunately, while primary energy inputs are priced, most forms of useful work are not. As a way around this problem, I use the price of electricity as a proxy for the price of all useful work. Remember that electricity is defined by Ayres and Warr as a type of useful work, but according to Giampietro and Mayumi, it is an energy carrier. I side with the latter authors, but compromise here by treating electricity as a form of useful work (that has a price ... because it is actually an energy carrier).

Thus, our ratio of final sales to useful work purchases becomes the ratio of nominal GDP (GDP_N) to the price of a kilowatt-hour of electricity (p_{kWh}). I call this combined quantity *kWh-deflated GDP* (GDP_{kWh}):

$$GDP_{kWh} = \frac{GDP_N}{p_{kWh}} \tag{27}$$

While the term kWh "deflated" GDP implies the conversion of current prices into constant prices, here I merely use it as a shorthand for the more unwieldy "differential comparison between nominal GDP and the price of a kilowatt-hour of electricity".

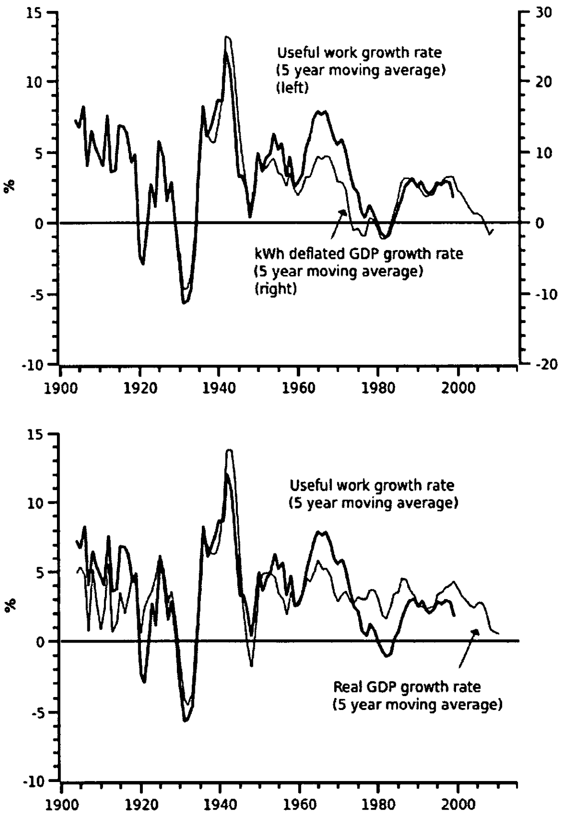

Figure 27: Growth rates of useful work, real GDP, & kWh-deflated GDP
Sources: Useful work data is from Benjamin Warr's REXS Database. Real & nominal GDP data (1929-2011) from BEA Current-Dollar and "Real" GDP. Real GDP data (1900-28) from HSUS Table Ca9, indexed to BEA data. Nominal GDP data (1900-28) from HSUS Table Ca9, indexed to BEA data. The price of electricity (1926-2000) is from HSUS Table Db234 (average price, all services). Average electricity prices for 2001-2011 calculated by weighting sectoral price by sectoral consumption (residential, commercial, industrial). Sectoral prices (2001-2011) from EIA (2012), Annual Energy Review 2011, Table 8.10 Average Retail Prices of Electricity. Sectoral consumption (2001-2011) from ibid, Table 8.9 Electricity End Use.

Again, I treat kWh-deflated GDP as the symbolic ability of the human-system to finance the consumption of useful work. My view is that this symbolic ability should logically be connected with the *actual* consumption of useful work. In order to test this view, I compare the growth rate of kWh-deflated GDP (the symbolic ability to consume useful work) with the actual growth rate of useful work $(\hat{U})$:

$$\hat{U} \Leftrightarrow G\hat{D}P_{kWh} \tag{28}$$

In order to contrast this approach with the production function approach, I also compare the growth rate of useful work with the growth rate of real GDP:

$$\hat{U} \Leftrightarrow G\hat{D}P_{R} \tag{29}$$

Figure 27 shows the results. The first notable trend is that prior to 1960, the useful work growth rate is remarkably well correlated with both real GDP and kWh GDP[28]. From a production function perspective, this means that useful work *alone* can almost entirely "explain" the growth of real GDP. However, after 1960, the growth of real GDP becomes decoupled from the growth of useful work. Again, from a production function perspective, this means that other inputs suddenly become more powerful at "producing" real GDP. Unfortunately, neither capital nor labour can account for this decoupling. Instead, Ayres and Warr (2012) successfully use "information and communications technology" as the missing ingredient.

Given two approaches for explaining the same phenomenon, Occam's razor would suggest that we choose the simpler of the two. By relating nominal GDP to the price of electricity, there is no need to look for missing "ingredients". Unlike real GDP, kWh-deflated GDP remains highly correlated with useful work for almost the entire period shown.

In *empirical* terms, the only difference between the two charts in Figure 27 is the choice of price index used to deflate nominal GDP. However, from a *conceptual* standpoint, they represent radically divergent approaches to monetary value. By using the GDP deflater, we get *real* GDP, which is ostensibly a measure of the *scale* of real production. By comparing the growth of real GDP to the growth of useful work, we are seeing if useful work can "explain" this growth in production.

However, by using the price of electricity to deflate nominal GDP, we get something else entirely. This no longer represents anything *real*. It is a symbolic representation comparing the *pecuniary* valuation of the biophysical output of the human-system to the price of an *essential* input – useful work. In my opinion, this differential measure represents society's ability to *symbolically* finance the consumption of useful work. However, this does *not* mean that the growth of kWh-deflated GDP *causes* the growth of useful work. I would suggest that the relationship is *impredicative*: useful work, the price of electricity, and nominal GDP are linked in such a way that causation *cannot* be determined.

To summarize, we have been successful at empirically connecting GDP to useful work without the need of a production function. I continue this methodological approach in the next section by relating differential pecuniary measures to energy & mining gross power.

---

[28] It should be noted that real GDP data begins in 1905 while kWh GDP deflated data begins in 1926. The apparent perfect correlation between the latter and the useful work growth rate (prior to 1926) is an *illusion* cause by the simple lack of kWh-deflated GDP data.

6.4 Primary Energy: Energy & Mining Gross Power

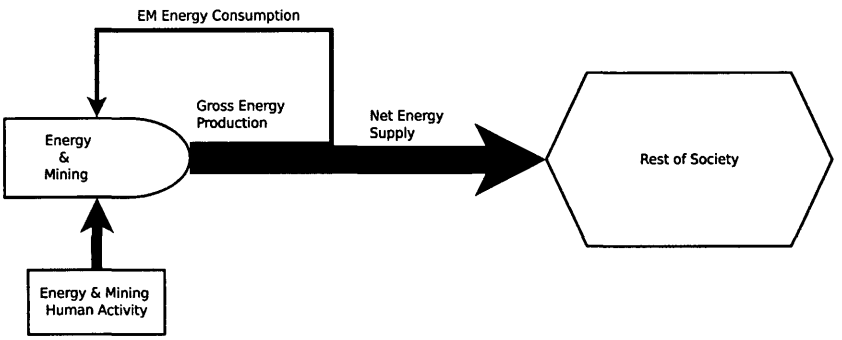

Figure 28: EM Inputs & Outputs

The energy & mining sector produces *all* the exosomatic energy used by the human-system. Thus, the growth in the productivity of this sector is central to the process of upward domain movement. Here, I focus on how pecuniary measures can be related to this productivity growth.

Productivity is a ratio that compares the scale of *output* to the scale of *input*. Looking at Figure 28, we see that the EM sector's output is energy, and its main inputs are human activity and energy[29]. Thus, one possible productivity measure would be to relate *energy* output to *energy* input. This is commonly called Energy Return on (Energy) Investment (EROI):

$$EROI_{EM} = \frac{Gross\ Energy\ Production}{EM\ Energy\ Consumption} \tag{30}$$

Another possible productivity measure would be to relate *gross energy* output to *human activity* inputs. I call this measure the ***energy & mining gross power*** (GP_{EM}):

$$GP_{EM} = \frac{Gross\ Energy\ Production}{HA_{EM}} \tag{31}$$

In physics, ***power*** is defined as energy per unit of time. While EM gross power is a measure of *labour productivity*, I call it gross *power* because the numerator carries units of energy, and the denominator carries units of (human) time[30].

Lastly, we could relate *net energy* output to *human activity* inputs. I call this measure *Net Power* (NP):

$$NP_{EM} = \frac{Net\ Energy\ Production}{HA_{EM}} \tag{32}$$

Both net power and EROI require knowledge of the energy consumption of the energy and mining sector. Surprisingly, this data is not published by the US Energy Information Administration[31], leaving EM gross power as the only alternative.

---

[29] Of course, the EM sector produces other things like metals and ores *and* it requires material inputs other than energy. I simply ignore these here.

[30] Human activity data in units of persons can easily be converted to units of time (hrs) by multiplying by $40\ hr/week \times 52.1775\ weeks/year$.

[31] Giampietro et al. (2012) argue that the lack of the category "energy used by the energy sector" is one of the main deficiencies of existing energy statistics.

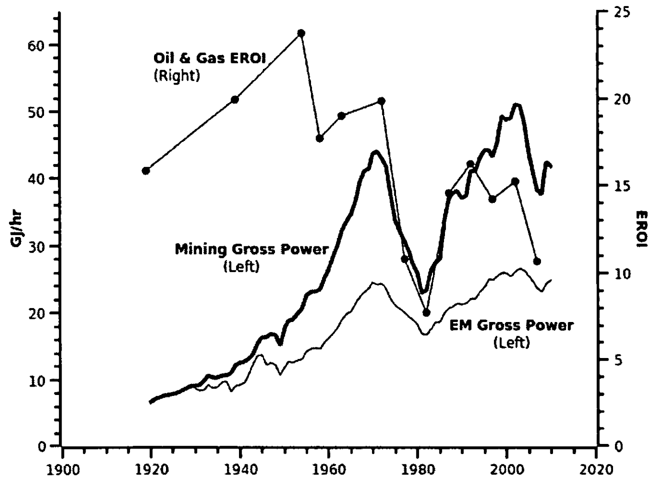

Figure 29: Mining Gross Power & Oil and Gas EROI

Sources: Mining gross power calculated by dividing annual fossil fuel energy production by mining sector human activity (in hrs). US Fossil Fuel Energy Production data from HSUS Table Db155-163, Energy Production by Source (1920-1948) & EIA Annual Energy Review 2011, Table 1.2 Primary Energy Production by Source (1949-2011). Mining human activity is the product of number of employees and average weekly hours times 52.1775 weeks/year. Mining Sector Employment is from HSUS Table Ba841 (1920-1999) & BLS Current Employment Statistics Online (2000-2011), indexed to HSUS data. Average work week from HSUS Table Ba4575 (1920-1963), BLS Employment & Earnings, January 2009 Vol. 56 No. 1, Table B-2 (1964-2008), & BLS Current Employment Statistics Online (2009-2011). EROI data from Guilford, Hall, O'Connor, & Cleveland, 2011. EM gross power is calculated by dividing US total primary energy production by EM human activity (in hours). US total primary energy production data is from EIA Annual Energy Review 2011, Table 1.2 (1949-2011) & HSUS Table Db155-163, Energy Production by Source (1929-48). For human activity data (BEA persons engaged in production) see Figure 8. Note that since EM and Mining gross power use different sources for human activity, comparison of their *absolute* scale should be done with caution.

I also make a distinction between *EM gross power* and ***mining gross power*** (GP_M). I define the latter as the productivity of *fossil fuel* energy production (as opposed to *total* energy production):

$$GP_M = \frac{Gross\ Fossil\ Fuel\ Production}{HA_M} \tag{33}$$

Figure 29 shows EM gross power, mining gross power, and EROI[32] estimates for US *oil and gas* production (from Guilford et al., 2011). I include oil and gas EROI only to show that it is clearly connected to measures of gross power. We can think of EROI as a proxy for the energy consumed by the energy and mining sector. When EROI *declines*, energy used by the EM sector *increases*. Since oil and gas EROI shows correlation with both EM and mining gross power (after 1970) we can guess that decline in *gross* power means an even steeper decline in *net* power.

Inspecting Figure 29, we see that both EM and mining gross power are characterized by four distinct eras:

1. 1920-1971: exponential growth
2. 1972-1981: Decline
3. 1982-2002: Recovery

---

[32] It should be noted that EROI calculated by Guilford et al. includes the energy embodied in capital goods consumption, whereas my conceptualization of the EROI of the entire EM sector (equation 30) includes only direct energy consumption.

4. 2003-2008: Decline

As with previous data, my intention is to compare these changes in EM and mining gross power with similar changes in the price structure of society. I begin with a differential methodology that I call *joule deflation*.

6.5 Mining Gross Power & Joule-Deflated Pecuniary Data

In section 6.3, we were interested in how differential pecuniary measures could be related to the growth of useful work. Thus, it made sense to deflate nominal GDP by a proxy for the price of useful work – the price of electricity. Here we are interested in the growth of the mining sector; therefore, it makes sense to deflate nominal data by the price of the *output* of this sector: primary fossil fuel energy. I call this process *joule deflation*[33].

The first step of joule deflation is to find the average price of one joule (J) of primary fossil fuel energy (p_J) as it leaves the mining sector. This is done by dividing the aggregate price of all primary fossil fuels (P_{FF}) by fossil fuel energy throughput (ET_{FF}) (in joules):

$$p_J = \frac{P_{FF}}{ET_{FF}} \tag{34}$$

We can then use the average price of one fossil fuel joule to deflate nominal data. Equations 35 and 36 show joule-deflated GDP (GDP_J) and the joule-deflated S&P 500 price index $(SP500_J)$:

$$GDP_J = \frac{GDP_N}{p_J} \tag{35}$$

$$SP500_J = \frac{SP500_N}{p_J} \tag{36}$$

Again, "joule-deflated GDP" does not imply a *real* measure; rather it is used in place of the more unwieldy "differential comparison between nominal GDP and the price of a joule of primary fossil fuel energy". Figure 30 shows joule-deflated GDP, the joule-deflated S&P 500 price index, and mining gross power – all indexed to the year 1920. I explain the significance of each relationship separately.

As with kWh-deflated GDP, joule-deflated GDP compares the price of an essential *input* to the human-system (fossil fuel energy) with the price of aggregate final *output* (nominal GDP). Thus, I see joule-deflated GDP as the symbolic pressure to consume primary fossil fuel energy. Figure 30 compares this *symbolic* output/input ratio with a *biophysical* output/input ratio: mining sector gross power. A clear relationship exists between the two. Society's ability to *finance* fossil fuel consumption seems to be deeply connected with the power output (productivity) of the mining sector. Again, I make no attempt to determine causation; rather, I suggest that nominal GDP, the price of fossil fuel energy, fossil fuel production, and mining sector human activity are all connected in an impredicative loop.

---

[33] For joule deflation data sources, see Appendix A.

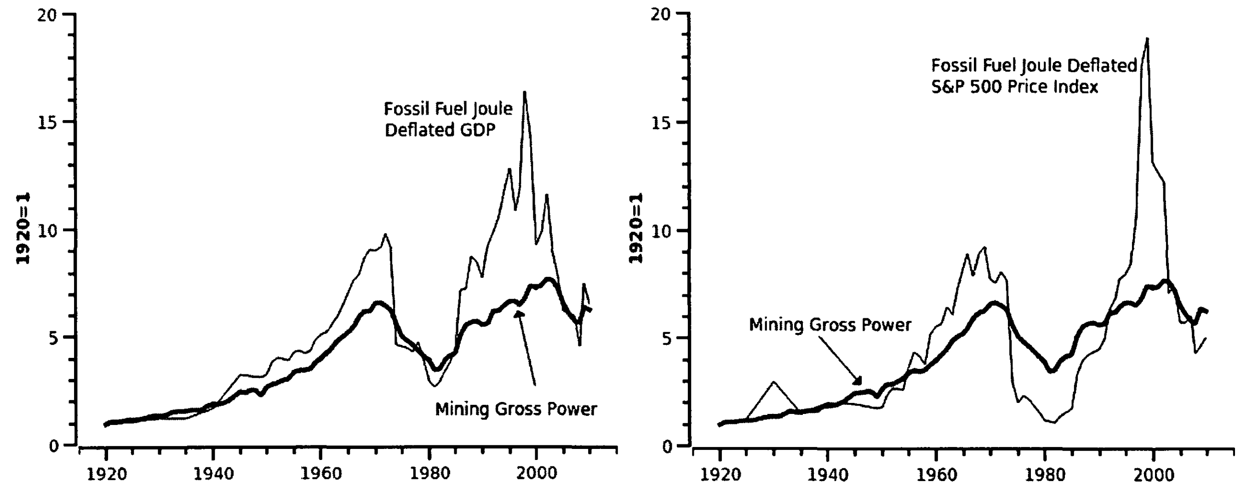

Figure 30: Mining Gross Power, joule-deflated GDP & joule-deflated S&P 500 price index

Sources: S&P500 price index from Robert Shiller's (2012) data site: www.econ.yale.edu/~shiller/data/chapt26.xls. Nominal GDP data (1929-2011) is from BEA Current-Dollar and "Real" GDP. Nominal GDP data (1900-28) is from HSUS Table Ca9, indexed to BEA data. For joule deflation methodology and sources, see Appendix A. For mining gross power methodology and sources, see Figure 29.

A very similar connection appears between the S&P 500 price index, the price of fossil fuel energy, and mining gross power. I find it useful to frame this connection in terms of *ownership*. I have previously referred to monetary value as a disembodied semiotic device – an abstract quantification of the biophysical sphere. However, we should recognize that price is fundamentally an outcome of *private property*. In order for something to have a market price, it *must be owned*[34]. While we are accustomed to thinking of the price of a *commodity*, it is more correct to think in terms of the price paid to the *owner* of a commodity.

I argue that there are two distinct types of ownership: ownership of a *stock* and ownership of a *flow*. A *stock* is a quantity at a given point in time, while flow is a rate *through* time. Using the example of energy, a tank of crude oil represents a stock, while its rate of consumption represents a flow. The price of energy, then, represents the price to gain (or liquidate) ownership over an energy *stock*. The price index of the S&P 500, however, is more abstract – it measures the price of corporate equity. The fact that corporate equity is usually referred to as a "stock" obscures the fact that it actually confers ownership over a flow. Let me explain. The equity of a particular corporation confers partial ownership rights over that corporation. But what does it mean to own part of a corporation? While there are many interpretations of the role of corporations in society, here I use Veblen's approach.

