# THE EVOLUTION OF ENERGY FLOWS THROUGH THE ECONOMY

## A THERMODYNAMIC PERSPECTIVE

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May 2011

Masters Project submitted in partial fulfillment of the

requirements for the Master of Environmental Management degree in

the Nicholas School of the Environment of

Duke University

2011

# ABSTRACT

Over time, the U.S. economy has continued to reduce its energy and materials intensities while at the same time increasing its total energy throughput. Taking the perspective of the economy as a system of evolving thermodynamic processes, these trends appear to be natural consequences of the economy's evolution. Connecting two distinct disciplines, this work takes the physical principles of minimum and maximum entropy production as a theoretical foundation for explaining the economic phenomena of dematerialization and efficiency rebound effects. Thermodynamic processes with freedom to morph (e.g. life forms) maximize the available energy flows through their system subject to the constraints of material requirements and inefficiencies in energy transformation. The natural evolution toward optimum is for systems to progressively relax these constraints through time, allowing a greater amount of energy throughput.

As a result, increased energy and material efficiencies should not be expected to reduce energy consumption for our economies in the long run. The policy implications for this work are critical, as we should expect energy efficiency improvements designed to reduce energy consumption to "backfire." The policy imperative with respect to climate change is to place primary emphasis on the carbon intensity of our available energy sources, as we cannot expect efficiency gains alone to yield carbon mitigation in the long run.

# ACKNOWLEDGEMENTS

This work owes a great debt to my advisor, Dr. Tim Johnson, who helped guide this process to a successful completion with insight, patience, and support. My understanding of thermodynamics has benefited greatly from the teaching and writing of Dr. Adrian Bejan, particularly with respect to Constructal Theory. Last and certainly not least, I owe my inspiration to pursue the implications of maximum entropy production to Dr. Peter Haff, who introduced and inspired the principle for me.

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## I. INTRODUCTION

The Earth is in a state of perpetual energetic disequilibrium due to constant flux of energy from the sun. This energy naturally tends toward equilibrium by the second law of thermodynamics. The flow of the sun's energy toward equilibrium induces a tremendous amount of activity on Earth. In time, the Earth has evolved better and better mechanisms for performing this equilibration process. We are one such mechanism.

Broadly, three categories of equilibrating mechanisms have evolved on Earth: physical, biological, and technological. Each mechanism processes a given quantity of the sun's energy toward equilibrium. On its route to equilibrium, energy from the sun travels by the path of least resistance. Successful mechanisms are those that provide this energy with low-resistance paths to equilibrium. More successful mechanisms process larger flows of energy.

The first task of this work is to solidify the thermodynamics linkage between reduced resistance and greater flows to equilibrium. I then discuss how this relationship holds across physical, biological, and technological processes. From there, I leverage the resistance-flow result on explaining efficiency-consumption patterns in economies. Specifically, greater efficiency should lead to greater energy and materials flows.

As a test case for the general plausibility of the hypothesis, I examine trends in the production patterns of the US economy. While I explicitly do not endeavor a causal claim, I find no contradiction in the patterns of energy and materials use in US production. To the extent my hypothesized efficiency-flows relation holds, efficiency improvements cannot be relied upon to satisfy carbon mitigation objectives. In fact, efficiency may well exacerbate carbon emissions absent a substantial change in the carbon intensity of our energy sources.

## II. ENTROPY PRODUCTION

### Entropy as a Modeling Principle

*Definition*

Scientific disciplines employ entropy in a variety of ways and with various functional definitions. Entropy has also become a widely analogized concept in both public and scientific discourse. For present purposes, I offer two explanations of entropy, one for conceptualization and another for calculation. First, entropy represents the extent of equilibrium in a system. This definition is perhaps most easily linked to statistical mechanics. In the late 1800's, Ludwig Boltzmann developed a means for describing entropy as the likelihood of a certain macrostate of a given system. Specifically, he offered the following equation (now carved on his gravestone in Austria):

$$\mathrm{S} = \mathrm{k} \cdot \log(\mathrm{W}) \tag{1}$$

Here, S represents entropy, k is Boltzmann's constant ($1.38*10^{-23}$ Joules/Kelvin, the units of entropy), and W is the number of possible microstates that can satisfy the observed macrostate. Here we see exactly how entropy scales with the number of possible microstates (W). The macrostate of a system is described by aggregate ("external") parameters such as temperature, volume, pressure, etc. A *microstate* describes the behavior of particles in the system. A macrostate is more likely (has greater entropy) the greater the number of microstates (W) that could satisfy it.

To take a classic example, suppose all of the molecules of air in your room were concentrated in a single corner as opposed to being distributed more or less evenly throughout the room as they are. The number of possible microstates (i.e. arrangement, position, and velocity of the molecules) given this corner-concentration macrostate is far fewer than the number of possible microstates that could satisfy the wide distribution of the molecules throughout the room. In the concentrated case, the possible microstates of the molecules are constrained to be within the corner of the room, but with the entire room available, the molecules can explore an exponentially greater number of microstates. Physicists take this difference in the number of possible states to indicate the relative probability of the two macrostates. More possible microstates also implies greater randomness or disorder (less predictability) in the behavior of the particles, an interpretation of entropy that is perhaps more familiar to most.

Now suppose that we intervene to concentrate nearly all of the particles in a given corner. In time, the system will evolve toward more and more likely macrostates provided it is not constrained from doing so. (That the system is free to morph toward its equilibrium is an important distinction discussed below.) In the process, the entropy and equilibrium of the system will increase. This tendency toward equilibrium, given by the second law of thermodynamics, is the conceptual lens through which the theoretical argument of this paper is most clearly seen.

While it is immensely difficult, if even possible, to measure entropy by calculating the number of possible micro states for a given macrostate, aggregate measures of entropy can be derived from macrostate properties. As pioneered by Sadi Carnot at the dawn of engineering thermodynamics, one can measure entropy by dividing the quantity of energy in a given system (Q) by its temperature, giving units of Joules per degree Kelvin (same as Boltzmann's constant), as follows:

$$\mathrm{S} = \frac{\mathrm{Q}}{\mathrm{T}} \tag{2}$$

Here, Q represents the quantity of energy in Joules and T the temperature in degrees Kelvin. This measure produces the average entropy of the system, which is uniform (i.e. accurate throughout the system) if the system is in equilibrium. An interesting result comes from combining equations (1) and (2) to derive an equation for temperature as follows:

$$\mathrm{T} = \frac{\mathrm{Q}}{\mathrm{k} \cdot \log(\mathrm{W})} \tag{3}$$

Equation (3) reveals that temperature is a measure of the extent to which the energy of a system is constrained by the order of magnitude of microstates it can express. The higher the constraint, the higher the temperature.

There is one final way to consider entropy that will be helpful for the purposes of this paper. Low-entropy energy is available to do work. Energy from the sun has very low entropy and provides a substantial share of the energy employed for work on Earth. For example, the sun's energy performs work by moving clouds (physical), growing plants (biological), or powering vehicles (technological).[1] When a process uses low-entropy energy to do work, the entropy of the system increases, and a smaller fraction of that energy is subsequently available for additional work. Such processes are said to degrade exergy (energy available for work) and generate entropy. Another common description of processes is to say that the exergy is dissipated.