Veblen (1923) made a distinction between ***industry*** and ***business***. For Veblen, industry was the holistic process though which society met its material needs. In this sense, I treat Veblen's *industry* as synonymous with the biophysical sphere. Veblen's *business*, on the other hand, represented *legal control* of the metabolic process. Using this approach, the ownership of corporate equity implies *control* over a particular aspect of the metabolic process. Metabolism, however, is a *flow* (a rate). Thus, I make the argument that while ownership of an energy

---

[34] Private property confers the institutionalized right of exclusion. The ability of an owner to realize a price for his property is predicated on his ability to exclude free access to it (Nitzan & Bichler, 2009; Veblen, 1923). Cochrane writes that " if the owner of [an] orchard were unable to prevent anyone who wanted an apple from gaining access to the orchard, its effective price would be zero" (2010, p. 6).

commodity confers control of an energy *stock*, ownership in corporate equity confers control over a metabolic *flow*.

The S&P 500 price index tracks the equity of the 500 largest publicly traded US corporations and, according to Standard and Poors (2012), it captures 75% of US equities. In addition, the index strives to maintain a "sector balance that is in line with the sector composition of the universe of eligible companies" (ibid). My interpretation of the S&P 500 price index is that it represents the average price of unit of control (ownership) over a *broad spectrum* of the US metabolic *flow*.

Figure 30 shows that when the mining sector's gross power output grows, the value of owning/controlling metabolic *flows* increases relative to the value of owning/controlling energy *stocks*. When the mining sector's gross power declines, the reverse situation is true. It would seem that there exists a deep connection between the labour productivity of the mining sector and the price of controlling metabolic *flows* relative to the price of controlling an energy *stock*.

To recap, the connection between joule-deflated GDP, the joule-deflated S&P 500, and the gross power of the mining sector illustrates a dynamic and non-reductionist relationship between the biophysical and the pecuniary spheres. Once again, it shows that the two spheres are connected *through* time, yet need not be connected in a one to one manner at any point *in* time.

6.6 Mining Gross Power & Differential Value-Added per Person

In Chapter 5.3, I attempted to connect differential per person value-added with upward domain movement (with varying degrees of success). Given my assertion that upward domain movement is made *possible* by increases in labour productivity, it would seem reasonable that labour productivity increases should also be linked with changes in differential value-added. Here, I test this claim by relating the growth rate of mining gross power to the differential per person value-added of the SG and Mining (M) sectors:

$$\hat{GP}_M \Leftrightarrow \frac{va_{SG}}{va_M} \qquad (37)$$

Figure 31 shows the results. Especially after 1970, the changes in va_{SG}/va_M nicely correspond with changes in mining gross power. Referring back to Figure 15, we can say that mining gross power, SG/M differential domain growth, and SG/M differential per person value-added are all connected. Before discussing my own interpretation of these results, I first show how the accepted neoclassical definition of labour productivity makes the results difficult to understand from a neoclassical perspective. I then show how it can interpreted using the work of Giampietro et al.

In order to calculate labour productivity, we require a *homogeneous* output that can be quantified in *one* universal unit. For mining gross power, this output was primary fossil fuel energy measure in joules. However, unlike the mining sector, the output of most other sectors is not homogeneous. For instance, in the BM sector, how are we to aggregate the output of a garment factory with the output of a construction firm? The neoclassical solution is to use *real value-added* as a measure of *output*. Thus the OECD (2001) defines labour productivity as:

$$Labour\ Productivity = \frac{Quantity\ index\ of\ value\ added}{Quantity\ index\ of\ labour\ input} \qquad (38)$$

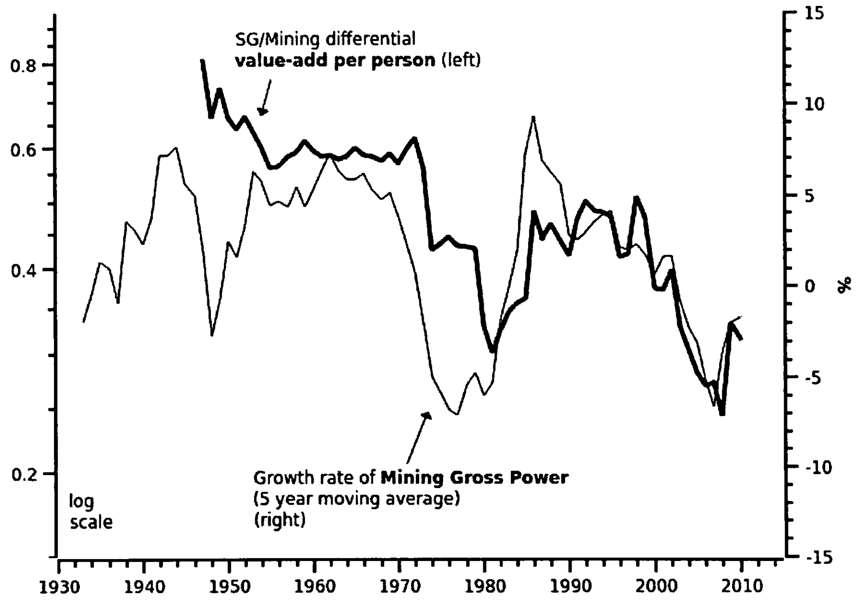

Figure 31: Mining differential value-added per person & mining gross power growth rate

Sources: For value-added, see Figure 13. Human activity data (for both mining gross power and value-added per person) comes from Series C (see Figure 8)

From a neoclassical perspective, differential per person value-added is actually a measure of differential *labour productivity*. This means that Figure 31 compares the *biophysical* labour productivity of the mining sector to its differential *value-added* productivity in relation to the SG sector. Oddly, when the mining sector's biophysical productivity *grows*, its differential value-added productivity *declines*[35]! This is truly counterintuitive.

However, if we abandon the idea that value-added per person is a measure of labour productivity, it is much easier to understand our results. Here, it is useful to introduce the binary distinction made by Giampietro et al. (2011, 2012) between the ***hypercycle*** and the ***dissipative cycle***. The hypercycle produces a ***surplus*** of materials and energy that is then *consumed* by the dissipative cycle. Figure 32 shows the sectoral composition of each cycle.

Hypercycle	Dissipative Cycle
Agriculture (AG)	Services & Government (SG)
Energy & Mining (EM)	Household (HH)
Building & Manufacturing (BM)	

Figure 32: The Hypercycle and Dissipative Cycle

Using this framework, it makes little sense to speak of the *productivity* of sectors contained within the dissipative cycle – their function is to ***dissipate*** rather than to produce. However, their ability to dissipate is contingent on their ability to *finance* the consumption of the surplus provided by the hypercycle. Thus, it seems

---

[35] It may appear that Figure 31 shows the opposite. However, because mining value-added is in the *denominator* of SG/M differential per person value-added, *increases* in this ratio correspond with *decreases* in relative value-added of the mining sector.

reasonable to treat SG/M differential per person value-added not as a measure of the relative labour productivity of each cycle, but as a measure of the SG sector's *symbolic* ability to *consume* the output of the mining sector.

In Figure 31, increases in the mining sector's gross power can be interpreted as increases in its productive surplus[36]. If this surplus is to be consumed, there must be an in kind increase in consumption. However, for *biophysical* consumption to increase, there must be an increase in the *symbolic* consumptive ability of the dissipative cycle – here represented as SG/M differential per person value-added. Figure 31 shows that this is indeed the case.

Again, I would suggest that the relationship between mining gross power and differential value-added is impredicative – I make no claim that one causes the other. My view is that increases in mining gross power are predicated on an increase in the symbolic consumptive power of the dissipative sector. If a larger biophysical surplus cannot be financed, it cannot be consumed. Similarly, an increase in symbolic consumptive power means nothing if it cannot be met with a rising biophysical surplus.

6.7 EM Gross Power & Differential Capitalization per Person

> *Conventional theories of capitalism are mired in a deep crisis: after centuries of debate, they are still unable to tell us what capital is.*
>
> – Jonathan Nitzan & Shimshon Bichler (2009, cover abstract)

Capital is one of the most important yet enigmatic quantities in political economic theory. The two dominant schools, neoclassical and Marxist, approach the concept of capital from very different starting points, but ultimately reach very similar conclusions: they both insist on a static connection between the *real* and the *nominal*, the *biophysical* and the *pecuniary.*

The neoclassical approach treats capital as a stock of pre-existing goods used during production. Nitzan and Bichler summarize the neoclassical approach succinctly:

> *The magnitude of capital in money terms is proportionate to its productivity – namely, to its ability to produce goods and services that satisfy human wants and generate happiness. This transmutation is meaningful because both capital and its productivity are counted in the same universal unit, the elementary particle of economics: the 'util'.*(2009, pp. 5–6)

The most fundamental critique of this approach, then, is the fact that the "elementary particle" – the util – *cannot be measured, nor shown to exist* (see Chapter 2.3). This leaves the neoclassical connection between the biophysical stock of capital and its monetary value in a tenuous position.

Marxists, on the other hand, approach the problem from a very different position. They see capital not as a thing but as a *social relationship*. Capital (monetary wealth) symbolizes ownership of the means of production and the ability to extract surplus-value. This relationship was famously formulated by Marx in the following expression:

$$M \rightarrow C \rightarrow M + \Delta M \qquad (39)$$

1. Monetary capital (M) is invested in production;

---

[36] Technically, mining sector *net* power, rather than *gross* power, should be used as a measure of surplus. While this data is not available, we do know that oil & gas EROI is positively correlated with gross power (see Figure 29). This supports the assumption that gross and net power increase/decrease together, meaning gross power is a reasonable proxy for net power.

2. Workers employed by the capitalist produce commodities (C);
3. The sale of these goods returns to the capitalist the original monetary capital (M) plus an extra amount $(\Delta \mathrm{M})$ that represents surplus value *extracted* from workers.

Capital, in the Marxist sense, is a pecuniary quantity, but it symbolizes the ownership of *real* machines and infrastructure. Capital is "dead labour" (Marx, 1867, Chapter 10, Section 1) and its value is determined by the quantity of dead labour embodied within it. As with the neoclassical approach and its dependence on utility, the Marxist approach hinges on the labour theory of value – the validity of which we have already questioned (Chapter 2.2).

Nitzan and Bichler argue convincingly for discarding both neoclassical and Marxist theories of capital and, along with them, the insistence on a static connection between the pecuniary and the biophysical. Instead, they argue that:

> *capital means one thing and one thing only: a pecuniary capitalization of earning capacity. It consists not of the owned factories, mines, aeroplanes, retail establishments or computer hardware and software, but of the present value of profits expected to be earned by virtue of such ownership. (2009, p. 231)*

Nitzan and Bichler argue that what is ultimately being capitalized is the *power* of owners to generate earnings and limit risk. Capital, then, is nothing more than a "*symbolic representation of power*" (ibid, p. 7).

The universal formula for the "religion" of capitalization (ibid, p. 8) is shown below. Capitalization (*K*) is defined as the perceived future earnings[37] (*E*) discounted by the perceived rate of return (*r*):

$$K=\frac{E}{r} \tag{40}$$

This approach completely severs the link between the biophysical and the pecuniary by insisting that capital has no *real* manifestation – it is the abstract quantification of social power. This framework fits nicely with the one advanced here – we can reject the notion that capital must "represent" something biophysical, but investigate how this purely pecuniary magnitude co-evolves with the biophysical sphere.

In Nitzan and Bichler's capital as power framework, the ability to generate an income stream from property rests upon two conditions:

1. Society (or some subset thereof) must desire what owners sell;
2. Owners must have the ability to *restrict* free access to this property.

Neoclassical economists have focused on condition one, yet quantifying desire (or the satisfaction of fulfilling one's desire) has proved problematic. However, if we focus on condition two, it follows that capitalization (perceived future earnings) should be predicated not on productivity, but on *strategic restriction.* Veblen referred to condition two as the "*legal right of sabotage*":

> *... any person who has the legal right to withhold any part of the necessary industrial apparatus or materials from current use will be in a position to impose terms and exact obedience, on pain of rendering the community's joint stock of technology inoperative for that extent. Ownership of industrial equipment and natural resources confers such a right legally to enforce unemployment, and so to make the community's workmanship useless to that extent. This is the Natural Right of Investment. ... Without the power of discretionary idleness, without the right to keep the work out of the hands of the workmen and the product out of the market,*

---

[37] Earnings are assumed to continue in perpetuity.

investment and business enterprise would cease. This is the larger meaning of the Security of Property. (1923, pp. 65–67)

This is a very different view than either the Marxist or neoclassical perspective. While Marxists see capital as *exploitative*, both they and neoclassicists fundamentally see it as *productive*. The capital as power framework, on the other hand, sees capital as fundamentally unproductive. Indeed, *decreases* in productivity should *increase* capitalization.

We can test this perspective by noting that EM gross power is a biophysical measure of productivity. If it *declines,* the capital as power framework predicts that the relative capitalization of energy and mining corporations should *increase*. Again, we want to compare capitalization on a per person basis. I use lower case letters to distinguish between *total* capitalization (K) and per person capitalization (k):

$$k=\frac{K}{HA} \tag{41}$$

My methodology is to compare EM gross power to SG/EM differential per person capitalization[38]:

$$GP_{EM} \Leftrightarrow \frac{k_{SG}}{k_{EM}} \tag{42}$$

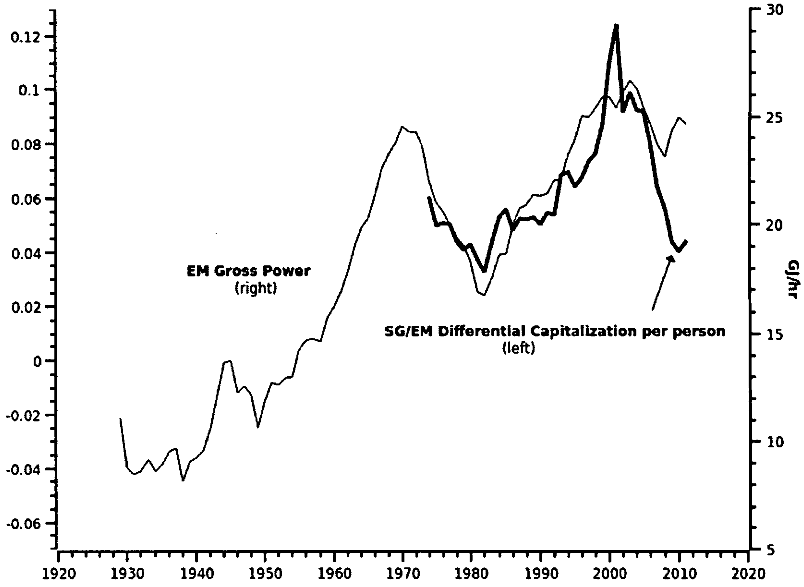

Figure 33: EM gross power & SG/EM differential per person capitalization

Sources: EM gross power is calculated by dividing US total primary energy production by EM human activity (in hours). US total primary energy production data is from EIA Annual Energy Review, Table 1.2 (1949-2011) & HSUS Table Db155-163, Energy Production by Source (1929-48). For human activity data (Series C) see Figure 8. Market capitalization data is from Datastream (Thomson Reuters, 2013). All series use market value (MV). For a detailed schematic of how Datastream series are categorized under the MuSIASEM taxonomy, see Appendix B. Capitalization data is time shifted forward by one year.

---

[38] A caveat to this methodology is that there is no guarantee that capitalization data from Datastream uses the same classification scheme as human activity data from the BEA. Appendix B shows how I have classified Datastream categories into the MuSIASEM taxonomy; however, without a detailed investigation of Datastream's methodology, we cannot determine the accuracy of this categorization. I proceed under the assumption that Datastream and BEA data are more or less compatible.

The results are shown in Figure 33. Two trends are significant. Firstly, per person capitalization in the SG sector is between 4% to 13% of the capitalization of the EM sector. From the neoclassical perspective, this implies that the EM sector requires between 7 to 14 times more capital goods to function. From the capital as power perspective, it means that the EM sector simply earns more profit per person (confirmed by Figure 17). Both approaches, it would seem, can easily explain this trend.

Unlike the static average, however, the behavior of differential capitalization *through* time is not easily explained by the neoclassical approach. Notice that *decreases* in EM gross power – a biophysical measure of productivity – are correlated with *increases* in the relative capitalization of the EM sector. Likewise, *increases* in EM gross power are correlated with *decreases* in EM differential capitalization. Thus, EM capitalization varies *inversely* relative to its productivity! This would seem to support a sabotage perspective – it is through *restriction*[39] that the EM sector is able to maximize its differential capitalization.

If we accept Nitzan and Bichler's notion that capital is symbolically quantified *power*, we can state that the balance of power between owners of the SG sector and owners of the EM sector is related to the biophysical productivity of the EM sector. We can go further and connect these findings with Figure 31. If we treat value-added not as something that is *produced*, but rather, as a function of the *power* of owners to raise the price of output above the price of inputs, we can say that differential value-added and differential capitalization should be connected. The fact that both can be positively correlated with EM gross power lends support to this view.

Because the capital as power framework investigates the pecuniary sphere by negating a direct connection with the biophysical sphere, it is one of the few political economic theories that is compatible with the methodology that I have advanced here.

6.8 Conclusions

In this chapter, I sought to answer the following question: what types of pecuniary signals (if any) are related to changes in energy throughput? I looked at two different biophysical measures (useful work and EM/Mining gross power) and four different pecuniary measures (GDP, sectoral value-added, the S&P 500 price index, and sectoral capitalization). In most cases, a consistent linkage existed between these biophysical quantities and the pecuniary sphere.

Wherever possible, rather than simply display biophysical-pecuniary linkages (as was done in Chapter 5), here I attempted to theorize the relationship. My basic premise was to begin with a biophysical view of production and then treat the pecuniary sphere as a tool for symbolically financing this production. This was most successful, in my view, when applied to the linkage between useful work and kWh-deflated GDP.

The link between per person differential value-added/capitalization and the EM/mining sector gross power was particularly interesting. It is certainly unexpected from the standpoint of most economic theory because it is usually *total* value-added/capitalization (rather than *per person* value-added/capitalization) that is considered important.. While my initial thoughts are that this might be an emergent phenomenon, little can be said without further study.

---

[39] It need not be the EM sector *itself* that is actively restricting output in order to increase capitalization. Decreases in EM productivity could easily be a response to some other form of sabotage – be it a war, an embargo, etc.

One of the unexpected findings in this chapter was that biophysical and neoclassical definitions of labour productivity do not seem to be compatible (section 6.6). This is a trend that continues through the next chapter. My own opinion is that a biophysical measure of labour productivity should be regarded as more fundamental than those based on the production of value. As we will see in the next chapter, such an approach leads to results that challenge conventional thinking.

7. Energy at the Sectoral Level

> *Surprisingly, most people do not seem to be aware that the metabolism of both societies and ecosystems is subject to the same simple rules as the human body.*
>
> – Giampietro, Mayumi, & Sorman (2011, p. 9)

This chapter continues to address the following question: what types of pecuniary signals (if any) are related to changes in energy throughput? While in the previous chapter, I used statistical data that was aggregated at the national level, here I use the MuSIASEM taxonomy to disaggregate national energy statistics. I then relate this data to changes in the pecuniary sphere.

The layout of this chapter is as follows: in section 7.1, I explain how energy data from the EIA was allocated to MuSIASEM categories, and I discuss the difficulties surrounding this process. In section 7.2, I explain Giampietro and Mayumi's concept of the ***exosomatic metabolic rate*** (EMR) and briefly discuss trends in historical US sectoral EMR. In section 7.3, I relate four biophysical measures of labour productivity (EMR_{PS}, EM gross power, mining gross power and useful work productivity) to kilowatt hour deflated unskilled wages. The results of this investigation show a clear linkage between the two time-series. Interestingly, unlike more traditional measures of labour productivity, these four metrics *do not* become decoupled from wages after 1970. In section 7.4, I use Giampietro and Mayumi's concept of the hypercycle and dissipative cycle to create a metric that I call the ***exosomatic metabolic balance*** (EMB). I then show how this metric can be related to changes in the US balance of payments in goods. In section 7.5, I demonstrate how the EMB can be disaggregated into two components: DISS/HYP differential domain growth and HYP/DISS differential EMR. In sections 7.5.1 and 7.5.2, I show how each of these components can, in turn, be related to differential changes in the pecuniary sphere.

7.1 Disaggregating National Energy Statistics

The taxonomy used in existing energy statistics makes it difficult to disaggregate national energy data into MuSIASEM sectors. The US Energy Information Administration uses the following four end-use sectors:

1. Residential
2. Transportation
3. Commercial
4. Industrial

While EIA end-use sectors do not easily map onto the MuSIASEM taxonomy, Figure 34 shows my attempt. Note that solid arrows show the *actual* allocation of data, while dotted arrows show data allocation that could not be completed at the present time.

The most obvious shortcoming of EIA data is that the category "Industrial" cannot be disaggregated into the AG, EM, and BM sectors. A further problem is that energy used by the Agriculture sector is often categorized into the Residential sector, rather than into the Industrial sector. This occurs because many farm residences receive a single utility bill, making it difficult to distinguish between energy used for household tasks versus energy used for farm tasks (Peabody, n.d.). I have not attempted to correct this shortcoming.

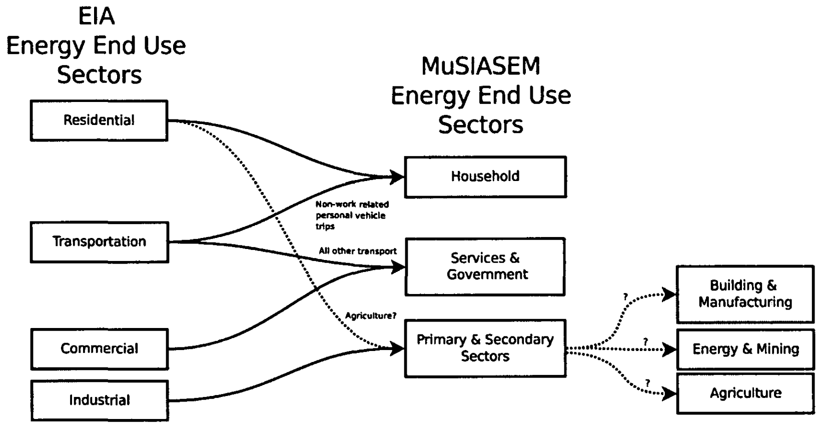

Figure 34: EIA vs. MuSIASEM energy end-use sectors
Source: Based on Figure 4.4 in Giampietro et al. (2012, p 87)

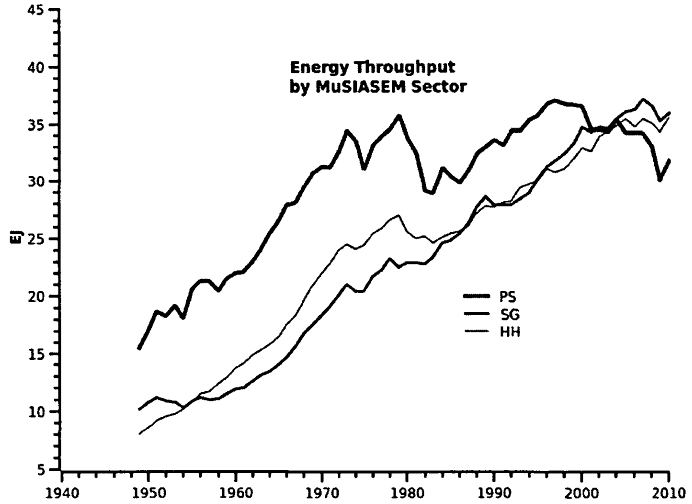

Figure 35: Energy Throughput by MuSIASEM Sector
All sectoral energy consumption data comes from EIA Annual Energy Review 2011, Table 2.1a. Note: Residential = HH, Commercial = SG, Industrial = PS. For the allocation of Transport data to HH & SG, see Appendix C1 & C2.

A major distinction between EIA and MuSIASEM taxonomies is that the latter does not contain a Transportation sector. The elimination of this category is accomplished by allocating, to the Household sector, all energy used by personal vehicles for non-work related purposes. All remaining Transportation energy is then allocated to the SG sector[40]. The logic of this mapping, according to Giampietro et al., is to distinguish between transportation energy used to "generate" added-value versus transportation energy used for leisure (2012, p. 87). While I make use of this mapping, I prefer to think in terms of transportation energy associated with monetized time versus transportation associated with non-monetized time. This way we can continue to think of monetary value as a symbolic accounting tool, rather than something that is "produced".

---

[40] For a detailed explanation of how transportation energy is allocated to the HH and SG sectors, see Appendix C1 & C2.

Figure 35 shows the final results for energy consumption by MuSIASEM sector. While this sectoral energy data is interesting in its own right, Giampietro et al. make convincing arguments for going a step further and calculating the *rate* of energy consumption per unit of human activity – the *exosomatic metabolic rate*. In the next section, I explore the evolution of this quantity.

7.2 Sectoral EMR

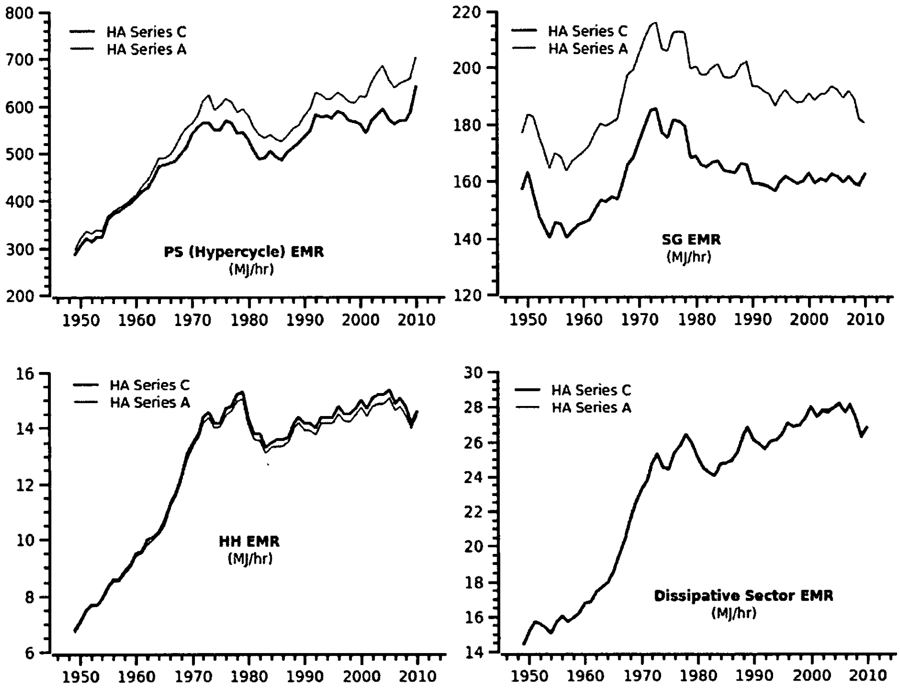

Figure 36: EMR: PS, SG, HH, & Dissipative Sector using BLS & BES Data
Sources: For energy, see Figure 35. For human activity sources (Series A & C), see Figure 8. The dissipative sector includes both SG & HH.

A drawback of only looking at energy throughput is that it conceals the fact that some sectors are far more energy *intensive* than others. Giampietro et al. use the analogy of *human* metabolism to demonstrate this principle. For instance, the total energy consumption rate for the brain (16.2 W) is about the same as for *all* the body's muscles (16.8 W)[41]. However, when we factor in the mass of each organ, we find that the brain and muscles differ in per kg energy consumption rates by an *order of magnitude* – the brain requires 11.6 W/kg, while muscle uses 0.6 W/kg (Giampietro et al., 2011, p. 164).

Very similar computations can be done for the human-system. Giampietro et al. define the ***exosomatic metabolic rate*** (EMR) as energy throughput per unit of human activity (in hours):

$$EMR=\frac{ET}{HA} \tag{43}$$

Here, the word ***exosomatic*** is used to indicate energy use that is *external* to the human body, as opposed to the ***endosomatic*** metabolic rate, which measures energy use *internal* to the body.

Figure 36 shows EMR calculations for the HH, SG, PS and Dissipative sectors[42]. Like the human body, we see that different sectors have *vastly* different metabolic rates. As of 2010, EMR_{PS} was almost 4 times as great as EMR_{SG} and over 40 times as great as EMR_{HH}! This is expected, because the latter two sectors are part of

---

[41] Based on a 70 kg average human male with a metabolic rate of 81 W.

[42] Calculations using both human activity series A and C are shown. Note the choice of source data for human activity data does affect the results (especially for the SG sector); however, the overall trends are very similar. For the rest of the paper, I use series C, unless otherwise indicated.

the dissipative cycle, while the PS sector is equivalent to the hypercycle. Producing goods, it would seem, requires much more energy than consuming them. As of 2010, the US hypercycle had an EMR approximately 20 times as great as the dissipative sector.

Looking at sectoral EMR, it is clear that the time period shown can be divided into two very distinct eras:

1. Pre-1970: exponential EMR growth
2. Post-1970: EMR stagnation

Interestingly, this post-1970 energy stagnation coincides with the onset of widening inequality, the stagnation in the real wages of the US working class, and rapid growth of the US pecuniary trade deficit. Is this a coincidence or are wages, inequality, the trade deficit, and energy consumption trends all related? As I show in the following sections, I think these trends are, in fact, quite tightly linked.

7.3 Energy Productivity & Kilowatt-hour Deflated Wages

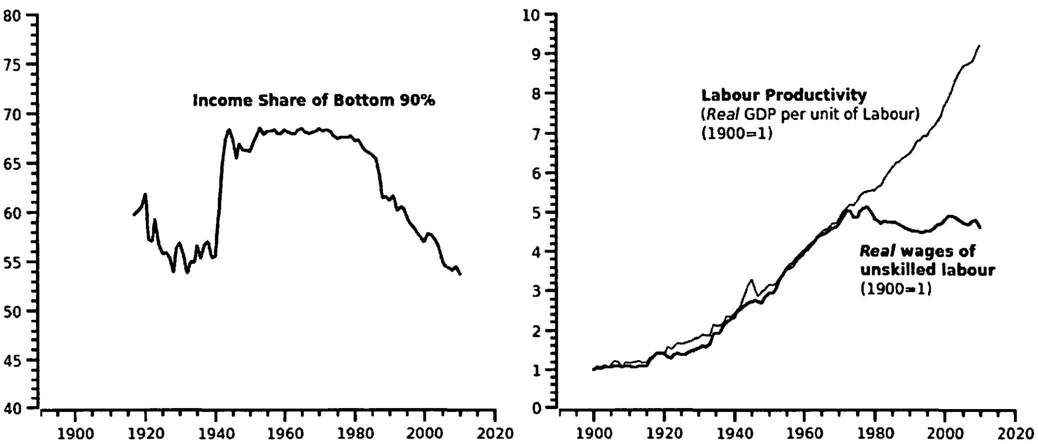

Figure 37: Income share & stagnation of real wages

Sources: US income share of the bottom 90% calculated as 100% less income share of top 10%. Top 10% income share from The World Top Incomes Database (Alvaredo, Atkinson, Piketty, & Saez, 2013). For unskilled labour wage index, see Figure 38. Real wages are calculated using the Consumer Price Index (CPI) from HSUS Table Cc1 (1900-2003) and BLS online Table CUSR0000SA0 (2004-2011). Real GDP data is from HSUS Table Ca9 (1900-1928), indexed to BEA Current-Dollar and "Real" GDP (1929-2011). US total labour hours are from Benjamin Warr's REXS Database, (1900-1947), indexed to BEA estimated labor hours of full & part-time employees (see Figure 8) (1948-2011).

In this section, I continue my attempts to link changes in energy consumption with changes in the pecuniary sphere. Here, energy consumption patterns take the form of biophysical measures of labour productivity, while from the pecuniary sphere, I choose to look at unskilled wages relative to the price of electricity. The empirical evidence seems to suggest that there is indeed a long-term linkage. Interestingly, this contradicts evidence that wages and productivity have become decoupled since 1970 (Figure 37, right).

As I noted in Chapter 6.6, the traditional method for measuring labour productivity is to quantify output in terms of its real monetary *value*. Thus, in Figure 37, labour productivity is defined in terms of real GDP:

$$Labour\ Productivity = \frac{GDP_R}{HA_{Paid}} \tag{44}$$

In this chapter, I ask: if we substitute a *biophysical* measure of material output in equation 44, can we still show that wages have become decoupled from labour productivity? The empirical evidence seems to suggest that we *cannot*.

I begin by noting that we so far have two biophysical labour productivity measures in our toolkit – EM and Mining gross power:

$$GP_{EM} = \frac{Gross\ Energy\ Production}{HA_{EM}} \tag{31}$$

$$GP_M = \frac{Gross\ Fossil\ Fuel\ Production}{HA_M} \tag{32}$$

I add to these two measures the concept of *useful work productivity*, defined as useful work output (U) per unit of paid human activity:

$$U_{Productivity} = \frac{U}{HA_{Paid}} \tag{45}$$

I also add a fourth measure – EMR_{PS} – which I treat as both a measure of the PS metabolic rate and a reasonable proxy for PS productivity[43].

$$EMR_{PS}=\frac{ET_{PS}}{HA_{PS}} \tag{46}$$

In Figure 38, I compare these four biophysical measures of productivity with kWh-deflated unskilled wages. While *real* wages are ostensibly an indicator of material standard of living, I make no such claim for kWh-deflated wages. Rather, I interpret them as the *symbolic* ability of workers to consume energy (electricity). It makes sense that this symbolic ability should be supported by biophysical reality; if workers gain symbolic power to consume energy, we expect that society's biophysical ability to supply it ought to grow in kind. Figure 38 shows that this is indeed the case.

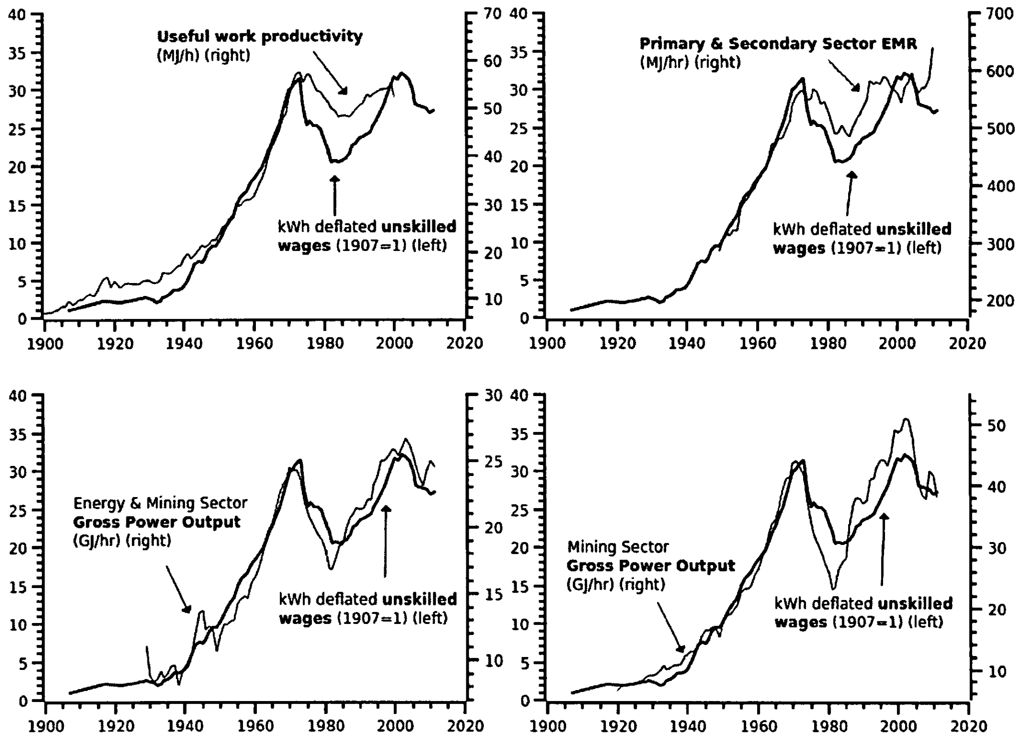

Figure 38: Wages & biophysical productivity

Sources: Unskilled wage index (1900-2008) comes from Samuel Williamson (2009) Index of Unskilled Labor from 1774 to the Present. Following Williamson's methodology, unskilled wages for 2009-11 come from the BLS Current Population Survey, using median weekly earnings for full-time wage and salary workers, 25 years and over with less than a high school diploma (Series Code LEU0252916700), indexed to Williamson's 2008 data point. For the price of electricity, see Figure 27. Useful work productivity is defined as useful work per unit of labour (in hours). Both useful work and total labour hours come from Benjamin Warr's REXS Database. For Primary & Secondary sector EMR sources, see Figure 36. For EM gross power output sources, see Figure 33. For mining gross power output sources see Figure 29.