### *Importance*

Entropy holds a privileged place in science that is only glimpsed in discussing its definition. Above I explained entropy as a measure of equilibrium and that there exists a universal tendency toward equilibrium (the second law of thermodynamics). This gives some indication of entropy's breadth but its importance bears emphasizing given the extent to which I will leverage it.

Entropy is one of the few, if not only, time asymmetries in physics. That is, when observing physical forces in time, absent entropy, there is no ability to distinguish events occurring forward or backward in time. As Eddington (1928, p. 69) explained, entropy is the "only distinction known to physics" of past

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[1] Note here that one need not consider conventional solar powered vehicles. The energy available in fossil fuel stocks (the consolidated remains of ancient life), was originally contributed by the sun.

and future. If the gravity of this unique distinction doesn't captivate, Eddington (1928, p. 74) offers an almost comical statement of the importance of the second law of thermodynamics:

> The law that entropy always increases—the second law of thermodynamics—holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations — then so much the worse for Maxwell's equations. If it is found to be contradicted by observation — well, these experimentalists do bungle things sometimes. 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.

This importance has persisted since Eddington and the gravity of the second law continues to receive debate (cf. Penrose 2005, pp. 686-734). Entropy is therefore a unique and central property of nature and has the standing from which broad theoretical implications can be leveraged with care. As mentioned by Eddington, the second law of thermodynamics indicates a fundamental tendency of systems toward greater equilibrium (greater entropy); however, the second law offers no indication of how quickly the system will approach equilibrium (produce entropy). The speed at which systems equilibrate from low entropy (less likely) to high entropy (more likely) states is of particular interest for this work. I argue that the process of evolution, from physical to biological to technological processes, corresponds to an increasing time rate of entropy production.

As preliminary motivation for this claim, note that order and complexity in nature represent relative low-entropy, disequilibrium states of matter and energy. The second law holds despite the evolution of greater order and complexity on Earth; from physical processes to complex biological processes, to technological processes. For each "unit" of order maintained in time, equal or greater disorder must continuously be generated to satisfy the second law. Since all matter and energy harbor a constant tendency toward disorder, the persistence of order requires the persistent generation of entropy (e.g.

all living things intake high-order food and generate waste). By the second law, greater incidence of order implies greater generation of entropy to sustain it (Ulanowicz and Hannon 1987).

## Entropy Optimization Principles

Two optimization principles, seemingly contradictory, have persisted in the thermodynamics literature: minimum entropy production (MnEP) and maximum entropy production (MxEP). The conflict is relaxed by noting that each principle is optimizing with respect to a different quantity. The MnEP principle, common in engineering applications, minimizes entropy production with respect to the quantity of energy. The MxEP principle, common in geophysics, maximizes entropy production with respect to time. By examining closely the relationship between the two rates, it is evident that MnEP implies MxEP. Before doing so, it is worth exploring the principles in further detail.

### *Maximum and Minimum Entropy Production Principles*

MxEP literature has attempted to isolate the appropriateness of the MnEP principle to linear systems under constrained conditions (e.g. Ozawa, Ohmura, Lorenz, and Pujol 2003). Early work by Prigogine (1945) attempted to tackle this issue more directly in identifying distance from equilibrium and fixedness of the boundary conditions as essential determining factors for distinguishing MnEP from MxEP systems and this work has continued by others (e.g. Dewar 2005; Kleidon and Lorenz 2005). Constrained systems, which lack the freedom to morph toward more likely states, are not expected to maximize entropy production. Also, if we consider the approach to equilibrium as more or less asymptotic, we should not be surprised that systems near equilibrium generate entropy at slower rates than those far away from equilibrium. For our purposes, understanding the evolution of Earth-scale processes, constrained systems close to equilibrium are not the appropriate object of study. Rather, understanding the evolution of Earth processes requires considering consistent and large disequilibrium with substantial freedom to morph. In other words, the Earth is subject to the strong and persistent disequilibrating force of the sun, and the arrangement of matter on Earth enjoys substantial freedom to morph in time.

Still, others have shown that Earth processes are morphing in time in accord with a MnEP principle (Bejan and Lorente 2008). Here I call on the distinction mentioned above, that the minimum entropy production principle applied in this way refers to entropy production *with respect to energy*. More specifically, MnEP minimizes entropy production per unit volume of the flow quantity that carries the exergy (energy available for work). The maximum entropy production principle refers to entropy production *with respect to time.* I show below how the former actually implies the latter in our systems of interest (i.e. those far from equilibrium with freedom to morph).

Bejan and Lorente (2008) examine the morphing of flow systems in time toward structures that minimize resistance to their flows, or which provide "greater global flow access" (p. xiii). Minimizing flow resistance is easily shown to be equivalent to minimizing the flow-volume rate of entropy production. Two common flow quantities in their analyses are mass (e.g. water) and heat. Bejan and Lorente (2008) refer to this process as reducing the imperfection of the flow system. Examining the evolution of physical, biological, and technological processes, Bejan and Lorente show how this evolution reveals a consistent MnEP pattern. That is, the arc of evolution points toward "less imperfect" flow mechanisms.

One might reasonably question the freedom of engineered structures to morph, but indeed this is a primary message of Bejan and Lorente's work; that technology undergoes evolution toward optimum (less imperfection) in time in much the same way that physical and biological processes do, though at much faster rates. Here again we catch a glimpse of the continuity in the evolution of entropy generation (equilibrating) mechanisms (flow structures) from physical to biological to technological. Moreover, seeing entropy principles applied to both mass and heat flows reveals how they operate for flows of both matter and energy.

*Unifying Entropy Production Minimization and Maximization*

The challenge of extracting the maximum possible work from a given quantity of heat input was a primary motivation for early engineers such as Sadi Carnot, whose thinking birthed classical thermodynamics.  Consider first the following closed system situated between a hot reservoir ($\mathrm{T_h}$) and cold reservoir ($\mathrm{T_c}$), allocating heat input (Q) to two channels, work (W) and generated entropy ($\mathrm{S_{gen}}$).

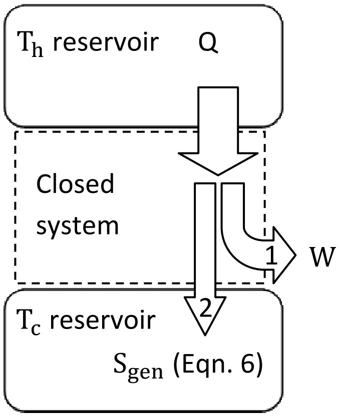

FIGURE 1:  A Closed System Generating Work and Entropy

Carnot's famous efficiency equation sets a theoretical bound on the amount of work able to be extracted from a given quantity of heat as proportional to the temperature differential across the source and sink heat reservoirs; i.e.,

$$\eta_c = 1 - \frac{\mathrm{T_c}}{\mathrm{T_h}} = \left(\frac{W}{Q}\right)_{max} \qquad (4)$$