---

[43] While PS productivity should measure the end-use work *output* of the PS sector, EMR_{PS} measures primary energy *inputs*. We can expect the growth of inputs and outputs to be reasonably well correlated, so long as energy converter efficiency gains are fairly small.

However, another interpretation of kWh-deflated *wages* is that they reflect the price of *human* work relative to *machine* work. While it is often a gross simplification to reduce human tasks to mere expenditures of energy, in the case of manual labour, this reduction has some validity. If we regard unskilled workers as engaged in mostly manual labour, their wage can be viewed as the price of *human* physical work. Likewise, the price of electricity can be viewed as a proxy for the price of electric-powered *machine* work.

Thus, the differential comparison of unskilled wages to the price of electricity can be viewed as the *pecuniary pressure* to replace unskilled workers with machines. An increase in the use of machines should be visible as both an increase in biophysical *productivity* (since machines increase output per worker) and as an increase in energy *consumption* (since machines require energy inputs). Putting it all together, we expect that the growth of kWh-deflated wages should be directly linked to our four biophysical productivity/metabolic metrics. Figure 38 shows that this linkage does indeed exist, and is quite robust.

Again, then, we find that there is a consistent and long-term linkage between changes in energy consumption and changes in the pecuniary sphere. What, then, are we to make of the fact that this evidence seems to contradict the more traditional method of relating productivity to wages? A conservative conclusion would be that they simply measure different things, while a more radical conclusion would be that quantifying output in terms of its value is not an accurate measure of material productivity.

Lastly, I do not think the evidence presented here suggests that wages have remained *fair*. Indeed, to draw conclusions about the fairness of wages, we need to know nothing other than that their relative income share has declined (Figure 37, left). Is there a way that wages can simultaneously remain correlated with biophysical labour productivity and grow increasingly unfair? This is a question in need of further investigation.

7.4 The Exosomatic Metabolic Balance & the US Trade Deficit

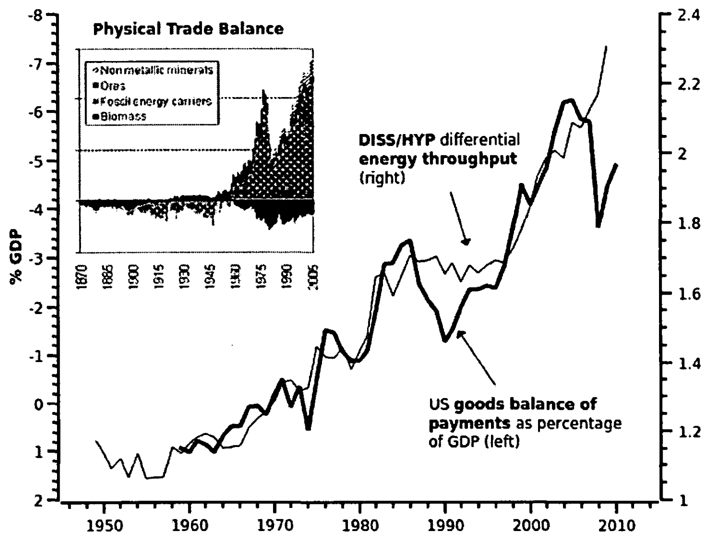

Figure 39: Metabolic balance and the balance of trade

Sources: US goods balance of payments from the United States Census Bureau data on Foreign Trade: Annual goods (BOP basis), services, and total balance, exports and imports, 1960 – present. For nominal GDP sources, see Figure 27. For energy throughput sources, see Figure 35. Physical trade balance (inset) from Gierlinger & Krausmann (2012, p. 7).

In this section I turn my focus to investigate US trade. Again, my goal is to relate changes in energy consumption to changes in the pecuniary sphere. On the energy side, I create a metric that I call the *exosomatic metabolic balance*, and I then relate it to the US trade deficit in goods.

I begin by defining the exosomatic metabolic balance (EMB) as the ratio of energy thoughput in the dissipative sector to the energy throughput in the hypercycle:

$$\text{Exosomatic Metabolic Balance (EMB)} = \frac{ET_{DISS}}{ET_{HYP}} \tag{47}$$

I view the EMB as essentially measuring the balance between ***consumption*** and ***production*** within the confines of the nation-state. The validity of the EMB relies on the following hypotheses:

1. The energy throughput of the *hypercycle* (ET_{HYP}) is a reasonable proxy for *production*;
2. The energy throughput of the *dissipative cycle* (ET_{DISS}) is a reasonable proxy for *consumption.*

The reasoning behind these hypotheses is that it takes energy to both produce and consume a commodity. We can use automobiles as a simple example. Since energy inputs are required to produce a car, it seems reasonable to assume that the energy used by the automobile sector should be roughly proportional to the number of cars produced. Similarly, since it takes energy to "consume" a car (ie: to drive it), an increases in automobile sales should correlate with increases in gasoline consumption. Even if a commodity does not consume energy directly (like a car) it still requires warehousing, packaging, transportation, eventual waste disposal – all of which require energy. Thus, I think that it is fair to state that increases in both production and consumption require increases in energy throughput.

In Figure 39, I test to see if the EMB index can be related to the physical and/or the pecuniary trade deficit. It turns out that the EMB shows qualitative similarity to the physical trade balance[44] and striking quantitative correlation with the pecuniary balance of payments in goods. This latter result is interesting, as there is no inherent reason that a *metabolic* imbalance should lead to a *pecuniary* trade imbalance. Because the balance of payments in goods (BOP_{Goods}) is a result of both the unit price (p) and the quantity (Q) of exports and imports, an increase in the *quantity* of imports (a biophysical metric) could conceivably be offset by an increase in the unit *price* of exports:

$$BOP_{Goods} = p_{Exports} Q_{Exports} - p_{Imports} Q_{Imports} \tag{48}$$

Obviously, the US has not been able to carry out such a price increase.

While these results were not expected, they are quite useful. In the next section I build on them to show how "decisions" about the allocation of energy and human activity can be directly linked with the growth of the EMB, and hence, to the pecuniary trade deficit.

7.5 Dissecting the EMB: Differential EMR & Differential Domain Growth

In order to further understand the growth of the EMB, it is useful to decompose it into two constituent parts. I begin with the following identity:

$$ET = \frac{ET}{HA} \cdot HA \quad \Rightarrow \quad ET = EMR \cdot HA \tag{49}$$

This identity allows us to decompose the EMB into *differential* EMR and *differential* HA:

$$\text{EMB} = \frac{ET_{DISS}}{ET_{HYP}} \quad \Rightarrow \quad EMB = \frac{EMR_{DISS}}{EMR_{HYP}} \cdot \frac{HA_{DISS}}{HA_{HYP}} \tag{50}$$

By carrying out this mathematical trick, we can differentiate between the two different ways that the EMB may change:

1. A change in DISS/HYP differential EMR;
2. A change in DISS/HYP differential HA.

Conversely, we can state that if the EMB is to remain *constant*, we should have an *inverse* relationship between DISS/HYP differential EMR and differential HA:

$$\text{if } \frac{EMR_{DISS}}{EMR_{HYP}} \cdot \frac{HA_{DISS}}{HA_{HYP}} = constant \quad \Rightarrow \quad \frac{HA_{DISS}}{HA_{HYP}} \propto \frac{EMR_{HYP}}{EMR_{DISS}} \tag{51}$$

Expression 51 is a mathematical statement about the relationship between productivity[45] and upward domain movement. Here, HYP/DISS differential EMR can be thought of as the *relative* productivity of the hypercycle, compared to the rate of consumption of the dissipative sector. If relative productivity grows and the EMB remains constant, expression 51 tells us that we should expect upward domain movement from the hypercycle to the dissipative cycle. Of course, we already know that the EMB has *not* remained constant, so we know that differential EMR and differential HA have not behaved as they "should". By carrying out a differential growth rate comparison (expression 52) we can look at their divergence.

$$\left[\frac{\hat{HA}_{DISS}}{HA_{HYP}}\right] \Leftrightarrow \left[\frac{\hat{EMR}_{HYP}}{EMR_{DISS}}\right] \tag{52}$$

---

[44] Gierlinger & Krausmann did not publish their raw data, making a more quantitative comparison impossible at the present time.

[45] To be more correct, a hypothesized proxy for productivity.

Figure 40 shows the results of this investigation: the two series are somewhat coupled, but note that they diverge after the 1970s. Again, this is what we expect: the gap between differential EMR and differential HA shows the growing metabolic *imbalance*. Upward domain movement proceeded *despite* the fact that the relative productivity of the hypercycle *declined.*

What Figure 40 tells us, is that choices about the allocation of energy and human activity played an integral role in the development of a metabolic imbalance. In both cases we have a binary choice. The allocation of energy could either be used to:

A) Increase the relative *productivity* of the hypercycle $\left(\uparrow \frac{EMR_{HYP}}{EMR_{DISS}}\right)$;

B) Increase the relative *consumption rate* of the dissipative cycle $\left(\downarrow \frac{EMR_{HYP}}{EMR_{DISS}}\right)$.

Similarly, human activity could flow either to:

A) The hypercycle, causing *downward* domain movement $\left(\downarrow \frac{HA_{DISS}}{HA_{HYP}}\right)$;

B) The dissipative cycle, causing *upward* domain movement $\left(\uparrow \frac{HA_{DISS}}{HA_{HYP}}\right)$.

In both cases, option B clearly dominated, and the EMB grew. My goal in the next two sections is to see if the two biophysical time-series shown in Figure 40 can be linked to similar changes in the pecuniary sphere.

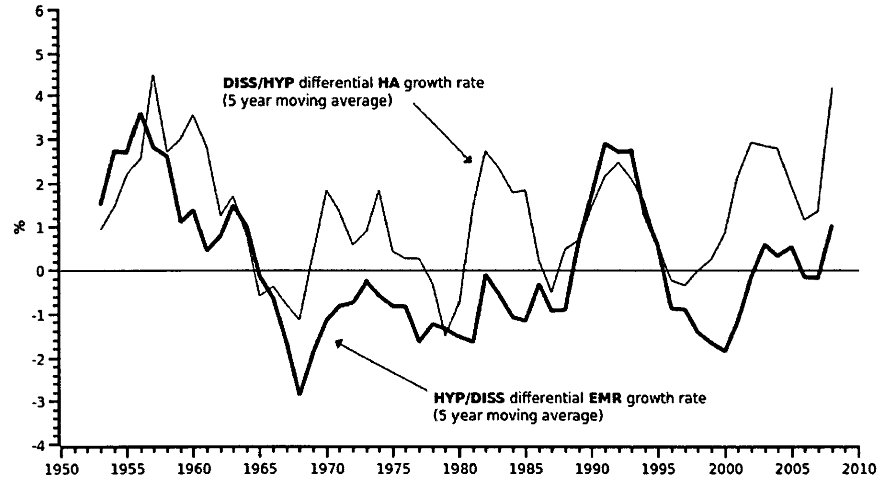

Figure 40: Differential HA & EMR growth between dissipative cycle & hypercycle
Sources: For human activity (Series C) see Figure 8. For EMR, see Figure 36.

7.5.1 Connecting DISS/HYP Differential Domain Growth with the Pecuniary Sphere

I begin with the DISS/HYP differential growth rate. In Chapter 5, I tested the linkage between upward domain movement and differential per person value-added, profit, and wages. As Figure 41 shows, it turns out that SG/BM differential per person *value-added* can be related nicely with DISS/HYP *differential domain growth.* When the SG sector has higher per person value-added relative to the BM sector, the *entire* dissipative sector grows in relation to the hypercycle. This is surprising, because the human activity of the dissipative sector is dominated by *unmonetized* household time. Nevertheless, it would seem that the pecuniary sphere is heavily linked to movement to and from the household sector.

It is not at all obvious why this behavior occurs – and I make no attempt to explain it here. Rather, I simply note that Figure 41 shows a linkage with no discernible “decoupling” after 1970. This is important because it means that the price structure of society continued to “incentivize[46]” upward domain movement, even when this led to a metabolic *imbalance*.

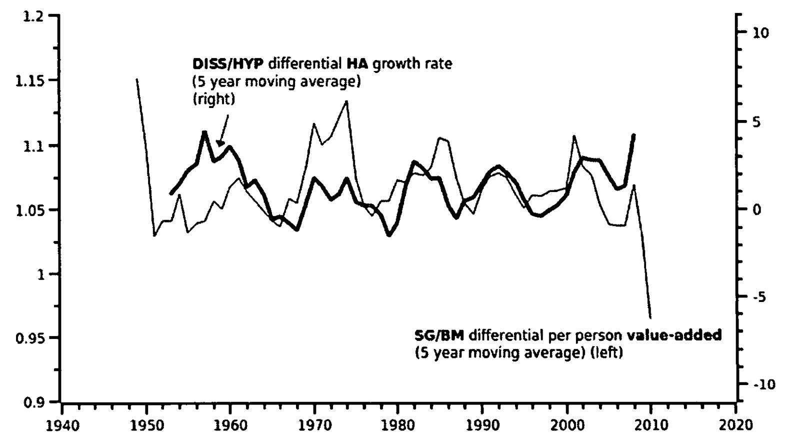

Figure 41: DISS/HYP differential domain growth & SG/BM differential value-added per person.

Sources: For EMR, see Figure 36. For human activity (Series C) see Figure 8. For value-added, see Figure 13.

7.5.2 Connecting HYP/DISS Differential EMR with the Pecuniary Sphere

In order to link differential EMR with the pecuniary sphere, I return to the connection between wages and biophysical productivity. In Chapter 7.3, I argued that kWh-deflated unskilled wages represented the symbolic pressure to replace workers with machines. Could we not make the same assertion for any type of kWh-deflated income – unskilled, skilled, professional, or capitalist? I argue that this is *not* the case. Rather, we need to make a distinction between the type of labour done by the working class versus the type done by upper classes.

I begin by assuming that machines are primarily used to replace manual labour done by unskilled workers. I argue that upper class[47] jobs – doctors, lawyers, engineers, managers, capitalists etc. – are almost *never* at risk of being replaced by machines. This could be due to the fact that it is more difficult to design machines to replace this type of labour, or to the fact that people in these positions simply have more power to preserve their jobs. Whatever the cause, we know historically that it is the working class, not the upper class, that is constantly at risk of being made redundant by machines,

It follows from this argument that the growth of these two types of incomes exerts different pressures on society. To start with, the growth in any type of income confers an increase in consumptive ability. However, I

---

[46] This assumes that differential per person value-added can be interpreted as an incentive. It may well be that it is not an incentive at all, but rather, a metric that correlates with upward domain movement for some entirely different reason.

[47] I use the term “upper class” loosely. My conceptualization of class is similar to Michael Albert (2004), who divides humanity into three classes: the working class (bottom 80%), the professional class (top 20%), and the capitalist class (top 1%). Since I later use the income share of the top 10%, I treat this as the “upper class” – a mixture of capitalists and professionals.

argue that working class income *alone* places pressure on increased mechanization, and hence, increased *productivity*. This means that if upper class income grows more quickly than working class income, we expect that the rate of *consumption* should grow more quickly than *productivity*. The reverse should also be true: if upper class income grows more slowly than working class income, we expect that the rate of *consumption* should grow more slowly than *productivity*.

I have argued that EMR_{HYP} and EMR_{DISS} can serve as proxies for the productivity of the hypercycle sector and the rate of consumption of the dissipative sector, respectively. Hence it makes sense that changes in HYP/DISS differential EMR should be related to changes in the income of the working class relative to the upper class.

In order to test this, I use unskilled wages for the income of working class labour and the average per capita income of the top 10% of US society ($i_{top10\%}$) for the income of the upper class. I then compare the differential growth rate of these two pecuniary metrics with the HYP/DISS differential EMR growth rate:

$$\widehat{\left[\frac{w_{Unskilled}}{i_{Top10\%}}\right]} \Leftrightarrow \widehat{\left[\frac{EMR_{HYP}}{EMR_{DISS}}\right]} \qquad (53)$$

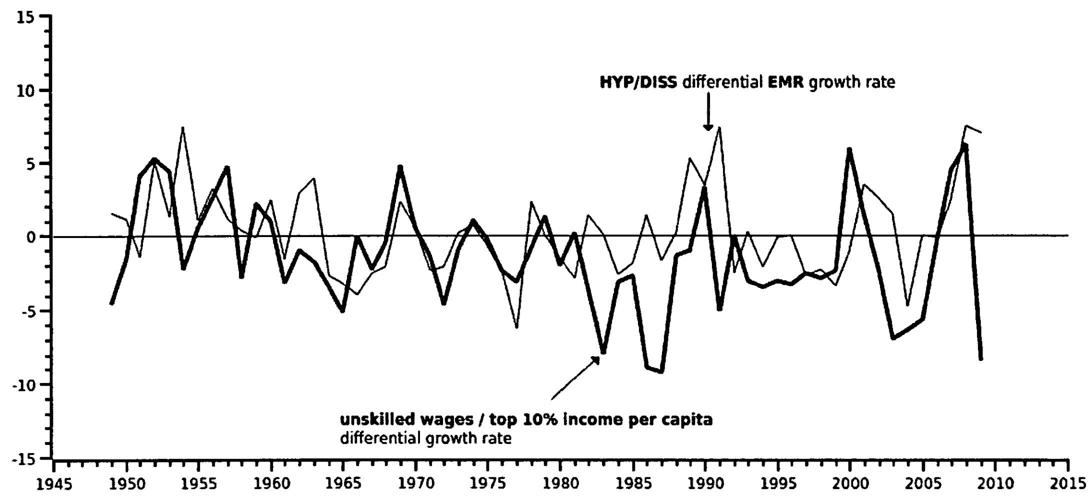

Figure 42: Differential income & differential EMR

Sources: Top 10% income per capita calculated by multiplying top 10% income share by national income and dividing by 10% of US population. National income is from BEA Table 1.12, National Income by type of Income. For income share of Top10%, see Figure 37. For US population, see Figure 40. For EMR, see Figure 36. For unskilled wages, see Figure 38.