Without a differential, no work can be done – the system has reached equilibrium.  The temperatures $\mathrm{T_c}$ and $\mathrm{T_h}$ (in degrees Kelvin) correspond respectively to the cold and hot reservoirs abutting the system, W represents work, and Q represents the amount of heat input.  If we multiply the Carnot efficiency by the quantity of heat passing through the system (Q), we obtain the maximum amount of work (W) that one can extract from the system through channel 1 (FIGURE 1). The lost work (i.e. $\mathrm{Q} * [\mathrm{T_c}/\mathrm{T_h}]$) represents the entropy generation ($\mathrm{S_{gen}}$) or exergy dissipation of the system through channel 2, which is constrained to be nonnegative by the second law. So the thermodynamic process partitions the energy (Q) it receives into work (W) and entropy ($\mathrm{S_{gen}}$) and, since the first law conserves energy (Q), we can arrange the following relation for a Carnot-efficient process:

$$\mathrm{Q_{in}} = \mathrm{Q_{out}} = \left( \underbrace{\mathrm{Q}\left(\frac{\mathrm{T_h}-\mathrm{T_c}}{\mathrm{T_h}}\right)}_{\mathrm{W}} + \underbrace{\mathrm{Q}\left(\frac{T_c}{T_h}\right)}_{\mathrm{S_{gen}}} \right)_{\eta_\mathrm{c}} \tag{5}$$

Of course, feasible systems do not perform this well; rather, this is the asymptote of least imperfection toward which systems evolve. The essential takeaway from equation (5) is that, for any process, there is a zero-sum trade-off between work (exergy transfer) and entropy generation. The engineer's optimization task is to construct an engine that performs as close to equation (5) as possible. From equation (5), one can derive an expression for the actual transformation of available energy ($\mathrm{Q_{in}}$) into preserved exergy (W; channel 1 in FIGURE 1) and dissipated exergy ($\mathrm{S_{gen}}$; channel 2 in FIGURE 1) by including a variable work parameter, which is bound above by the Carnot limit (i.e. the first term of equation 5). Here, the work-maximization – MnEP duality is apparent given a fixed temperature differential ($\mathrm{T_c} - \mathrm{T_h}$) and quantity of available energy (Q):

$$\underbrace{S_{gen}}_{\partial \mathrm{S}} = \underbrace{\frac{Q-W}{T_c}}_{\mathrm{S_{out}}} - \underbrace{\frac{Q}{T_h}}_{\mathrm{S_{in}}} \tag{6}$$

In this way, MnEP is a functional equivalent to work maximization. Again, the fraction of exergy (Q) not channeled into work is not completely dissipated. Many industrial processes exhaust exergy, often in the form of heat, to the ambient. This heat exergy must then do work in the atmosphere to continue on its path toward equilibrium. Understanding the place of the MxEP principle requires considering the system along an additional dimension, time. We can decompose entropy generation per unit time, by the chain rule, into the product of two rates, entropy generation per quantity energy flow and energy flow per unit time.

$$\underbrace{\frac{\partial S}{\partial t}}_{S_t} = \underbrace{\frac{\partial S}{\partial Q}}_{S_Q} \underbrace{\frac{\partial Q}{\partial t}}_{Q_t} \tag{7}$$

Engineers optimize system efficiency by minimizing the first term in Equation (7). Geophysicists and others interested in the natural phenomena, however, often employ the entire product as a modeling principle by maximizing it. With respect to the second term (flow rate), we know from Constructal Theory (Bejan and Lorente 2008) that systems with freedom to morph in time will evolve “toward greater global flow access” (p. xiii). The primary mechanism of this evolution is the reduction of flow resistance; i.e., the flow-quantity rate of entropy production or $S_Q$ in equation (7). This indicates that changing the first term in equation 7 ($S_Q$) could induce a change in the second term ($Q_t$; the flow rate). The relation between the change in $S_Q$ and the change in $Q_t$ will dictate the net impact on our outcome of interest, the change in the time-rate of entropy generation ($\partial S_t$) as follows:

$$\frac{S_t'}{S_t} = \frac{(S_Q+\partial S_Q)(Q_t+\partial Q_t)}{S_Q Q_t} \tag{8}$$

That is, the percentage change in entropy generation with respect to time is equal to the product of the percentage changes in the rate of entropy generation with respect to flow quantity and the flow rate. If equation (8) is greater than one, a reduction in entropy generation with respect to Q increases entropy generation with respect to time.

The challenge is to identify relationships among entropy generation, flows and resistance. For this task, I take the example of entropy generation at the boundary layer of a river. That is, the entropy generated by the friction between water and the river bed in which it flows. First, we can restate equation (7) by simply changing our flow quantity from heat to mass (of water) as follows:

$$\underbrace{\frac{\partial S}{\partial t}}_{S_t} = \underbrace{\frac{\partial S}{\partial m}}_{S_m} \underbrace{\frac{\partial m}{\partial t}}_{Q_t} \qquad (7')$$

The next step is to define each of the rates to understand their interaction. In our river example, the water must overcome the sheer stress imposed by the riverbed in order to flow. In performing this work on the riverbed, some of the exergy in the water is dissipated. The time rate of dissipation per unit length swept by the river is given as follows (from Bejan and Lorente 2008, p. 78):

$$p\tau U \text{ (Joules / meter)} \qquad (9)$$

This is the work the water must perform on the riverbed in order to flow one meter. (It is helpful to visualize the geometry of the riverbed as a half pipe.) Here, p is the bed perimeter, U is the flow velocity, and τ is the shear stress, which equals (Bejan and Lorente 2008, p. 78):

$$\tau = C_f \rho U^2 \qquad (10)$$

Here, $C_f$ is a dimensionless friction coefficient determined by the properties of the bed surface and flow regime (i.e., laminar or turbulent), and ρ is the water density (mass/volume). If we divide the rate of exergy dissipation from the shear stress (eqn. 9) by the ambient temperature ($T_0$) we produce the entropy generation from the exergy dissipation per unit time per length traveled.

$$\frac{\partial S_t}{\partial L} = \frac{p\tau U}{T_0} \qquad (11)$$

Here, L is the length traveled by the flow perpendicular to the bed perimeter. Integrating with respect to L (and neglecting the constant), we can represent our target rate (entropy generation with respect to time; $S_t$) as:

$$S_t = \frac{A\tau U}{T_0} \tag{12}$$

Our next step is to derive the equation for $S_m$, the first term in equation (7’). If we integrate once more with respect to time (and neglect the constant), we get:

$$S = \frac{A\tau U}{T_0} t \tag{13}$$

Here, t represents time in seconds. Now, if we multiply both sides of equation (13) by a height scale parameter (h in meters) we transform the surface area (A=p*L) on the right hand side into volume. Differentiating with respect to volume and dividing the height parameter to the right hand side we get entropy production per unit volume ($S_V$):

$$S_V = \frac{\tau U}{h T_0} t \tag{14}$$

We see here that entropy generation with respect to flow volume decreases with the flow resistance (τ). Next, we derive change in volume per unit change in mass ($V_m$) so that we may obtain $S_m$ by the chain rule (i.e. $S_m = S_V V_m$). This is easily related through density ($\rho = \mathrm{mass/volume}$):

$$V_m = \frac{1}{\rho} \tag{15}$$

Thus the product of the previous two rates gives:

$$S_m = \frac{\tau U}{h \rho T_0} t \tag{16}$$

Next, the second term of our product of rates is our mass flow rate ($m_t$). We can express this as (Bejan and Lorente 2008, p. 78):

$$m_t = \rho U A \tag{17}$$

Substituting the density for mass over volume, the mass flow rate reduces to:

$$\mathrm{m_t} = \frac{\mathrm{mU}}{\mathrm{h}} \tag{18}$$

Returning to our objective function, we now have expressions for the two rates we originally sought in equation (7’), namely $\mathrm{S_m}$and $\mathrm{m_t}$:

$$\mathrm{S_t} = \left(\frac{\tau \mathrm{U}}{\mathrm{h}\rho \mathrm{T_0}}\mathrm{t}\right)\left(\frac{\mathrm{mU}}{\mathrm{h}}\right) \tag{19}$$