The results of this comparison, shown in Figure 42, give stunning support for our theoretical argument. Other than for a brief period in the 1980s, there is excellent correlation between HYP/DISS differential EMR growth and unskilled/top10% differential income growth. Thus, we have shown that the *distribution* of pecuniary wealth seems to be intrinsically linked to growth in the *relative* productivity of the hypercycle. When the distribution of wealth grows more *unequal*, growth in the rate of *consumption* outpaces growth in *productivity*; conversely, when the distribution of wealth grows more *equal*, growth in *productivity* outpaces growth in the rate of *consumption*.

As with differential domain growth and differential per person value-added, there is no discernible change between the pre-1970 and post-1970 period. Again, this is important because it means that the same price mechanisms that functioned to keep the EMB *stable* later functioned to move it towards *imbalance*. Putting these findings together with those from Figure 41, we have powerful evidence showing that diverse aspects of the pecuniary sphere can be directly linked to the EMB imbalance.

This is, I think, a fitting end to our meandering empirical journey. We have managed to tie together such disparate quantities as the distribution of wealth, differential per person value-added, differential EMR, differential domain growth, differential energy throughput, and the pecuniary and biophysical trade deficit. This would seem to put the central assertions of this paper on very sound empirical ground.

8. Conclusions

This thesis sought to address the following question: how can a biophysical approach to economics be used to gain insight into the complex interrelationship between the biophysical sphere of economic activity and its monetary image? More specifically:

1. What types of pecuniary signals (if any) are related to the movement of human activity?
2. What types of pecuniary signals (if any) are related to changes in energy throughput?

In order to position my approach against existing literature, I first reviewed and critiqued the most prominent theories of value within political economy. It was my view that land, labour, utility, and energy theories of value all posited simplistic connections between monetary value and the material world. I argued that their validity was predicated on what I called a *universal quantifier* – a unit capable of quantifying and comparing the biophysical world without specifying the exact narrative to be adopted by the analyst. Thus, while *units* allow quantitative comparison based on the constraints of a very *specific* narrative, theories of value based on *universal quantifiers*, I argued, supposedly allow comparison across all possible narratives. However, I argued that universal quantifiers are a logical impossibility, rendering problematic the theories of value that are predicated on their existence

I agreed with Nitzan and Bichler (2009) that the "fundamental particles" proposed by utilitarian and Marxist theories of value (the "util" and socially necessary abstract labour, respectively) could not be measured nor shown to exist. I further argued that land theories of value (implied by the physiocrats, but never actually fully developed) would be plagued by similar problems. Building on the arguments made by Giampietro et al. (2011), I argued that difficulties with the calculation of embodied energy plagued energy theories of value (and labour and land theories as well). Indeed, the "truncation problem" raises serious epistemological difficulties with the notion of a metaphysical substance "embodied" in an object, since it showed that the concept depended inherently on the subjective choice of boundaries made by the analyst.

Having rejected the major existing theories of value, I then reviewed existing literature in search of a suitable methodology for empirically connecting monetary and biophysical data. While the "ecological world-systems" approach offered a very interesting agenda, I opted not to use its methodologies because they searched for *divergences* between biophysical and monetary flows, whereas I was concerned with long-term *correlation.* I also opted not to use a production function approach because I argued that it implied that monetary value was "produced" by the factors of production and that this ultimately depended on a utilitarian theory of value.

Instead of these approaches, I settled on two distinct currents of thought that were radically different in their pre-analytic visions. On the biophysical side, I chose the MuSIASEM approach proposed by Giampietro and Mayumi, while on the pecuniary side, I used Nitzan and Bichler's analytical framework. The resulting synthesis used the biophysical categorization scheme of the MuSIASEM approach and the differential methodology of Nitzan and Bichler.

I framed this theoretical synthesis as a tool for the investigation of the co-evolution of the biophysical and pecuniary spheres. While the resulting empirical study is extremely broad in scope, there are two important unifying elements. The first is my pre-analytic vision that fossil fuel societies can be defined by their use of increases in energy consumption to facilitate upward domain movement. This situates the empirical study within my specific research questions: namely the search for pecuniary data that can be related to the movement of human activity and changes in energy consumption. The second important unifying element is the *methodology itself*. My empirical approach is to maintain an analytical separation between the two spheres by presenting a "parallel history" (Borzoni, 2011a). In each case I attempt to relate an entirely biophysical time-series to an entirely pecuniary time-series[48].

Because of the breadth of empirical results, it is difficult to offer overall conclusions. Here I offer thoughts about their meaning, and suggest areas for further research. I begin with the investigation into the movement of human activity. First, it is important to acknowledge that except for wages, the pecuniary metrics that were used (*per person* value-added and *per person* profit) were unusual. As I have stated previously, there is little within political economic theory to suggest that these per person metrics inform decisions made by individuals or institutions. Since it is ultimately the actions of individuals and/or institutions that leads to the movement of human activity, it is unclear why these metrics would influence our behavior.

Why, then, is there good correlation (in some cases) between the movement of human activity and these per person metrics? One possible explanation is that we are simply seeing a spurious correlation based on the auto-correlation between human activity and itself. For instance, the comparison of SG/BM differential per person value-added with SG/BM differential domain growth contains the same human activity elements in both terms:

$$\frac{VA_{SG}/HA_{SG}}{VA_{BM}/HA_{BM}} \Leftrightarrow \left[\frac{\hat{HA}_{SG}}{HA_{BM}}\right] \tag{54}$$

$$\frac{VA_{SG}}{VA_{BM}} \cdot \frac{HA_{BM}}{HA_{SG}} \Leftrightarrow \left[\frac{\hat{HA}_{SG}}{HA_{BM}}\right] \tag{55}$$

Here, equation 55 is simply an algebraic rearrangement of equation 54. In equation 55, it is conceivable that the BM/SG human activity ratio might be somehow correlated with its inverse growth rate. Unfortunately, this is not born out by evidence: the correlation between the two HA terms has an R-squared of 0.0035. This is two orders of magnitude less than the correlation between per person value-added and the human activity growth rate. Clearly, then, auto-correlation plays little role in the resulting relationship. Thus, we must search for another explanation.

Within this paper I have characterized this surprising correlation between per person value-added/profit and differential domain growth as an *emergent* relationship. At the present time, I do not have the theoretical tools to explain it. However, if I were to continue this research, there are certain questions that are important to answer. Most importantly, is upward domain movement predominantly *push* or *pull* dominant? By push dominant, I mean that it is the loss of a job in one sector that *pushes* human activity to another sector, whereas, by pull dominant, I mean that it is the creation of a new job that *pulls* human activity to a new sector. For instance, I think that one of my most important empirical findings was that it is only when leaving *agriculture* that higher wages could be linked to the movement of human activity. For all other sectors, upward domain movement constituted a wage *decline*. This certainly hints at a push dominant model.

Secondly, for the SG and BM sectors – which constitute the vast majority of paid human activity – I found that peaks in *differential* domain growth correlated with troughs in *absolute* domain growth, meaning

---

[48] Because I usually rely on per person metrics (profit per person), one could argue that the resulting ratio is actually a mix of biophysical (human activity) and pecuniary data.

differential and absolute domain growth occur under different "regimes". Furthermore, it was the *decline* in BM human activity, rather than an increase in SG human activity, that led to differential growth. Again, this hints at a push model. However, the scale and level of aggregation adopted within this study limit our ability to further investigate this phenomenon.

A major problem with the MuSIASEM approach is that it investigates the workings of a *system* without ever identifying *actors*. Further integration of the capital as power framework could help solve this problem. Within the capital as power framework, the most important actors are the largest corporations – what Nitzan and Bichler call "dominant capital". At the present time, the top 100 US corporation control about 50% of total US profits (Nitzan, 2009, p. 318) and it is my feeling that these institutions play the most important role in deciding how to allocate paid human activity. Certainly on a qualitative level films such as Michael Moore's *Roger & Me* (1989), a visceral (but humourous) documentary about the social effects of General Motors' decision to outsource tens of thousands of jobs during the 1980s, demonstrates this concept. Of central importance, then, is to understand why large firms behave the way that they do, and how this relates to the price structure of society (and by extension, the power structure of society).

The central problem with asking such questions within the confines of the MuSIASEM approach is that it is difficult (if not impossible) to use the same categorization scheme for both biophysical flows and the legal superstructures that control these flows. For instance the concept of differential accumulation is not easily integrable into the MuSIASEM approach because the latter relies on *sectoral* analysis, while the former operates *across* all sectors. The largest firms exist as horizontal legal superstructures, controlling establishments across numerous industries. At the present time, I do not know if this theoretical difficulty can be overcome, but it certainly is food for thought.

Another practical issue with my human activity analysis is the need to distinguish between upward domain movement that is supported by increases in labour productivity versus that which is not. The latter case implies that lower domain jobs are simply being outsourced out of country. For instance, in the case of the autoworker layoffs documented by Michael Moore, the vast majority of workers were not replaced by machines, but by cheaper Mexican counterparts. In this example, we really cannot get the whole picture without looking at a system larger than US nation-state. Integrating a world-systems approach into the MuSIASEM methodology would avoid this problem. For instance, rather than define the United States as the "whole", we might expand the boundary to include all of North America (or even the world). Of course, the more global our scope, the more enormous the task. Data availability and commensurability would likely prove an enormous hurdle to this approach.

A more modest approach would be to draw on some of the results that came later in my energy analysis. Here, in particular, the exosomatic metabolic balance (EMB) is useful. The basic hypothesis is that if upward domain movement proceeds at the same pace as made viable by productivity gains (relative to the rate of consumption), the EMB should remain balanced. Similarly, if the decline in primary sector human activity occurs more quickly than productivity gains, the EMB should grow. Since the EMB is meant as proxy for the ratio of consumption to production, its growth indicates that consumption exceeds production and that the nation-state is no longer metabolically self-sufficient. The fact that the EMB corresponds nicely with the growth of the US trade deficit (both biophysical and pecuniary) lends credence to this approach. This seems to provide evidence that much of the upward domain in the last 30 years has been unsupported by productivity gains.

To return to my initial thesis question, I asked: what types of pecuniary signals (if any) are related to the movement of human activity? I think that I have clearly shown that differential wages, differential per person value-added, and differential per person profit can all be linked to the movement of human activity. However, the connection is complex and often counterintuitive. I think that the best conclusion that can be drawn is that my methodological *approach* was successful, but that the results opened more questions than they answered.

Turning to energy, I argued from a thermodynamic standpoint that the movement of human activity should be linked with increases in energy consumption. The idea was that increases in energy throughput allow work to be done by machines that increases labour productivity, thereby allowing upward domain movement. I was able to show that there was an empirical linkage between the growth of per capita useful work and the movement of human activity from AG to BM. This result is important because it empirically grounds my pre-analytic vision, and it connects the two major portions of this paper (human activity and energy). It is also interesting that this useful work connection exists between AG and BM, rather than BM and SG. I do not know why this is the case.

In order to interpret the results of this energy/money investigation, I looked at the process of production from two angles. In biophysical terms, I conceptualized the human-system as a ***dissipative structure*** that did work on itself in order to maintain itself (or grow). Ignoring matter, I viewed this process entirely as a series of energy transformations, with the end result being the self-reflexive application of useful work by the system onto itself. The monetary image of this process, I argued, was a method of accounting that allowed this process to be symbolically financed.

As a test of this principle, I looked for a linkage between Ayres and Warr's useful work and kWh-deflated GDP. The idea was that the price of electricity could be used as a proxy for the price of all useful work, and that kWh-deflated GDP represented the symbolic ability to purchase useful work "inputs" from the sale of finished product "outputs". The empirical results were quite striking – much better, in fact, than the relationship between real GDP and useful work.

I used a similar argument for fossil fuel joule-deflated GDP. Rather than measuring energy in its final end-use form, we measured it as it entered the system as a product of the energy and mining sector. The results indicated that the labour productivity of this sector (EM gross power) were clearly linked to the symbolical ability to purchase fossil fuel inputs from the sale of finished products (GDP). I was also able to show that mining gross power was related to the joule-deflated S&P 500 price index; however, I am less sure of what this means.

In many ways, this conceptualization of GDP has interesting implications for the way that we think about value. Firstly, it discards the notion that GDP is useful as a *quantity* measure of production. Instead, GDP is seen only as the aggregate *value* of production. When related to the price of energy, this becomes a symbolic representation of the ability to mobilize energy flows. It follows from this argument, that raising the price of output faster than the price of energy inputs is a suitable strategy for increasing energy flows (or at least the symbolic ability to purchase energy flows). Again, the MuSIASEM approach says nothing about how prices rise; however, the capital as power framework focuses on this issue. For instance, the ability of large corporations to raise their markup faster than average (thereby increasing prices) is a central element to the capital as power framework (see Nitzan & Bichler, 2009, p. 373, as well as Nitzan, 1992, pp. 418–22). It would certainly be interesting to attempt to connect energy flows with differential markup, but again we are faced with the sectoral categorization problems outlined above.

Moving on, I was able to further show that EM/mining gross power could be linked both to SG/EM differential per person capitalization and to SG/mining differential per person value-added. I think the most important aspect of these empirical results are that they seemed to contradict traditional (neoclassical) notions of productivity. For instance, (real) value-added is often used as a quantity measure of the output of a sector. Thus if (real) value-added increases per unit of labour, it is assumed that labour productivity has increased. However, I was able to show that when the biophysical labour productivity of the mining sector increased, traditional metrics appeared to show that its labour productivity actually *decreased* relative to the SG sector. Similarly, in neoclassical discourse, it is assumed that capital is productive, and that increases in capitalization should result in increases in labour productivity. However, the empirical results showed the opposite – when the biophysical labour productivity of the EM sector increased, its per person capitalization *decreased* relative to the SG sector. In my view, these results indicate that traditional theories of productivity need to be questioned.

In fact, this is a unifying trend to much of the energy portion of this paper: the use of biophysical metrics of labour productivity leads to different (if not completely contradictory) results than if traditional measures are used. A case in point is the comparison between biophysical labour productivity and wages. When labour productivity is measured using real GDP as an output, it appears that unskilled wages "decouple" from productivity after 1970. However, when biophysical metrics are used, no such decoupling occurs. Again, I think this evidence suggests that we need to seriously question the validity of productivity metrics based on the production of value.

Like my arguments with kWh-deflated GDP, I argued that kWh-deflated wages represented the ability of workers to symbolically consume energy. However, in this instance, I further argued that kWh-deflated wages also represented the relative price of human labour relative to electric powered machines. I suggested that this metric could be interpreted as the symbolic pressure to replace humans with machines, and thus, the symbolic pressure to increase productivity. In many ways these arguments are very Keynesian – effective demand for energy is maintained by keeping wages high, and high wages spur the increases in productivity that ultimately raise material standards of living.

The long-term correlation between unskilled wages and biophysical productivity ties in nicely with the last empirical case study: the US trade deficit. Since 1970, we know that the income of the upper echelons of US society has vastly outpaced those at the bottom. And yet, it is those at the bottom whose wages remain correlated with the biophysical metrics of labour productivity used in this paper, meaning the growth in income of those at the top has outpaced this productivity. This seems to suggest that the top strata of US society can consume more than is domestically viable. It is very interesting, then, that we can ultimately link the growth of the US trade deficit (by way of dissecting the EMB) to the growth of income inequality!

Indeed, it is the results of the final case study of this paper that I personally find most exciting. Firstly, I was able to link the ratio of energy throughput in the dissipative sector to the energy throughput in the hypercycle (what I called the *exosomatic metabolic balance*) with the growth of the US trade deficit. Furthermore, I showed how this metric could be dissected into two components: differential domain growth and differential EMR. In this one metric, then, we have a linkage with all the major components of this paper (energy, human activity and money). Both of these dissected metrics could be further linked to pecuniary measures. In the case of DISS/HYP human activity, it could be linked to SG/BM differential per person value-added, while in the case of HYP/DISS differential EMR, it could be linked to the differential income growth rate between the top 10% and unskilled labour. In my view it is absolutely startling that such disparate data can be shown to be connected.

To return to my thesis question, I asked: what types of pecuniary signals (if any) are related to changes in energy throughput? In this thesis, I was able to show that GDP, the S&P500 price index, sectoral value-added, sectoral capitalization, wages, the trade deficit, and the distribution of wealth can all be linked to changes in energy consumption. As with human activity, it is difficult to make general conclusions about these findings, other than that they are complex.

In many ways, I think that the most important aspect of this paper is not the results of the various empirical case studies, but the methodological approach itself. I began by asking: how can a biophysical approach to economics be used to gain insight into the complex interrelationship between the biophysical sphere of economic activity and its monetary image? The resulting methodology that I used – a synthesis of the MuSIASEM approach and differential analysis, proved quite useful at offering insight into this question. While this co-evolutionary approach is admittedly incomplete, I think it is a fruitful area for future research.

Appendix

A. Data Sources for Joule Deflation

Sources:

Fossil Fuel Energy Throughput

1949-2010 from EIA Annual Energy Review Table 1.1.
Prior to 1949, consumption assumed to be equal to production.
Fossil fuel Production (1900-1949) from HSUS Table Db155-163.

Aggregate Price of Fossil Fuel Consumption (price of production and imports – raw resources only)

Production: 1949-2010 from EIA Annual Energy Review 2011, Table 3.2.
Net imports: 1949-2010 from EIA Annual Energy Review 2011, Table 3.9.

Prior to 1949, the value of total fossil fuel production is found by multiplying the unit price (below) by total production (above)

Natural Gas (unit price) 1930-1949: EIA Historical Natural Gas Annual 1930 Through 2000, Table 1.
Crude oil (unit price) 1920-1949: BP Statistical Review of Energy 2011.
Coal (anthracite unit price): 1920-28: HSUS Table Cc238
1929-31: HSUS Table Cc239
1932-49: HSUS Table Cc240

Total value of fossil fuels prior to 1949 is indexed to EIA 1949 data point.