Substituting for the shear stress force (τ) by equation (10) gives:

$$\mathrm{S_t} = \left(\underbrace{\mathrm{C_f}\frac{\rho \mathrm{U}^3}{2\mathrm{h}\rho \mathrm{T_0}}\mathrm{t}}_{\mathrm{S_m}}\right)\left(\frac{\mathrm{mU}}{\underbrace{\mathrm{h}}_{\mathrm{m_t}}}\right) \tag{20}$$

A reduction in flow resistance means reducing the dimensionless friction coefficient $\mathrm{C_f}$, this happens in time as, for example, the water flow smoothes the bed surface or the flow regime evolves. With all else constant, reducing the flow resistance reduces the entropy generation per unit volume and per unit time; however, fluid flow is a richly dynamic system and we should not be satisfied to hold all else constant. By the notion that flows go with the inverse of the resistance, we can expect that the flow rate will increase with decreases in flow resistance. Specific to our fluid flow example, we can express the flow-rate response to a reduction in resistance in a turbulent flow regime as follows[2]:

$$\mathrm{U} = \left(\frac{0.01\nu}{\mathrm{C_f^4 D}}\right) \tag{21}$$

We see here that the velocity scales with the inverse of the resistance to the power four. Here, ν represents the kinematic viscosity of the fluid. Simplifying equation (20), the net effect on entropy generation from a decrease in the friction comes within sight:

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[2] This relation holds for turbulent flow and was developed by Paul Blasius. The corresponding relation for laminar flow (not appropriate for the example of a river) is $\mathrm{U} = 16\nu/\mathrm{C_f D}$.

$$S_t = C_f\left(\frac{m}{2h^2T_0}t\right)U^4 \tag{22}$$

$$S_t = C_f\left(\frac{m}{2h^2T_0}t\right)\left(\frac{1.01e^{-8}v^4}{C_f^{16}D^4}\right) \tag{22'}$$

Equation (22') substitutes our expression for velocity (U) as expressed in equation (21). Finally, we can derive the change in the time rate of entropy generation with respect to a unit change in the flow resistance ($C_f$) as:

$$\frac{\partial S_t}{\partial C_f} = \left(\frac{-1}{C_f^{16}}\right)\left(\frac{15.01e^{-8}mtv^4}{2h^2T_0D^4}\right) \tag{23}$$

Equation (23) gives the entropy generation relation desired from the river example and we can confirm that the units agree (i.e. Joules per Kelvin per second). The negative sign indicates that reducing flow resistance increases the time rate of entropy production.[3] Thus, I have shown that while reducing the flow surface resistance reduces the flow-volume rate of entropy production, it also leads to an *increase* in the time rate of entropy production. This is a preliminary but important result, as I discuss in the following sections.

### *Limitations*

This result is rather preliminary and particular. Based on a limited example, it gives a plausible indication as to how entropy production minimization and maximization principles can relate; however, the methods by which I arrived at the above result are not wholly adequate for the task. Ideally, any attempt at modeling the highly complex dynamics of fluid flow should employ total, not partial, differential equations as in the Navier-Stokes equations. Regrettably, such treatment is beyond the current capacity, or at least time constraints, of the author. Second, entropy production

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[3] It is worth mention that the dimensionless friction coefficient to the power negative four is significantly less than one (and greater than zero), especially in the case of turbulent flows.

at the flow surface is only one part of the flow regime. The internal mechanics of the flow and their interaction with surface behavior must also be considered. Fuller treatment of this and other flow examples are left to future research.

### *Summary Discussion*

The evolution of morphing systems in time toward lower flow resistances, a phenomenon Bejan and Lorente (2008) explore in detail under the heading of Constructal Theory, is coterminous with the path to more and more likely states of matter and energy configurations on our planet. The method of this evolution is the generation of less and less imperfect design for flow facilitation, from physical to biological to technological processes. The emergence of each of these types of processes marks an inflection point in the history of Earth's entropy generation capacity. In time, Earth processes are evolving more and more effective means for equilibrating the exergy fluxes incident on the planet.

## **Entropy Production Maximization Literature**

As mentioned at the outset, entropy generation principles have been utilized extensively in the academic literature. Given the breadth and acceptance of the minimum entropy production principle, particularly in engineering, and my primary interest on maximum entropy production, I focus on the use of maximum entropy production and explain how others have approached it. This will lend some support to the result derived above.

### *Entropy Production in Physical Systems*

In an article reviewing the principle of maximum entropy production Ozawa, et al. (2003) detail how climatic phenomena maximize entropy production. The authors identify a long body of literature employing entropy production maximization (MxEP) as an empirically consistent constraint in modeling atmospheric phenomena. For example, they show agreement between actual and predicted temperature, cloud cover, and heat flux distributions on Earth. As can be seen in FIGURE 2 (from Ozawa, et al. 2003), modeling with maximum entropy production constraint has proven remarkably successful.

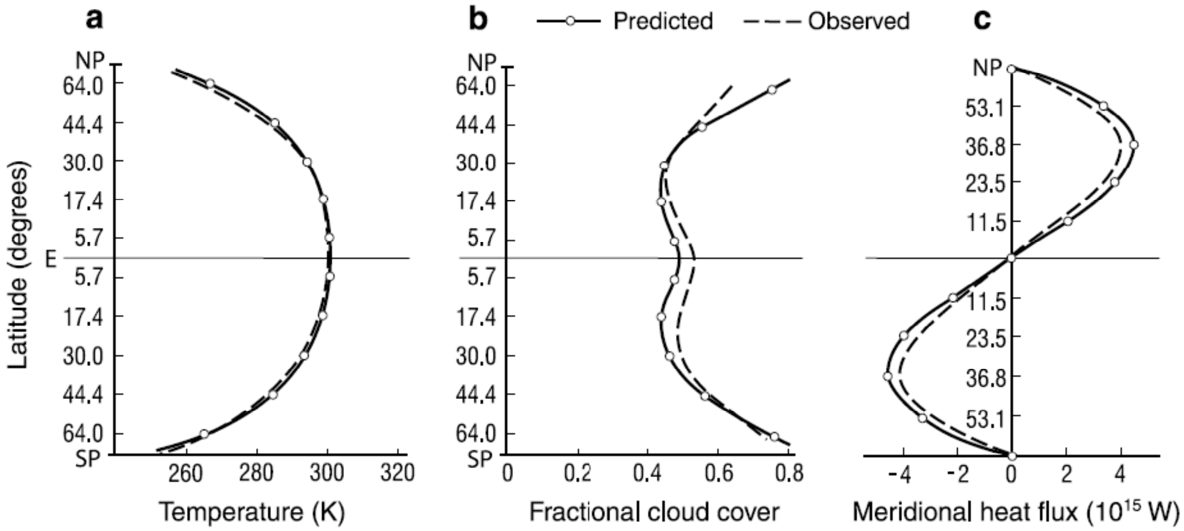

**Figure 2.** Latitudinal distributions of (a) mean air temperature, (b) cloud cover, and (c) meridional heat transport in the Earth. Solid line curves indicate those predicted with the constraint of maximum entropy production (equation (9)), and dashed lines indicate those observed. Reprinted from *Paltridge* [1975] with permission from the Royal Meteorological Society.

FIGURE 2: Actual & Modeled Atmospheric Phenomena (reprinted from Ozawa, et al. 2003, Figure 2)

As noted in the caption, FIGURE 2 is based on the early work of Paltridge (1975).[4] Ozawa, et al. (2003) also note that Lorenz, Lunine, Withers, and McKay (2001) have applied the MxEP principle to successfully model the atmospheres of Mars and Titan (Saturn's largest moon), which were formerly modeled quite poorly by pressure differentials. In independent work, Lorenz (2002) models atmospheric behavior using the MxEP principle and gives a preliminary example of how the MxEP principle can be used to model tectonic activity. Ozawa, et al. 2003 also offer an important supplement to the MxEP case I analyzed above at fluid flow boundary. They show how the internal dynamics of fluid

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[4] The figure is reprinted from Ozawa, et al. (2003) instead of from Paltridge (1975) for better image quality.

flow, specifically thermal and viscous dissipation, which I excluded from the analysis above, act in accord with the MxEP principle. This leaves only the interaction of the boundary and internal dynamics of the flow regime unexamined in our river flow example.

Dewar (2005) takes on the maximum entropy production principle in a broad sweep of the historical literature focusing particularly on work advanced in information theory by Jaynes (cf. Jaynes 1979). Dewar's treatment emphasizes the breadth of applications for which entropy principles have been employed. Dewar's treatment also elucidates how the most likely path to the most likely (high-entropy) state is the one that gets there most rapidly. This draws on Jayne's notion of the caliber of paths between states. The number of paths to a given entropy macrostate is greater (has a higher caliber) if the end state is of higher entropy; i.e., there are more possible end microstates in a higher entropy macrostate, meaning more paths to that state are available. This casts maximum entropy production in a different light, one richly entropic in nature. Maximum entropy production is the most likely rate of production because greater increases in entropy from state to state are more likely than lesser ones. (Dewar also gives more technical treatment to this information theory approach in Dewar 2003.)

### *Entropy Production in Biological Systems*

The discussion above highlighted the general dynamics of a series of thermodynamic processes dissipating exergy. This conceptualization has a rich application for biological (eco-) systems. Along the physical-biological-technological arc of evolution, entropy production capacities have increased both across and within these three regimes. In considering biological evolution, Schneider and Kay (1994, p. 37) remark:

> As ecosystems develop or mature, they should increase their total dissipation, and should develop more complex structures with greater diversity and more hierarchical levels to abet energy degradation. Species which survive in ecosystems are those that funnel energy into their own

> production and reproduction and contribute to autocatalytic processes which increase the total dissipation of the ecosystem. In short, ecosystems develop in a way which systematically increases their ability to degrade the incoming solar energy.

To examine this claim, Schneider and Kay (1994) take an approach common in this literature and examine remotely sensed radiation fluxes for ecosystems of various levels of development situated at similar latitudes. The approach was proposed earlier by Ulanowicz and Hannon (1987) and the results are consistent with their hypothesis; i.e., Schneider and Kay find a positive relationship with ecosystem development and exergy dissipation. Work is done much more rapidly in biologically rich environments than in biologically sparse environments under similar thermal flux conditions. (Cf. Schneider and Sagan 2005 for a broader exploration of entropy production and life.)

When the exergy gradients (differential between the reservoirs abutting the process) overwhelm the system processes, new regimes emerge. Schneider and Kay (1994) point to the emergence of Bénard cells in heating liquids. At a critical point in the flow of exergy dissipation, convective Bénard cells emerge to degrade the exergy induced more rapidly than conduction can achieve. These cells are then sub-processes of a larger dissipative process. In a biological context, Aoki (1995) highlights a similar biological hierarchy among ecosystems, positing that ecosystems are “superorganisms” to their constituent organisms (citing Clements and Shelford 1939). This unifying perspective is helpful in considering the evolution of channels of exergy dissipation and the relation of higher and lower order dissipation processes. Aoki also calculates higher time rates of entropy production for a biologically productive lake in the United States (Lake Mendota) relative to a biologically unproductive lake in Japan (Lake Biwa).

Finally, Lineweaver (2005) identifies reproducibility as a criterion for identifying MxEP systems. If systems emerge as a result of a MxEP process, they should do so repeatedly. That is, if we rewind the cosmological clock and let the processes unfold an evolution of matter and energy arrangements again, if they follow a maximal path, that series of macrostates visited along that path ought to be identical, or perhaps at least sufficiently indistinguishable. In the context of biological evolution, Lineweaver highlights that not all phenomena that emerge in the biosphere should necessarily be considered as a result of an MxEP process. This highlights the probabilistic nature of entropy. To the extent that macrostate phenomena are reproduced in successive “runs” of the evolutionary process, then they are likely component to the MxEP process.

### *Entropy Production in Technological Systems*

The final component to the above review is logically a survey of literature on technological processes. Perhaps because thermodynamic treatment of technology is an area of research largely dominated by engineering, it is difficult to identify treatment of entropy production principles in a manner consistent with the view taken in this paper. Bejan and Lorente’s work on Constructal Theory is one notable exception; however, to the extent they focus on entropy production, they highlight minimization, not maximization. Still, the loud and clear emphasis on MnEP in engineering, combined with Bejan and Lorente’s evolutionary treatment of technology and the firm linkage between MnEP and MxEP makes the dynamics of technological systems appear entirely consistent with the MxEP principle as explored in physical and biological systems. Finally, in sections below, I explore implications of MxEP in the context of the US economy. In recent history, this is very much the story of the evolution of technological processes – this parallel will be evident.

### *Summary*

I have outlined the maximum entropy production literature with particular attention to physical and biological processes. Again, the broad view of MxEP casts the three regimes of thermodynamic processes (physical, biological, and technological) as a continuum of ever-improving equilibrating mechanisms. The empirical success of MxEP in the case of physical processes (e.g. climatology) appears quite strong in the literature and my modest contribution at the outset of this work is affirming to that story. The literature on biological processes bears similar but less resounding conclusions with respect to MxEP. The constraints on biological systems are more challenging to specify and may influence the manifestation of MxEP processes in ways not yet understood. Technological processes are perhaps the least well studied in this context, with the notable exception of Bejan and Lorente (2008).[5] Still, the strong linkage between MnEP and MxEP processes and the firm establishment of MnEP in engineering reveals a pattern entirely consistent with MxEP writ large.

## Maximum Entropy Production Implications

Maximum entropy production is a potent principle by which we can model the phenomena we witness on Earth. As I have argued and attempted to demonstrate above, the principle emerges as a natural result of, not a contradiction to, the classical thermodynamics principle of minimum entropy production. Extant literature indicates that MxEP is an empirically successful principle for modeling physical processes on Earth and other bodies in our solar system. The principle offers a potential bridge between the dynamics of physical, biological, and technological systems.