B. Classification of Datastream series into MuSIASEM sectors:

Services & Government

1.	Computer Software &Services	(SFTCSUS)
2.	Consumer Services	(CNSMSUS)
3.	Financials	(FINANUS)
4.	Health Care	(HLTHCUS)
5.	Telecommunications	(TELCMUS)

Building & Manufacturing

1.	Chemicals	(CHMSLUS)
2.	Computer Hardware & Equip.	TECHDUS)
3.	Consumer Goods	(CNSMGUS)
4.	Forestry & Paper	(FSTPAUS)
5.	Industrials	(INDUSUS)

Energy & Mining

1.	Industrial Metals & Mining	(INDMTUS)
2.	Mining	(MNINGUS)
3.	Oil & Gas	(OILGSUS)
4.	Utilities	(UTILSUS)

Agriculture: no data available.

C1. Distributing Transportation Energy

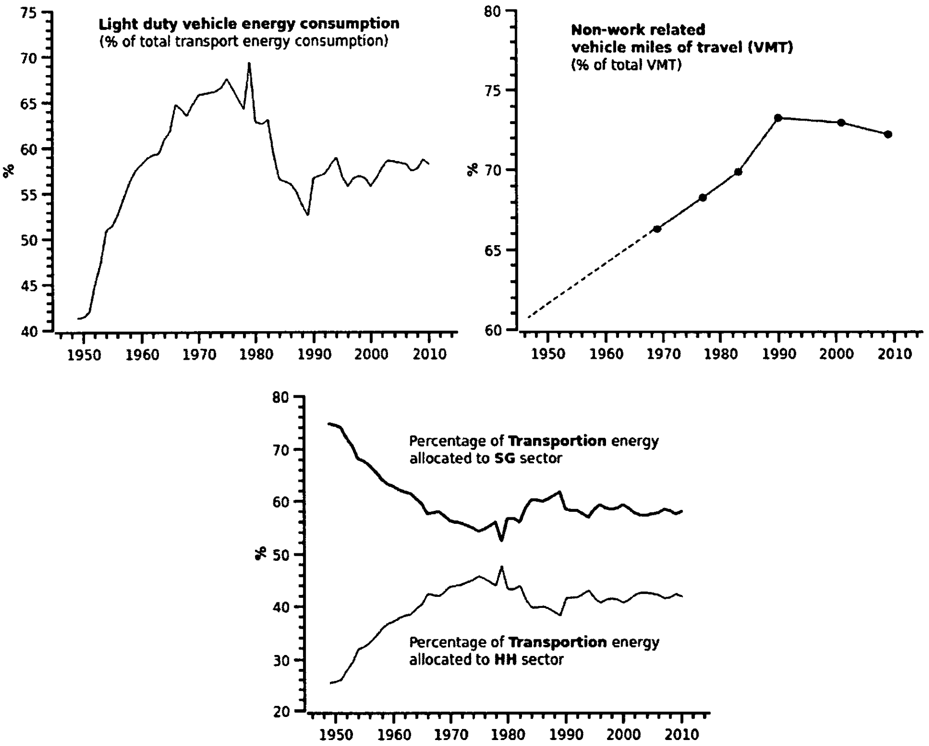

Figure 43: Distributing transport energy between HH & SG
Sources: Light-duty vehicle (LDV) energy consumption (1970-2010) is compiled from numerous editions of IEA Annual Energy Outlook (see Appendix C2 for detailed list & methodology). LDV data for 1949-69 is derived from passenger car & 4 tire vehicle fuel consumption data from the Department of Transportation, Table VM-201A (Note: the category 4 tire vehicles is introduced in 1966 at a non-zero value. Data prior to 1966 is estimated by exponential extrapolation).This data is then indexed to IEA light-duty vehicle data for 1970 . All LDV data is then divided by IEA data for total transport energy consumption (AER 2011, Table 2.1e). Data for non-work related vehicle mile trips (as a percentage of total VMT) comes from the 2009 National Household Travel Survey (Santos, McGuckin, Nakamoto, Gray, & Liss, 2009), Table 6 (Note: data between points is interpolated linearly & data prior to 1969 is extrapolated linearly from 1969-83 trend).

Portion of Transport Energy alloted to HH

Only transportation energy consumption associated with *non-work related, personal vehicle trips* is allocated to the household sector. This involves the following steps:

1. Calculate energy consumption of light-duty vehicles (LDV) as a percentage of total transport energy throughput (Figure 43, top left).
2. Calculate non-work related vehicle miles of travel (VMT) as a percentage of total VMT (Figure 43, top right).
3. Multiply these two quantities:

$$\% ET_{Transport \rightarrow HH} = \frac{ET_{LDV}}{ET_{Transport}} \cdot \frac{VMT_{\text{Non-work}}}{VMT_{Total}} \qquad (56)$$

Portion of Transport Energy alloted to SG

All transport energy not alloted to the HH sector is alloted to the SG sector

$$\% ET_{Transport \rightarrow SG} = 100 - \% ET_{Transport \rightarrow HH} \qquad (57)$$

C2: Sources for Light-duty Vehicle Energy Consumption

Note: For the years 1970, 1973-75, 1979, & 1981-88, no data was available for LDE energy consumption. Instead data for motor fuel was used; however, motor fuel encompasses both diesel and gasoline and is, therefore, not strictly equal to LDE energy consumption. Sources for the years 1980 and 1989 contain data for both LDV energy consumption and motor fuel (MF). For these years, the ratio LDV:MG was calculated. Data was then interpolated linearly between these two points, and extrapolated linearly into the past. These interpolations were then multiplied by yearly motor gas data to derive an estimate for LDV energy consumption.

Date	Source
1970	AEO 1986, B2
1971	no data
1972	no data
1973	AEO 1983, A4
1974	AEO 1985, A2
1975	AEO 1986, B2
1976	no data
1977	no data
1978	AEO 1979, 5.10
1979	AEO 1985, A2
1980	AEO 1982, A4.4
1981	AEO 1982, A.1.3
1982	AEO 1982, A.1.3
1983	AEO 1984, A9
1984	AEO 1985, A2
1985	AEO 1987, A2
1986	AEO 1989, A2
1987	AEO 1989, A2
1988	AEO 1990, A10
1989	AEO 1991, A14
1990	AEO 1994, A7
1991	no data
1992	AEO 1995, A7
1993	AEO 1996, A7
1994	AEO 1997, A7
1995	AEO 1998, A7
1996	AEO 1999, A7
1997	AEO 2000, A7
1998	AEO 2001,A7
1999	AEO 2001, A7
2000	AEO 2003, A7
2001	AEO 2003, A7
2002	AEO 2005, A7
2003	AEO 2006, A7
2004	AEO 2007, A7
2005	AEO 2007, A7
2006	AEO 2007, D3
2007	AEO 2010, A7
2008	AEO 2010, A7
2009	AEO 2012, A7
2010	AEO 2012, A7

(AEO = IEA Annual Energy Outlook)

D. Energy Throughput Data

	EJ	EJ	EJ
	PS	**SG**	**HH**
1949	15.53	10.17	8.04
1950	17.14	10.79	8.60
1951	18.65	11.16	9.20
1952	18.26	10.93	9.57
1953	19.21	10.77	9.76
1954	18.10	10.34	10.21
1955	20.56	10.93	10.93
1956	21.32	11.20	11.53
1957	21.33	11.01	11.75
1958	20.38	11.12	12.43
1959	21.45	11.53	12.88
1960	21.99	11.88	13.70
1961	22.11	12.05	14.10
1962	22.99	12.63	14.84
1963	24.00	13.11	15.27
1964	25.44	13.41	15.82
1965	26.48	13.99	16.52
1966	27.88	14.63	17.65
1967	28.08	15.66	18.41
1968	29.42	16.84	19.59
1969	30.71	17.60	20.92
1970	31.26	18.35	21.96
1971	31.21	19.08	22.80
1972	32.63	20.10	23.95
1973	34.42	20.96	24.46
1974	33.54	20.43	24.06
1975	31.03	20.45	24.45
1976	33.12	21.66	25.37
1977	34.04	22.35	25.86
1978	34.49	23.26	26.60
1979	35.79	22.52	27.00
1980	33.80	22.92	25.64
1981	32.40	22.86	25.03
1982	29.13	22.75	25.23
1983	28.94	23.40	24.65
1984	31.20	24.55	25.10
1985	30.40	24.82	25.38
1986	29.83	25.42	25.61
1987	31.00	26.30	26.12
1988	32.37	27.68	27.21
1989	33.04	28.56	27.84
1990	33.56	27.89	27.69
1991	33.13	27.85	28.10
1992	34.36	27.93	28.21
1993	34.42	28.40	29.42
1994	35.37	28.92	29.72
1995	35.84	30.21	29.99
1996	36.83	31.29	31.08
1997	37.14	31.84	30.82
1998	36.76	32.42	31.07
1999	36.68	33.33	31.95

2000	36.57	34.74	32.94
2001	34.52	34.33	32.62
2002	34.47	34.69	33.90
2003	34.32	34.62	34.43
2004	35.35	35.54	34.78
2005	34.23	36.09	35.48
2006	34.17	36.27	34.67
2007	34.20	37.22	35.52
2008	33.01	36.61	35.11
2009	30.08	35.28	34.31
2010	31.80	36.04	35.56

E: EMR Data

	Using BLS HA			**Using Bea HA**		
	MJ/hr	MJ/hr	MJ/hr	MJ/hr	MJ/hr	MJ/hr
	PS	**SG**	**HH**	**PS**	**SG**	**HH**
1949	295.85	176.88	6.70	287.94	157.54	6.75
1950	320.62	183.57	7.05	306.29	163.33	7.11
1951	336.71	182.97	7.46	321.23	155.40	7.54
1952	330.18	175.74	7.64	313.99	147.84	7.73
1953	339.99	171.04	7.66	324.93	144.29	7.74
1954	337.28	164.72	7.84	322.77	140.42	7.92
1955	369.40	170.03	8.24	361.69	145.65	8.31
1956	378.06	168.79	8.54	373.02	145.14	8.61
1957	385.40	163.76	8.53	377.85	140.45	8.60
1958	394.54	167.10	8.83	387.45	142.58	8.90
1959	402.10	168.72	9.00	396.49	144.81	9.08
1960	414.06	170.60	9.42	408.02	145.47	9.50
1961	430.54	172.46	9.51	419.62	146.31	9.60
1962	442.87	176.91	9.86	427.71	150.12	9.96
1963	464.44	180.26	9.99	447.55	153.46	10.09
1964	489.13	179.50	10.21	472.14	152.87	10.31
1965	490.13	180.62	10.56	474.26	154.63	10.66
1966	498.42	181.79	11.19	481.07	154.01	11.30
1967	511.97	189.27	11.56	482.75	158.79	11.70
1968	533.84	197.74	12.18	498.69	165.94	12.34
1969	552.78	199.47	12.90	511.55	168.35	13.07
1970	562.56	205.15	13.37	539.73	174.10	13.52
1971	579.98	210.56	13.67	555.22	179.31	13.82
1972	611.27	214.87	14.19	563.84	184.86	14.36
1973	624.53	216.41	14.38	564.51	185.78	14.57
1974	591.06	206.68	14.03	548.93	176.97	14.21
1975	601.21	205.87	14.07	550.82	175.53	14.25
1976	616.59	212.65	14.49	568.22	181.38	14.67
1977	609.17	212.77	14.65	563.77	180.98	14.84
1978	586.95	212.51	14.96	541.76	179.60	15.17
1979	594.82	199.75	15.04	544.78	168.19	15.26
1980	580.00	200.46	14.09	527.78	168.69	14.31
1981	556.89	197.84	13.62	507.67	165.68	13.83
1982	540.10	197.69	13.55	488.26	164.89	13.77
1983	532.02	200.19	13.12	490.81	166.65	13.32
1984	539.24	201.38	13.30	503.88	167.28	13.50
1985	528.69	196.92	13.34	491.81	163.72	13.56
1986	524.08	196.29	13.35	485.90	163.35	13.57
1987	536.60	197.25	13.51	501.40	163.01	13.74
1988	552.30	200.99	13.98	512.08	166.29	14.22
1989	560.33	202.41	14.18	522.10	165.99	14.44
1990	580.14	193.46	13.94	535.01	159.26	14.20
1991	595.39	193.72	13.93	548.29	159.30	14.18
1992	628.47	191.74	13.77	581.70	158.95	14.01
1993	623.94	190.50	14.19	576.48	157.95	14.43
1994	613.71	186.60	14.19	579.51	156.78	14.42
1995	617.55	189.98	14.17	575.62	159.57	14.40
1996	629.23	192.28	14.52	588.70	161.74	14.76

1997	620.59	189.34	14.26	584.75	160.44	14.48
1998	609.20	187.63	14.22	570.05	159.40	14.45
1999	607.63	188.00	14.47	566.38	160.18	14.70
2000	621.40	191.10	14.75	560.92	162.78	15.01
2001	619.39	188.56	14.43	543.04	159.42	14.69
2002	650.31	190.84	14.82	569.09	161.04	15.09
2003	670.02	190.91	14.89	581.45	160.00	15.17
2004	686.36	193.49	14.90	595.13	162.55	15.18
2005	655.90	192.37	15.08	571.93	161.90	15.36
2006	639.48	189.25	14.62	561.95	159.80	14.88
2007	648.92	191.78	14.82	569.61	161.71	15.09
2008	653.99	189.08	14.49	569.25	159.15	14.75
2009	659.48	181.80	14.00	586.71	158.66	14.19
2010	703.99	180.60	14.41	640.09	162.46	14.57

Glossary

Allopoietic	A system that creates something other than itself. Example: a car factory makes cars, not more car factories.
Autopoietic	A self-creating system. Example: an ecosystem constantly reproduces itself.
Biophysical Sphere	A metaphysical concept containing all things biological and physical. When applied to the *human-system*, the *biophysical* sphere refers to all matter and energy controlled by humans (including human activity itself). See also *metabolic pattern*.
Black Box	A system that is opaque to the observer – it cannot be opened to "reveal" its contents. Deductions about the workings of the system must be made from external observations only.
Business	A term used by Thorstein Veblen, meaning the legal control over *industry*. For Veblen, business was characterized by the pursuit of profit while industry was characterized by the pursuit of workmanship.
Capitalization	Market value of a firm as measured by multiplying the current price per share by the number of shares outstanding.
Capital	A duality in both Neoclassical and Marxist economic theory referring both to financial capital (capitalization) and a physical capital stock (machines, infrastructure, etc.). In this paper I negate this duality and use the word "capital" only in the financial sense.
Cardinal Utility	Cardinal refers to the property of a number when used as a *quantity*. Cardinal numbers are often called the "counting numbers". Cardinal utility refers to the idea that utility can be transformed into a quantity.
Causation	A fundamental axiom of scientific reductionism is that phenomena can be separated into *cause* and *effect,* independent and dependent variables. The classic statement of cause and effect remains Newton's explanation of gravitation, in which a gravitational force *causes* acceleration. However, in Einstein's general relativity, acceleration is *caused* by the curvature of space-time near a massive object – there is no gravitational force. In both cases, empirical correlation (between mass and acceleration) remains the same; however, what constitutes *cause* and *effect* depends on the scientific *model* used by the analyst. Thus, moving beyond correlation involves the adoption of an explanatory framework. As a system becomes more complex, the adoption of such a *model* becomes more problematic (see *model*).
Closed System	In thermodynamics, a closed system exchanges energy, but not matter, with its surroundings.
Company	A unit used by the BLS and BEA for measuring monetary data such as profit. It refers to a distinct unit of legal ownership.
Consumption	The *dissipation* of a finished product. See *production* for more detail.
Differential	A quantitative comparison in unitless ratio form.
Disequilibrium (thermodynamics)	The state occupied by a system *not* in equilibrium. The laws of thermodynamic stipulate that an *isolated system* will spontaneously evolve towards of state of equilibrium. Therefore, the maintenance of disequilibrium requires a steady inflow of matter and/or

	energy into a system (open and closed systems). *Dissipative structures* continually exist in a state of disequilibrium.
Dissipate	To transform matter and energy from a highly ordered (low entropy) form to a disordered (high entropy) form.
Dissipative Cycle	The portion of the human-system that consumes (in biophysical terms) more than it produces. Defined by Giampietro, Mayumi, and Sorman (2011, 2012) as containing both the services & government sector and the household sector.
Dissipative Structure	A term proposed by Ilya Prigogine (1984) to refer to a structure that remains in a state of thermodynamic *disequilibrium*. Dissipative structures require a constant throughput of energy to maintain this state. Examples: boiling water, an living organism, an ecosystem.
Domain	A specific type of human activity, classified according to the role of this activity in the metabolic process. A domain is similar to a sector, but does not imply a division of labour. For instance, a farmer might work in multiple domains in a given day – sowing seed would be an agricultural domain while building a barn would be a building & manufacturing domain.
Economy	A word typically referring to the production, distribution, and consumption of goods and services. The *economy* is usually seen as distinct from society, politics, culture, and/or power structures. I am not sure that calling a subset of human activity "the economy" is meaningful. How are boundaries to be drawn? I prefer to think holistically in terms of the *human-system* as a whole.
Effect	The outcome of a *cause* – the dependent variable in a scientific *model.* (See *cause*)
Efficiency	Refers to a unitless output/input ratio for a given process. In thermodynamics, efficiency is defined as the ratio of energy output (work) of a system to the energy input. The units of output and input must both be the same (units of energy). The word *efficiency* is also ubiquitous in economic literature, however I use the word solely in a thermodynamic sense.
Embodied Energy	A metaphysical concept referring to the cumulative energy required to produce a given item. According to Giampietro, Mayumi, and Sorman (2011, 2012) embodied energy only has meaning once the boundaries of the system are defined.
Emergy	Howard Odum's word meaning "energy memory". A synonym for embodied energy.
End-Use Energy	The physical *work* delivered at the end of an *energy* conversion process. Giampietro, Mayumi, and Sorman (2012) argue that end-use energy is unquantifiable due to the enormous diversity of end-use energy conversion processes.
Endosomatic	Inside the human body.
Energy	A metaphysical concept often defined as the ability to do *work* (physical). The word *energy* only has meaning when referring to a specific energy transformation process. For instance, the energy in a barrel of oil has no meaning without reference to how the oil will be used. If the oil is to be burned, chemical bond energy is applicable. If the barrel of oil is to be used as a projectile, kinetic energy is applicable. If it is to be placed on top of a mountain, gravitational potential energy is applicable.
Energy & Mining Gross Power	Defined as the total domestic energy production of society per unit of human activity in the energy & mining sector.