Given its apparent robustness, I leverage the MxEP principle as a key determinant for two economic phenomena: dematerialization and the so-called “rebound effect.” Dematerialization refers to the decreased materials intensity of economic output over time. The rebound effect refers to lost energy savings from energy efficiency improvements. Through a thermodynamic lens, material and energy efficiency improvements indicate reduced flow resistance for the economic system. From the argument

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[5] It is worth noting that my view of the compatibility of Constructal Theory with MxEP is not shared by Bejan.

above, we should expect these efficiency improvements to induce increased material (mass) and energy flows through the economy. Increased flows stemming from efficiency improvements go either to intensive expansion (increased output from existing industries asymptotically toward the point of maturity) or to extensive expansion (growth of new, more efficient processes). To summarize, we should observe increased mass and energy flows through the economy concomitant with efficiency gains in economic processes. The following sections explore the evidence and mechanisms for these economic manifestations of the MxEP principle.

## III. ECONOMIC MANIFESTATIONS OF ENTROPY PRODUCTION

### Entropy Production Principles in the Economy

To draw the discussion of entropy production to a finer point, I now offer a conceptual sketch of entropy production principles in the context of an economy. In the sections below, I consider explicitly the implications of MxEP in the US economy. To motivate the thermodynamic theory for this example, let's return to heat as our flow quantity (Q). Consider the flow path of this heat through a series of processes. In FIGURE 1, I emphasized the tradeoff between work produced and entropy generated; however, I did not follow the work (exergy) output through channel 1 to its logical conclusion; i.e., dissipation. This work will be the input to yet another thermodynamic process (within the economy or in the environment). Here we might imagine appending a second closed system to the right of our closed system in FIGURE 1 to receive its work output. For example, process one could be a generator producing electricity and process two a space heater. The heat will do work in the environment of the home and its environs until the low-entropy fuel source is dissipated to equilibrium. The more complete the picture we draw of the flow process, the more process boxes we append.

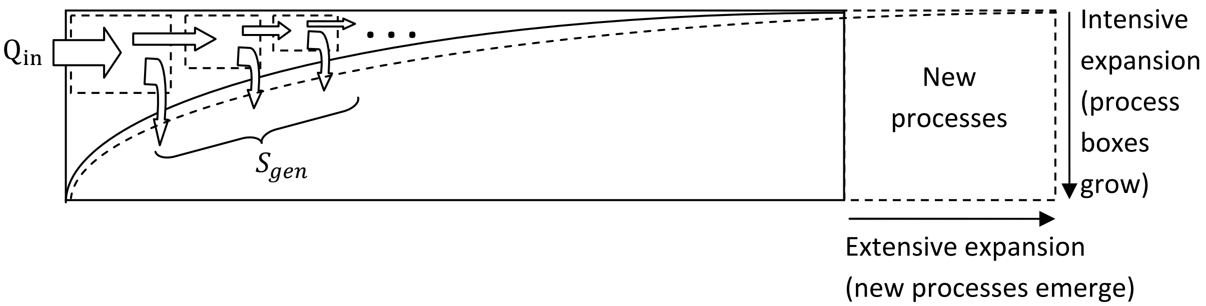

FIGURE 3: A Series of Thermodynamic Processes Dissipating a Given Quantity of Energy

FIGURE 3 provides a stylized example of this chain of processes. Entering at left is a low-entropy fuel quantity (Q). Each process box transforms the available energy to work and entropy from left to right. By the end of the chain of processes, Q remains in quantity (by the first law of thermodynamics) but has changed in quality (by the second law). The arc within the box delineates the quantity of low-entropy Q (above) from the high-entropy Q (below). Each process brings the energy closer to equilibrium (the arc closer to the top).

Now consider what happens when the system evolves to lower flow resistance (greater efficiency). The solid arc moves to the dashed arc and at the end of the original frame of processes, some high-entropy Q remains. To be complete, the figure must now account for how the remaining Q is dissipated. In the example of a river system, the water flows farther. Similarly, FIGURE 3's system of processes expands. They can do so intensively (more of the same processes) or extensively (new processes). Each process has a thermodynamic limit to its transformation efficiency. By the relations between the flow-quantity rate of entropy generation and the flow rate, peaking efficiency implies peaking flow rates and a peaking time rate of entropy production. This means that, if the system is to continue to evolve toward greater time rates of entropy production (greater global flow access), it must eventually generate new, less flow-resistive processes that will reduce the aggregate resistance of the system (i.e. it must expand extensively).

Considering this stylized example in the context of an economy, we might take industries (groupings of similar processes) as represented by the process boxes above. As each industry becomes more efficient at producing its output, it attracts greater demand and greater flows of energy and materials through its process. When its efficiency reaches maturity, it can no longer rely on its own efficiency gains to induce additional flows through its process. The industry must now rely on new processes to improve the aggregate efficiency of the system of processes, which will induce greater flows through the industry as an intermediate process. In this way, efficiency improvements lead to system (economic) growth by eliciting greater flows and spreading the dissipation of those flows over a broader landscape of processes.

To summarize, systems survive by inducing exergy flows through their processes. Much like our simple thermodynamic process in FIGURE 1, a system of processes is situated along an entropy gradient; i.e., between high and low entropy reservoirs. The successful evolution of biological systems is driven by those systems' ability to provide low-resistance paths to equilibrium for the low-entropy reservoirs on the planet. As Lorente and Bejan (2010, p. 3) summarize in the human context:[6]

> The challenge is to channel most of this heat through our homes, power plants and enterprises before discharging it into the environment. The challenge is to place humans and enterprises in the right places on the landscape, as optimally positioned interceptors.

To induce greater flows, systems evolve toward lower flow resistances. The marginal flows induced by these improvements pressure expansion of the system, either intensively (more similar processes) or extensively (new, more efficient processes). In either expansion, the net effect of reducing entropy

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[6] It is worth noting again that, while I find Bejan and Lorente's Constructal Theory affirming of my argument for MxEP, Bejan does not support this characterization of Constructal Theory.

production with respect to the flow quantity is to increase the rate of entropy production with respect to time.

## Economics of Efficiency Improvements

### *Overview*

An economy's structure indicates what mix of energy processing activities take place within it. By analyzing this structure through time, we can see to what extent it evolves to optimize energy throughput and thereby grow. An industry or sector of the economy is a group of similar processes performed in the economy (as stylized in the process boxes of FIGURE 3). Production transforms labor, capital, energy, and material inputs into higher-value assembled outputs. As discussed above, following an efficiency improvement, intensive expansion increases flows through existing sectors, whereas extensive expansion increases flows to new sectors. Extensive expansion toward more efficient processes has been a clear trend in the histories of industrialized economies such as the United States. While process efficiencies have reduced the material wastes from older industries at diminishing rates, the new industries that have emerged have relied on markedly fewer material and energy inputs to produce a given unit of output (see FIGURE 8 and FIGURE 5) and have continued to increase total throughput (see FIGURE 9 and FIGURE 7) .

### *Mechanisms*

Although I explored in some detail the thermodynamic mechanisms by which efficiency improvements lead to greater system flows (and entropy production), it is also necessary to specify the economic mechanisms by which the use (flow) response to efficiency gains will manifest. Three types of mechanisms account for increased flow (use) rates following efficiency improvements: direct, indirect, and general equilibrium.

Before discussing the mechanisms, I first define the target in economic terms. Increased use (flow) following efficiency improvements is called a (positive) “rebound effect” in the economics literature. This term refers to the extent to which usage following an efficiency improvement differs from prior usage minus the efficiency savings. This marginal usage as a fraction of the savings is referred to as the rebound. For example, if a ten percent efficiency improvement leads only to a five percent decrease in consumption, the rebound is fifty percent. A rebound greater than one hundred percent indicates usage following the efficiency improvement is greater than it was before the improvement. This scenario is called efficiency “backfire.” Backfire is what I hypothesize should ultimately occur based on the thermodynamic theory outlined above; i.e., greater materials and energy efficiency reduces resistance to energy and materials flow through the economy thereby inducing greater flows.