Energy Carrier	A term used by Giampietro, Mayumi, and Sorman to refer to an *energy* form midway between primary energy and end-use work. *Energy* carriers include electricity and hydrocarbon fuels.
Energy Conversion	A transformation between different semantic categories of energy. For instance, an automobile first converts chemical potential energy into thermal energy and then into kinetic energy. All energy conversions incur losses, as dictated by the second law of thermodynamics.
Energy Return on (Energy) Investment	A ratio of gross energy output to the energy input required to harvest a resource. Like embodied energy, energy return on investment is only meaningful in reference to specific choices of system boundaries.
Entropy	A metaphysical concept used in thermodynamics. In an *isolated* system, *entropy* is theorized to be maximized when the system is in equilibrium. In statistical mechanics, *entropy* is theorized to represent the number of specific ways in which a system may be arranged, often taken to be a measure of disorder. Note: entropy *cannot* be measured
Environmental Load Displacement	Hornborg's (2011) term for the relegation of an ecological burden to a different geographic area by means of trade. For Hornborg, European colonialism was a means for environmental load displacement.
Equilibrium (Economics)	In neoclassical economics, equilibrium refers to the point at which quantity demanded and quantity supplied are equal. A requirement for equilibrium is that the economy be perfectly competitive. Nitzan and Bichler have argued that there are no objective criteria for determining when equilibrium occurs.
Equilibrium (Thermodynamics)	A system in a state of balance. Specific to thermodynamics, this refers to a state of "thermal equilibrium, mechanical equilibrium, radiative equilibrium, and chemical equilibrium" meaning there are no "net flows of matter or of energy, no phase changes, and no unbalanced potentials (or driving forces), within the system. A system that is in thermodynamic equilibrium experiences no changes when it is isolated from its surroundings" ("Thermodynamic equilibrium," 2013).
Establishment	An economic unit (used by the BLS and BEA) such as a factory, mine, store, or office that produces goods or services. It generally is at a single location and is engaged predominantly in one type of economic activity.
Exergy	The available energy of a system in reference to a specific process and specific background environment. For instance, the chemical exergy of gasoline depends on the temperature at which the gasoline is used. Giampietro, Mayumi, and Sorman (2012) have critiqued the notion of exergy because "when dealing with large-scale processes, e.g. time durations of several years and large space domains, it becomes impossible to define a meaningful reference environment" (ibid, p. 314).
Exosomatic	External to the human body.
Exosomatic Metabolic Balance	Defined as the ratio of energy throughput in the dissipative sector to the energy throughput in the hypercycle.
Exosomatic Metabolic Rate	Defined as the energy throughput per hour of human activity in a given sector.
Feedback	A process in which information about the past or the present influences the same

	phenomenon in the present or future.
Finance	To render an activity symbolically possible under the terms of a given monetary accounting scheme. For instance, being paid $20 for an hour of work might finance a worker's symbolic ability to consume gasoline. So long as the "rules" of the monetary accounting scheme are followed (ie: the worker does not simply take the gasoline for free), symbolic consumption ability should be related to actual consumption.
Grammar	Proposed by Giampietro, Mayumi, and Sorman (2011, 2012) a *grammar* is an alternative to a scientific *model*. A grammar consists of a methodology based on an *open* pre-analytic vision. That is, the narrative adopted by the analyst is made as explicit as possible and remains open for reinterpretation based on new information. For instance, in cases dealing *truncation,* the system boundary adopted by the analyst is necessarily arbitrary – there is no "correct" choice of boundary. A *grammar* is capable of dealing with issue. Rather than outlining the exact pre-analytic decisions that should be made, a *grammar* is a guide for making, expressing, and refining these decisions.
Hedonic Regression **(Hedonic Quality Adjustment)**	A method for quantifying the monetary value of the individual qualitative components of a given commodity. Hedonic regressions decompose the item being researched into its constituent characteristics, and obtain estimates of the contributory value of each characteristic. Like all measurement, the isolation of a specific qualitative component requires the adoption, by the analyst, of a specific narrative. Despite the "rigorous" nature of hedonic regression, the choice of narrative remains a subjective pre-analytic decision made by the analyst.
Human Activity	A quantification of the human-system (or any subset of it) in terms of either number of people or person hours.
Human-System	A metaphysical concept referring to the sum total of all activity conducted by humans (both monetized and unmonetized), including all exosomatic matter and energy controlled by humans. The term *human-system* is influenced by Wallerstein's (1976) notion of the *world-system.* I use *human-system* to differentiate my more biophysical treatment of humanity from the world-system approach. The use of the term *world-system* also implies analysis of core-periphery dynamics based on a global division of labour. The analysis of such dynamics exceeds the scope of this paper, thus I prefer to use a different term. Because of the national basis of data, in this paper I have treated the United States as a human-system; however, I should be clear that I actually see it as a subset of a larger whole. Analysis of this whole exceeds the scope of this paper.
Hypercycle	The portion of the human-system that produces more (in biophysical terms) than it consumes. Defined by Giampietro, Mayumi, and Sorman (2011, 2012) as containing agriculture, energy & mining, and building & manufacturing.
Impredicative	A self-referential process. In linguistics, a definition is said to be *impredicative* when it contains the word being defined. Impredicativity means that *cause* cannot be separated from *effect*. Giampietro, Mayumi, and Sorman (2011, 2012) argue that complex systems are impredicative.
Industry	A term used by Thorstein Veblen (1923), meaning the holistic process of production. *Industry* constitutes the cumulative state of knowledge, skills, and technology inherited from previous generations of humanity.
Inflation	An increase in prices. The ability to objectivity quantify inflation depends on an

	uncontested quantification of changes in output and an uncontested quantification of the qualitative changes in a given commodity over time. Following Nitzan (1992), I contend that such uncontested quantifications do not exist.
Isolated System	In thermodynamics, a system that exchanges *neither* matter *nor* energy with its surroundings.
Metabolic Pattern (of Society)	A term used by Giampietro, Mayumi and Sorman (2011). I use it to mean a particular quantification of the *biophysical sphere* at a particular point in time.
Mining Gross Power	Defined as total domestic fossil fuel production per unit (hrs) of mining sector human activity.
Model (scientific)	A scientific *model* is a formalized representation of the world based on a set of fixed axioms. A model relies on a *closed* pre-analytic vision, while a grammar relies on an *open* pre-analytic vision. Models can vary from simplistic to complex. Systems models allow for complicated, self-referential relationships between variables. While systems models are capable of emergent behavior, the range of emergent behavior is limited by the pre-analytic decisions coded into the model. *A model cannot evolve* – its axioms do not changed during model operation. Giampietro, Mayumi, and Sorman propose a *grammar* as an alternative to a *model.*
Monetary Image	Refers to the metaphysical realm of all objects, institutions, or ideas that have a monetary *price*. The monetary image refers not to the objects, institutions, or ideas themselves, but to their representation as an abstract monetary quantification. My investigation of the monetary image involves comparing relative prices. This may be done at any level of aggregation; however, at each higher level of aggregation, essential information from lower hierarchical levels is lost. At the same time, aggregation may reveal emergent properties not visible at lower hierarchical levels. *Monetary Image* is used synonymously with *pecuniary sphere*, and the *price structure of society*.
Monetary Value	A monetary quantification at the time and place of a market exchange. Used synonymously with *price* and *pecuniary value*.
Money	A unit for quantifying a market exchange. A unit of account used by humans for making the biophysical world universally commensurable. In the work of Nitzan and Bichler, capital is treated as an abstract unit of social power. Since money is the unit for denominating capital, it follows that money is a unit of power.
Narrative	A story or purpose guiding the pre-analytic decisions made by an analyst. A *narrative* determines what *unit* is relevant for quantitative comparison.
Nominal	A price that is not adjusted for inflation. I treat nominal prices as part of the pecuniary sphere. Changes in nominal prices give no indication of changes in the biophysical sphere.
Open System	In thermodynamics, a system that exchanges *both* matter and energy with its surroundings.
Ordinal Utility	Ordinal numbers refer to a ranking rather than a quantity. Ordinal utility assumes that consumer preferences can be ranked, but not compared in absolute terms.
Pecuniary Sphere	Used synonymously with *monetary image* and the *price structure of society*. See

	monetary image.
Pecuniary Value	A monetary quantification at the time and place of a market exchange. Used synonymously with *monetary value* and *price.*
Power (MuSIASEM)	Energy output per unit of *human activity* (MJ per person hour). This measure is actually a biophysical measure of labour productivity, but carries similar units to *power (physics).* See *mining gross power* and *energy and mining gross power.*
Power (social)	The ability to influence the behavior of other people.
Power (physical)	Energy output per unit of time. Typically measured in Watts (W), defined as a Joule per second.
Power Capacity	A term used by Giampietro, Mayumi and Sorman (2011) meaning the ability to do physical *work.* Power capacity can be treated as a synonym for *biophysical productivity.* Machines increase the *power capacity* of human beings.
Price	A monetary quantification at the time and place of a market exchange. "Price" is used synonymously with "relative price", thus a monetary quantification only has meaning in relation to other prices.
Price Structure of Society	Used synonymously with *monetary image* and the *pecuniary sphere.* See *monetary image.*
Primary Energy	An energy resource in its raw form that remains untransformed by humans.
Production	I define *production* as the transformation of raw materials into finished products. Measuring production (and distinguishing it from *consumption*) is difficult, and depends on the narrative and the hierarchical scale adopted by the analyst. For instance, at the level of the entire human-system, I would argue that production and consumption are equivalent – all that is produced is consumed. At the nation-state state level, production and consumption may not balance if there is net biophysical trade. Using Giampietro, Mayumi, and Sorman's framework of the hypercycle vs. dissipative cycle, we simply *define* that the former is engaged in production, while the latter is engaged in *consumption* (*dissipation*).
Production Function	A mathematical function relating a given set of inputs to the output of a process. Traditional inputs are capital and labour, but more recently, energy/useful work have been added. At the national level, the Cobb-Douglas production function is typically used. Ayres and Warr (2009) use a LINEX (linear-exponential) function. The mathematical construction of a production function implies that inputs are substitutable.
Productivity (biophysical)	A measure of biophysical output per unit of biophysical input. Biophysical measures of productivity used in this paper include: *useful work productivity*, *energy & mining gross power*, primary & secondary sector EMR
Real	Usually used to mean "having adjusted for inflation". Real measures, especially real GDP, are usually interpreted as a *quantity* measure of economic output. The validity of such a measure, however, depends on the objective ability to separate changes in the quantity and quality of output from pure price changes. I follow Nitzan and Bichler (2009) in rejecting such an objective ability.
Sabotage	A term used by Thorstein Veblen to mean the purposeful limitation of *industry* by *business.*

Sector	A portion of the human system characterized by similar types of human activity. A sector, unlike a domain, implies a division of labour.
Semiotic	Having to do with a sign or symbol.
Social Metabolism	The study of the flow of matter and energy through the human-system and its relationship to societal structure. In many ways, the study of social metabolism can be seen as an attempt to incorporate industrial ecology into the social sciences.
Surplus	The word *surplus* is central to Marxism, world-systems analysis, and many biophysical theories. In each instance, it has a different meaning. Marxists use the word in reference to the surplus-*value* extracted from workers through exploitation. World-system theorists generally drop the word *value* and refer only to the transfer of *surplus* (usually between periphery and core). In world-systems literature, it is often unclear how *surplus* should be measured (Clelland, 2012). I use the word *surplus* solely in a biophysical sense to mean the difference between production and consumption. For instance, the hypercycle produces a biophysical surplus that is then used by the dissipative sector. As with all biophysical measures, aggregation is a problem. For instance, a construction company produces more houses than required to house its employees. Here, the unit of surplus is "houses". However, it is far from clear how a surplus of "houses" should be added to a surplus of "automobiles". I have opted to circumnavigate this problem by using energy throughput as a proxy for both production and consumption.
Truncation Problem	Refers to a fundamental problem with the notion of a substance (land, labour, energy, etc.) "embodied" in something else. For instance, the notion of embodied energy has no meaning without a stringent definition of spacial and temporal boundaries. The definition of such a boundary is always arbitrary and depends on the narrative adopted by the analyst. Thus, the truncation problem cannot be "solved"; rather, it can be responded to by making assumptions about boundaries as clear as possible. Giampietro et al. (2012) propose the use of a *grammar* as way of clarifying pre-analytic decisions.
Unequal Exchange	An exchange of non-equivalent goods or services. The measurement of this non-equivalence depends on the narrative and unit adopted by the analyst. Market exchanges, *by definition*, are *always* equivalent in monetary terms. However, biophysical aspects of the exchange will likely be different. For instance, exchanging $100 worth of crude oil for $100 worth of electronics will clearly be asymmetrical in terms of the chemical exergy of each product. This measurement of asymmetry may differ from one measured through embodied pollution. My conception of unequal exchange is very similar to Hornborg's (2011); however, I contest his assertion that it may be "objectively measured", because the decision of relevant units depends on the subjective decisions made by the analyst. Also, "embodied" measurements are subject to the *truncation problem*.
Unit	A standard of measurement used for quantitative comparison. Units are fundamental to quantitative science. Units allow the *quantification* of the *qualities* defined by a given narrative. The exactitude with which a unit can be defined sets the basis for the exactitude of quantitative comparison. If our narrative is length, the appropriate unit is the metre, presently defined as the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second ("Resolution 1 of the 17th CGPM," 1983). In economic literature, the notion of units is often ignored. However, the inability to exactly define (and measure) the fundamental units of economic theory is a problem raised by both Nitzan and Bichler (2009) and Mayumi, Giampietro, and Sorman (2011, 2012). See *universal quantifier*.

Universal Quantifier **or (Universal Unit)**	While a *unit* allows quantitative comparison within the confines of a specific narrative, I define a *universal quantifier* (or *universal unit*) as a unit capable of meaningful comparison *across all narratives*. For instance, it is meaningful to compare two people in units of time if we are discussing their life expectancy. Units of time are not useful if we are discussing their height. However, a universal quantifier would be capable of accurately capturing and comparing all aspects of two people in a single unit. The idea of a universal quantifier is grossly reductionist, and I argue, nonsensical. However, it is seductive for rhetorical purposes *because* it cannot actually be defined. For instance, Marx's notion of socially necessary abstract labour seeks to universally quantify different types of people's contribution to the production of value. What narrative should we use for this comparison? Should we compare people in terms of educational attainment? Muscle power? Intelligence? Because no narrative is given, abstract labour becomes a (non-existent) universal quantifier. Similarly, utility seeks to universally quantify human desires. Should this be measured in terms of the endorphins released after a purchase? The results of an MRI scan? Over what time frame after a purchase? Seconds, hours, years? If it is a ranking of preferences, what set of goods should be ranked? What about preferences for unmonetized goods? Again, in the absence of a specific narrative, utility becomes a (non-existent) universal quantifier.
Upward Domain Movement	The movement of human activity from a lower to a higher domain. I argue that upward domain movement is one of the defining features of the 20th century and that it is made possible by increases in the physical work done by fossil fuel powered machines.
Useful Work	Ayres & Warr's (2009) term for *end-use energy*. It refers to the physical work done by the energy conversion process controlled by humans. Useful work is defined simply as the exergy input multiplied by the thermodynamic efficiency of the process. Their calculation of useful work relies on simplifications of the actual application of end-use work. See *work (physics)* for more detail.
Utility	A term used to denote the satisfaction of a human desire. In neoclassical economics, the purchase of commodity gives utility to the consumer.
Value	A commodity's market *price*.
Value (Marx)	The embodied labour in a commodity. For Marx, the *value* of a commodity determined its average long run price. Deviations from this average were caused by supply and demand.
Work (physics)	In mechanics, work is defined as the application of a force over a given distance. In thermodynamics, work is defined as the heat added to a system minus the change in total internal energy of a system. The physical work done by a process can by defined as the energy input multiplied by the *efficiency* of the process.
Work (human)	Unlike its use in physics, the word *work* has numerous definitions when applied to human activity. For instance, if an activity is undesirable, it is considered work (as opposed to leisure time, which is desirable). Alternatively, *work* often refers to the activity for which a person receives monetary compensation. I opt to call this *paid time* or *monetized* activity. In this paper, I have attempted to use this word solely in its physical sense (see *work (physics)*).

World-System	A term coined by Immanuel Wallerstein (1976) as a means of rethinking the appropriate unit of analysis in the social science. Prior to Wallerstein, the "whole", in the social sciences was taken as the nation-state. However, Wallerstein's approach placed the nation-state within the wider context of a world-system – a socioeconomic system that encompasses part or all of the globe.

Bibliography

Albert, M. (2004). *Parecon: Life After Capitalism*. Verso.

Alvaredo, F., Atkinson, T., Piketty, T., & Saez, E. (2013). The World Top Incomes Database. Retrieved from http://topincomes.parisschoolofeconomics.eu/#

Amin, S. (1977). Imperialism and unequal exchange. *New York: Monthly Review*.

Ayres, R., & Warr, B. (2005). Accounting for growth: the role of physical work. *Structural Change and Economic Dynamics*, *16*(2), 181–209.

Ayres, R., & Warr, B. (2009). *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Northampton, MA: Edward Elgar Pub.

Baran, P. A., & Sweezy, P. M. (1966). *Monopoly Capital: an Essay on the American Economist and Social Order*. New York: Monthly Review Press.

Bentham, J. (1891). *A fragment on government*. Clarendon Press. Reprinted 2001 by The Lawbook Exchange, Ltd.

Berners-Lee, M. (2010). *How bad are bananas?: the carbon footprint of everything*. Toronto: Greystone Books.

BLS Handbook of Methods. (2009). Retrieved from http://www.bls.gov/opub/hom/

Borzoni, M. (2011a). *Integrated assessment of renewable energies for decision making: A two-case analysis* (PhD Dissertation). Scuola Superiore Sant'Anna. Retrieved from http://www.phdmanagement.sssup.it/documenti/awarded/borzoni_thesis.pdf

Borzoni, M. (2011b). Multi-scale integrated assessment of soybean biodiesel in Brazil. *Ecological Economics*, *70*(11), 2028–2038.

British Petroleum. (2012). BP statistical review of world energy. *British Petroleum, London*.

Bunker, S. (2007). *Natural values and the physical inevitability of uneven development under capitalism*. Altamira Press, USA.

Bunker, S. G. (1985). *Underdeveloping the Amazon: Extraction, unequal exchange, and the failure of the modern state*. University of Chicago Press.