The British economist William Jevons is credited with first identifying backfire with respect to UK coal consumption in 1865.[7] Jevons proposed the counter-intuitive result that improvements in coal efficiency would lead to increased coal consumption. The result earned the name “Jevons paradox” and has been much studied since. Subsequent work has expanded the debate to consider, empirically and theoretically, the channels through and extent to which the rebound effect occurs. As mentioned above, the rebound effect manifests through three types of mechanisms: direct, indirect, and general equilibrium.

Direct effects come from the classical economic income and substitution effects. Efficiency improvements effectively lower the price to gain marginal utility from consuming a given good. Following an efficiency improvement, a producer (or consumer) can do more work with one dollar’s worth of energy. This frees resources for additional production (income effect) and reduces the price of

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[7] Jevons is famous for a number of achievements in economics and logic. Perhaps most notable with respect to the former are his contributions to the theory of marginal utility amidst the so-called “marginal revolution” in economics during the mid-late 19th century.

energy relative to other goods, inducing the producer or consumer to use more of that good (substitution). FIGURE 4 illustrates the two effects in a production context.

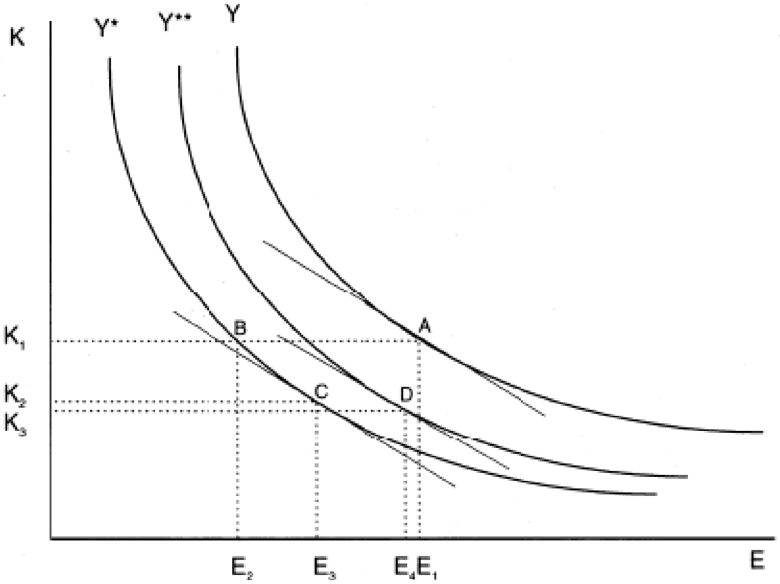

FIGURE 4: The Rebound Effect for a Producer[8]

The curves in FIGURE 4 are isoquants of production, or combinations of energy and capital (x and y axis) inputs that can be used to produce a given level of output. Following an energy efficiency improvement, the isoquant moves from Y to Y*. (We could just as well swap energy with materials and consider that case.) Y* represents the same total amount of output as Y. If the producer maintains its level of capital input at $K_1$ it will now be allocating its resources inefficiently. The optimal allocation is to move from point B to point C, where the slope of the isoquant equals the relative prices of the two inputs (slope of the budget line). By doing so, the producer is substituting away from capital toward higher energy use. This substitution effect is the first of our direct rebound effects. Next, provided market conditions permit, the producer can use the savings from reduced input to support expanded production to point D. This income effect is the second of our direct rebound effects and, as shown in the stylized example

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[8] Image from Berkhout, Muskens, and Velthuijsen 2000, p. 427, Figure 1,

above, it induces further energy inputs, though not to the point of backfire in this case. While this model is highly simplified, it provides a useful example for illustrating the income and substitution effects, which has direct analogs in the case of consumption. The magnitude of rebound ultimately depends on a variety of factors. For example, the efficiency improvement could change the shape of the producer's isoquant, or the producer might face a saturated market and not expand production. In either case, the new wealth created from the lower cost of doing business remains, and it is chiefly a matter of how that wealth is then put to work.

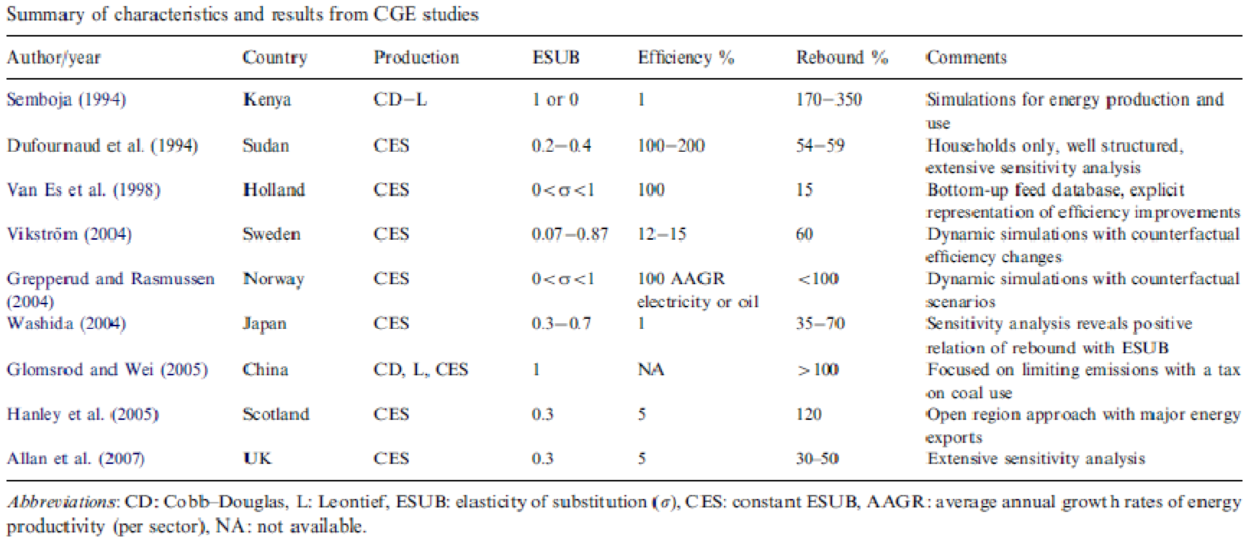
Sorrell (2009) outlines indirect effects of efficiency improvements in the case of energy. New equipment is often required to facilitate efficiency gains. Producing this equipment requires additional materials and energy. Persistent savings may be used for additional consumption of other goods, which embody energy and materials. Next, significant changes in market demand can generate reductions in energy and materials prices. Depending on consumption elasticities, these price changes may produce consumption rebounds. Price reductions can also shift the composition of consumption toward more energy and materials intensive goods.

### *Estimation Efforts*

Clearly, given all of the mechanisms through which gains from efficiency improvements are allocated, calculating the total rebound in a general equilibrium sense entails substantial complexity. However, in broad economic terms, the essential take-away is that new wealth is created by efficiency improvements and that wealth will be consumed or re-invested in the economy. The task of the researcher interested in the general equilibrium effect of efficiency improvements is to allocate that wealth throughout the economy, tracing the energy and materials impacts of that allocation. Finally, there is also a temporal dimension to rebound effects. While direct effects are likely to be realized in the near term, indirect effects take additional time to filter through the economy and induce system expansion. Understanding the nature and magnitude of these lags is an important aspect of quantifying changes in the use of energy and materials.