Carter, S. B., Gartner, S. S., Haines, M. R., Olmstead, A. L., Sutch, R., & Wright, G. (2006). *Historical Statistics of the United States: Millennial Edition*. Cambridge: Cambridge University Press.

Chapman, P. F. (1974). Energy costs: a review of methods. *Energy Policy*, *2*(2), 91–103.

Chase-Dunn, C. (1998). *Global formation: Structures of the world-economy*. Oxford: Rowman & Littlefield Pub Inc.

Clelland, D. (2012). Surplus drain and dark value in the modern world-system. In S. J. Babones & C. K. Chase-Dunn (Eds.), *Routledge Handbook of World-Systems Analysis* (pp. 197–2005). New York: Routledge.

Cleveland, C., Costanza, R., Hall, C., & Kaufmann, R. (1984). Energy and the US economy: a biophysical perspective. *Science*, *225*(4665), 890–897.

Cobb, C. W., & Douglas, P. H. (1928). A theory of production. *The American Economic Review*, *18*(1), 139–165.

Cochrane, D. T. (2010). Death Grip: Scapegoating the Subprime Loser. *SCAPEGOAT Architecture/ Landscape/Political Economy*, (00), 6–8.

Cockshot, P., Shimshon, B., & Nitzan, J. (2010). Testing the Labour Theory of Value: An Exchange. *Nitzan & Bichler Archives*. Retrieved May 19, 2013, from http://bnarchives.yorku.ca/308/02/20101200_cockshott_nitzan_bichler_testing_the_ltv_exchange_web.htm

Concepts and Methods of the U.S. National Income and Product Accounts. (2012, November). Bureau of Economic Analysis. Retrieved from http://www.bea.gov/national/pdf/methodology/ALLchapters.pdf

Costanza, R. (1980). Embodied energy and economic valuation. *Science, 210*(4475), 1219–1224.

D'Alisa, G., Cattaneo, C., & Gamboa, G. (2009). Time allocation in Catalonia: Policy implications for unpaid work. In *Comunicación. www. upo. es/congresos/export/sites/congresos/.../Giacomo_Dxalisa. pdf. Accessed March* (Vol. 31, p. 2010). Retrieved from http://www.upo.es/congresos/export/sites/congresos/economiafeminista/documentos/area3/Giacomo_Dxalisa.pdf

Daly, H. E. (1997). Georgescu-Roegen versus Solow/Stiglitz. *Ecological Economics, 22*(3), 261–266.

Diaz Maurin, F. (2012). Assessing the viability of power-supply systems: a tentative protocol. Retrieved from http://www.recercat.net/handle/2072/200847

Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings, 42*(8), 1238–1247.

Drimmer. (2007). An Introduction to Saussure. *What is a Sign?* Retrieved May 29, 2013, from http://www.learn.columbia.edu/saussure/

Eddington, A. S. (2005). *The Nature of the Physical World.* Kessinger Publishing.

Emmanuel, A., & Bettelheim, C. (1972). *Unequal exchange: A study of the imperialism of trade.* Monthly Review Press New York.

FedDev Ontario. (2012, April 10). Harper Government Invests in Universities to Create Value-added Jobs through Innovation. Retrieved April 7, 2013, from http://www.feddevontario.gc.ca/eic/site/723.nsf/eng/00783.html

Fiorito, G. (2013). Can we use the energy intensity indicator to study "decoupling" in modern economies? *Journal of Cleaner Production, 47*, 465–473. doi:10.1016/j.jclepro.2012.12.031

Frank, A. G., & Press, N. E. F. (1966). *The development of underdevelopment.* New England Free Press.

Frequently Asked Questions about Hedonic Quality Adjustment in the CPI. (2010). *Bureau of Labor Statistics.* Retrieved June 24, 2013, from http://www.bls.gov/cpi/cpihqaqanda.htm

Gardner, H. (1985). *Frames Of Mind: The Theory of Multiple Intelligences.* Basic Books.

Garrett, T. J. (2011a). How persistent is civilization growth? *arXiv:1101.5635.* Retrieved from http://arxiv.org/abs/1101.5635

Garrett, T. J. (2011b). Are there basic physical constraints on future anthropogenic emissions of carbon dioxide? *Climatic Change, 104*(3), 437–455.

Georgescu-Roegen, N. (1971). *The entropy law and the economic process.* Cambridge, Mass.: Harvard University Press.

Georgescu-Roegen, Nicholas. (1979). Comments on the papers by Daly and Stiglitz. *Scarcity and Growth Reconsidered. Johns Hopkins University Press, Baltimore*, 95–105.

Giampietro, M., Allen, T. F. H., & Mayumi, K. (2006). The epistemological predicament associated with purposive quantitative analysis. *Ecological Complexity, 3*(4), 307–327.

Giampietro, M., & Mayumi, K. (2000). Multiple-scale integrated assessments of societal metabolism: integrating biophysical and economic representations across scales. *Population & Environment, 22*(2), 155–210.

Giampietro, M., & Mayumi, K. (2009). *The biofuel delusion: the fallacy of large-scale agro-biofuel production.* Earthscan/James & James.

Giampietro, M., Mayumi, K., & Sorman, A. (2011). *The Metabolic Pattern of Societies: Where Economists Fall Short.* New York: Routledge.

Giampietro, M., Mayumi, K., & Sorman, A. (2012). *Energy Analysis for a Sustainable Future: Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism.* New York: Routledge.

Giampietro, M., Sorman, A., & Gamboa, G. (2010). Using the MuSIASEM Approach to Study Metabolic Patterns of Modern Societies. *Energy Options Impact on Regional Security*, 37–68.

Gierlinger, S., & Krausmann, F. (2012). The Physical Economy of the United States of America. *Journal of Industrial Ecology*, *16*(3), 365–377.

Giljum, S., & Eisenmenger, N. (2004). North-South trade and the distribution of environmental goods and burdens: a biophysical perspective. *The Journal of Environment & Development*, *13*(1), 73–100.

Giljum, S., & Hubacek, K. (2001). International trade, material flows and land use: developing a physical trade balance for the European Union. *Interim Report. IIASA, Laxenburg*.

Graeber, D. (2010). *Debt: The First 5,000 Years*. New York: Melville House Pub.

Guilford, M. C., Hall, C., O'Connor, P., & Cleveland, C. . (2011). A new long term assessment of energy return on investment (EROI) for US oil and gas discovery and production. *Sustainability*, *3*(10), 1866–1887.

Hall, C., Powers, R., & Schoenberg, W. (2008). Peak oil, EROI, investments and the economy in an uncertain future. *Biofuels, Solar and Wind as Renewable Energy Systems*, 109–132.

Hall, R. L., & Hitch, C. J. (1939). Price theory and business behaviour. *Oxford economic papers*, (2), 12–45.

Heinberg, R. (2009). Searching for a miracle. In *A Joint Project of International Forum on Globalization and Post-Carbon Institute*.

Hornborg, A. (1992). Machine fetishism, value, and the image of unlimited good: Towards a thermodynamics of imperialism. *Man*, 1–18.

Hornborg, A. (2001). *The power of the machine: global inequalities of economy, technology, and environment* (Vol. 1). Altamira Pr.

Hornborg, A. (2003). The unequal exchange of time and space: Toward a non-normative ecological theory of exploitation. *Journal of Ecological Anthropology*, *7*(1), 4–10.

Hornborg, A. (2011). *Global ecology and unequal exchange : fetishism in a zero-sum world*. New York, NY: Routledge.

Hunt, E. K. (2011). *History of economic thought : a critical perspective*. Armonk, N.Y.: M.E. Sharpe.

Ivanov, V. V., & Bradbury, D. (1978). The Science of Semiotics. *New Literary History*, *9*(2), 199.

Jevons, W. S. (1879). *The theory of political economy*. London: Macmillan and co.

Kalecki, M. (1971). *Selected essays on the dynamics of the capitalist economy 1933-1970*. Cambridge: Cambridge University Press.

Kallis, G. (2012). Societal metabolism, working hours and degrowth A comment on Sorman and Giampietro. *Journal of Cleaner Production*. Retrieved from http://www.sciencedirect.com/science/article/pii/S0959652612003095

King, C. W., & Hall, C. (2011). Relating financial and energy return on investment. *Sustainability*, *3*(10), 1810–1832.

Kondepudi, D. K., & Prigogine, I. (1998). *Modern thermodynamics: from heat engines to dissipative structures*. John Wiley & Sons Chichester.

Korten, D. C. (2001). *When corporations rule the world*. Berrett-Koehler Pub.

Layard, R. (2003). *Happiness: Has social science a clue?* Centre for Economic Performance. Retrieved from http://stoa.org.uk/topics/happiness/Happiness%20-%20Has%20Social%20Science%20A%20Clue.pdf

Lenzen, M. (2000). Errors in Conventional and Input-Output—based Life—Cycle Inventories. *Journal of Industrial Ecology*, *4*(4), 127–148.

Lenzen, M., & Dey, C. (2000). Truncation error in embodied energy analyses of basic iron and steel products. *Energy*, *25*(6), 577–585.

Lobo Aleu, A., & Baeza, M. Á. (2009). A first attempt of geographically-distributed Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Mapping Human Time and Energy Throughput in metropolitan Barcelona. Retrieved from http://www.recercat.net/handle/2072/40697

Marx, K. (1867). *Capital, volume I*. Harmondsworth: Penguin/New Left Review.

Max-Neef, M., Elizalde, A., & Hopenhayn, M. (1992). Development and human needs. *Real-Life Economics: understanding wealth creation, edited by: Ekins, P. and Max-Neef, M., Routledge, London*, 197–213.

Mayumi, K., Giampietro, M., & Ramos-Martin, J. (2012). Reconsideration of Dimensions and Curve Fitting Practice in View of Georgescu-Roegen's Epistemology in Economics. *Journal for Economic Forecasting*, (4), 17–35.

McNally, D. (2010). *Global slump: The economics and politics of crisis and resistance*. Oakland: PM Press.

Menger, C. (1871). Principles of Economics, translated by James Dingwall and Bert F. *Hoselitz with an introduction by FA Hayek (New York and London, New York University Press), first published.*

Mill, J. S. (1848). Principles of Political Economy, Book III. Retrieved March 30, 2013, from http://www.econlib.org/library/Mill/mlP36.html

Moore, M. (1989). *Roger & Me*. Warner Bros.

Muradian, R., O'Connor, M., & Martinez-Alier, J. (2002). Embodied pollution in trade: estimating the environmental load displacement'of industrialised countries. *Ecological Economics*, *41*(1), 51–67.

Murphy, D., & Hall, C. (2010). Year in review—EROI or energy return on (energy) invested. *Annals of the New York Academy of Sciences*, *1185*(1), 102–118.

Murphy, D. J., & Hall, C. (2011). Energy return on investment, peak oil, and the end of economic growth. *Annals of the New York Academy of Sciences*, *1219*(1), 52–72.

Nitzan, J. (1992). *Inflation as restructuring. A theoretical and empirical account of the US experience*. University Library of Munich, Germany. Retrieved from http://ideas.repec.org/p/pra/mprapa/5624.html

Nitzan, J., & Bichler, S. (2006). New imperialism or new capitalism? *Review (Fernand Braudel Center)*, 1–86.

Nitzan, J., & Bichler, S. (2009). *Capital as power: a study of order and creorder*. New York: Routledge.

Occupational Employment Statistics Overview. (2013). *Bureau of Labor Statistics*. Retrieved June 24, 2013, from http://www.bls.gov/oes/oes_emp.htm

Odum, H. T. (1983). Systems Ecology; an introduction.

Odum, H. T. (1988). Self-organization, transformity, and information. *Energy*, *1*, 30.

OECD. (2001). Measuring Productivity - OECD Manual. Retrieved from www.oecd.org/dataoecd/59/29/2352458.pdf

Pastore, G., Giampietro, M., & Mayumi, K. (2000). Societal metabolism and multiple-scale integrated assessment: empirical validation and examples of application. *Population and Environment*, *22*(2), 211–254.

Peabody, G. (n.d.). Energy Consumption by End-Use Sector: A Comparison of Measures by Consumption and Supply Surveys. EIA. Retrieved from ftp://ftp.eia.doe.gov/consumption/0533.pdf

Physiocrat. (2013). *Encyclopedia Britannica*. Retrieved March 23, 2013, from http://www.britannica.com/EBchecked/topic/458805/physiocrat

Podobnik, B. (2002). Global energy inequalities: Exploring the long-term implications. *journal of world-systems research*, *8*(2), 252–274.

Prebisch, R. (1950). The economic development of Latin America and its principal problems. *Economic Bulletin for Latin America 1962*, *7*.

Prigogine, I., Stengers, I., & Toffler, A. (1984). *Order out of Chaos*. Toronto: Bantam.

Ramos-Martín, J., Cañellas-Boltà, S., Giampietro, M., & Gamboa, G. (2009). Catalonia's energy metabolism: Using the MuSIASEM approach at different scales. *Energy Policy*, *37*(11), 4658–4671.

Ramos-Martin, J., Giampietro, M., & Mayumi, K. (2007). On China's exosomatic energy metabolism: An application of multi-scale integrated analysis of societal metabolism (MSIASM). *Ecological Economics*, *63*(1), 174–191.

Recalde, M., & Ramos-Martin, J. (2012). Going beyond energy intensity to understand the energy metabolism of nations: The case of Argentina. *Energy*, *37*(1), 122–132.

Resolution 1 of the 17th CGPM. (1983). *Bureau International des Poids Mesures*. Retrieved June 27, 2013, from http://www.bipm.org/en/CGPM/db/17/1/

Ricardo, D. (1891). *Principles of political economy and taxation*. London: G. Bell and sons.

Rice, J. (2007). Ecological unequal exchange: Consumption, equity, and unsustainable structural relationships within the global economy. *International Journal of Comparative Sociology*, *48*(1), 43.

Robinson, J. (1953). The production function and the theory of capital. *The Review of Economic Studies*, *21*(2), 81–106.

Robinson, J. (1962). *Economic philosophy*. Chicago: Aldine Pub. Co.

Russi, D., Gonzalez-Martinez, A. C., Silva-Macher, J. C., Giljum, S., Martínez-Alier, J., & Vallejo, M. C. (2008). Material flows in latin America. *Journal of Industrial Ecology*, *12*(5-6), 704–720.

Samuelson, P. A. (1938). A note on the pure theory of consumer's behaviour. *Economica*, 61–71.

Santos, A., McGuckin, N., Nakamoto, H., Gray, D., & Liss, S. (2009). Summary of Travel Trends: National Household Travel Survey. US Department of Transportation. Retrieved from http://nhts.ornl.gov/2009/pub/stt.pdf

Shiller, R. (2012). Long term stock, bond, interest rate, and consumption data since 1871. Retrieved from www.econ.yale.edu/~shiller/data/chapt26.xls

Shirt. (2013). *Online Etymology Dictionary*. Retrieved May 29, 2013, from http://www.etymonline.com/index.php?term=shirt

Siciliano, G., Crociata, A., & Turvani, M. (2012). A Multi-level Integrated Analysis of Socio-Economic Systems Metabolism: an Application to the Italian Regional Level. *Environmental Policy and Governance*, *22*(5), 350–368. doi:10.1002/eet.1596

Singer, H. W. (1950). The distribution of gains between investing and borrowing countries. *The American Economic Review*, *40*(2), 473–485.

Smil, V. (2010). *Energy transitions: history, requirements, prospects*. Praeger Publishers.

Smith, A. (1863). *An Inquiry into the Nature and Causes of the Wealth of Nations*. Edinburgh: A. and C. Black. Originally published in 1828.

Solow, R. M. (1956). A contribution to the theory of economic growth. *The quarterly journal of economics*, *70*(1), 65–94.

Standard and Poors. (2012). S&P 500 Fact Sheet. McGraw-Hill. Retrieved from http://www.standardandpoors.com/indices/articles/en/us/?articleType=PDF&assetID=1221190434733

Thermodynamic equilibrium. (2013, June 15). In *Wikipedia, the free encyclopedia*. Retrieved from http://en.wikipedia.org/w/index.php?title=Thermodynamic_equilibrium&oldid=559339362

Thomson Reuters. (2013). Datastream. Retrieved from https://forms.thomsonreuters.com/datastream/

T-shirt. (2013). *Wikipedia, the free encyclopedia*. Retrieved May 29, 2013, from http://en.wikipedia.org/wiki/T-shirt

UK Business & Enterprise Committee. (2009). Risk and Reward: sustaining a higher value-added economy. *parliament.uk*. Retrieved April 7, 2013, from http://www.publications.parliament.uk/pa/cm200809/cmselect/cmberr/746/74605.htm

US Bureau of Economic Analysis. (2012). Retrieved from http://www.bea.gov/

U.S. Bureau of Labor Statistics. (2012). Retrieved from http://www.bls.gov/

US Energy Information Administration. (2012, September). Annual Energy Review 2011. Retrieved from http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

Veblen, T. (1923). *Absentee ownership: business enterprise in recent times: the case of America*. Transaction Pub.

Victor, P. (2008). *Managing without growth : slower by design, not disaster*. Northampton, Mass.: Edward Elgar.

Wallerstein, I. (1976). A world-system perspective on the social sciences. *The British Journal of Sociology, 27*(3), 343–352.

Walras, L. (1896). *Éléments d'économie politique pure, ou, Théorie de la richesse sociale*. F. Rouge.

Warr, B. (2009). REXS Database. Retrieved from https://sites.google.com/site/benjaminwarr/the-economic-growth-engine/rexs-database

Warr, B., & Ayres, R. (2012). Useful work and information as drivers of economic growth. *Ecological Economics, 73*, 93–102.

What are full-time equivalent employees? (2007). *US Bureau of Economic Analysis, FAQ*. Retrieved from http://www.bea.gov/faq/index.cfm?faq_id=368

Whitaker, A. C. (1904). *History and criticism of the labor theory of value in English political economy*. The Columbia University Press.

Williamson, S. H. (2009). An Index of the Wage of Unskilled Labor from 1774 to the Present. *Measuringworth.org*. Retrieved from http://eh.net/databases/unskilledwage/

Wong, S. (1978). *Foundations of Paul Samuelson's Revealed Preference Theory*. New York: Routledge.

Zencey, E. (2012). Energy as Master Resource. Presented at the 4th Annual Biophysical Economics Conference, Burlington, VT. Retrieved from http://www.uvm.edu/~jdericks/BPE4/k2.pdf