As a result of the complexity of the interaction of rebound effects, early empirical attempts to estimate rebound focused on direct effects (cf. Greening, Greene, and Difiglio 2000 for a helpful survey). Early theoretical work on economy-wide rebound effects was developed by Khazzoom (1980, 1987) and Brookes (1990). Extant literature has estimated a wide range of rebound effects, though most are significantly less than 100%. Most also focus primarily on direct effects, which is insufficient for our purposes. Some have attempted to model the overall rebound with computed general equilibrium methods. Here too, the evidence for backfire is limited. Dimitropoulos (2007) surveys this literature and finds that only a third of the studies he reviews predict backfire. This is a generally poor result for my hypothesis. Still, CGE models can exhibit high sensitivity to their inputs or initial conditions and without reviewing the literature myself, it is difficult to comment on the overall appropriateness for my purposes of the studies Dimitropoulos reviewed.

TABLE 1: Rebound Estimates from CGE Modeling (reprinted from Dimitropoulos 2007, Table 1)



Summary of characteristics and results from CGE studies

| Author/year | Country | Production | ESUB | Efficiency % | Rebound % | Comments |
|---|---|---|---|---|---|---|
| Semboja (1994) | Kenya | CD–L | 1 or 0 | 1 | 170–350 | Simulations for energy production and use |
| Dufournaud et al. (1994) | Sudan | CES | 0.2–0.4 | 100–200 | 54–59 | Households only, well structured, extensive sensitivity analysis |
| Van Es et al. (1998) | Holland | CES | $0<\sigma<1$ | 100 | 15 | Bottom-up feed database, explicit representation of efficiency improvements |
| Vikström (2004) | Sweden | CES | 0.07–0.87 | 12–15 | 60 | Dynamic simulations with counterfactual efficiency changes |
| Grepperud and Rasmussen (2004) | Norway | CES | $0<\sigma<1$ | 100 AAGR electricity or oil | <100 | Dynamic simulations with counterfactual scenarios |
| Washida (2004) | Japan | CES | 0.3–0.7 | 1 | 35–70 | Sensitivity analysis reveals positive relation of rebound with ESUB |
| Glomsrod and Wei (2005) | China | CD, L, CES | 1 | NA | >100 | Focused on limiting emissions with a tax on coal use |
| Hanley et al. (2005) | Scotland | CES | 0.3 | 5 | 120 | Open region approach with major energy exports |
| Allan et al. (2007) | UK | CES | 0.3 | 5 | 30–50 | Extensive sensitivity analysis |

*Abbreviations*: CD: Cobb–Douglas, L: Leontief, ESUB: elasticity of substitution ($\sigma$), CES: constant ESUB, AAGR: average annual growth rates of energy productivity (per sector), NA: not available.

### *Research Needs*

Relatively little attention has been paid to developing robust methods for tracing the gains from efficiency improvements through the economy in a general equilibrium sense. Additionally, measuring genuine efficiency improvements is a rather difficult task. For the case of the US economy (below), I proxy for efficiency improvements by measuring materials and energy intensities, but this represents a mix of effects. Substantial work has been done by David Popp (cf. Popp 2001) to associate energy technology patents with efficiency gains, but this is not an entirely perfect measure either as it is not able to explicitly scale the impact of new energy technologies qualitatively or quantitatively.

## The Case of the US Economic Production

### *Overview*

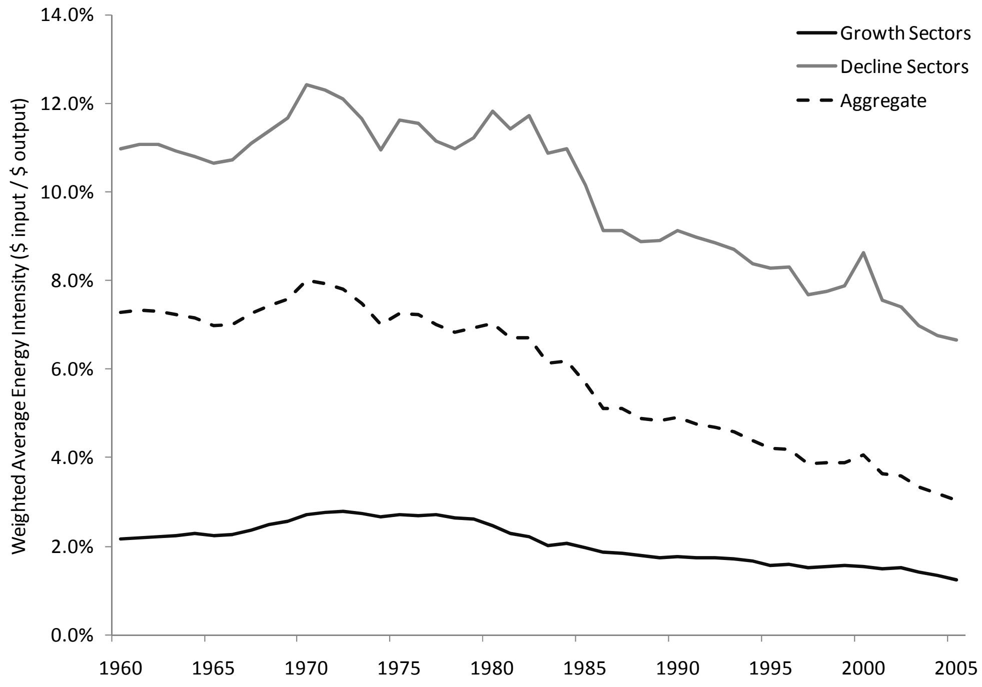
Here I present some suggestive trends in the evolution of US materials and energy use in production over the 45 year period 1960-2005. In broad terms, both the energy and materials intensity of production has declined for the economy as a whole while use has increased substantially. None of the following trends support a causal argument for my backfire hypothesis. Rather, the consistency of these trends with backfire indicate merely that the hypothesis is worth further examination. The trends presented below are derived from sectoral estimates by Dale Jorgenson (Jorgenson 2007). Jorgenson's "KLEM" data set provides a summary of the capital (K), labor (L), energy (E), and materials (M) prices and inputs of the US economy over a group of thirty-five industrial classifications.

Throughout, I present trends for the economy as a whole, the growth sectors of the economy, and the decline sectors. Growth sectors are those industries that have increased their share of economic output over the period and decline sectors are those industries whose output shares have declined. The purpose of this disaggregation is to assess whether there exists preliminary support for my arguments with respect to intensive and extensive expansion. Specifically, I argue that as old industries reach maturity with respect to their ability to make efficiency improvements to their processes, new, more efficient processes must emerge (extensive expansion). These processes enable the expansion of the economic system by reducing aggregate flow resistance. Thus, we should expect new industries to be less energy and materials intensive than old industries. While the industries in the data are constant, we can proxy for new industries by growth according to the standard economic treatment of industrial life cycles. Let's now turn to the data to examine whether the supposed implications of the thermodynamic theory can coexist with the empirical reality of the economy.

### *Economic Trends*

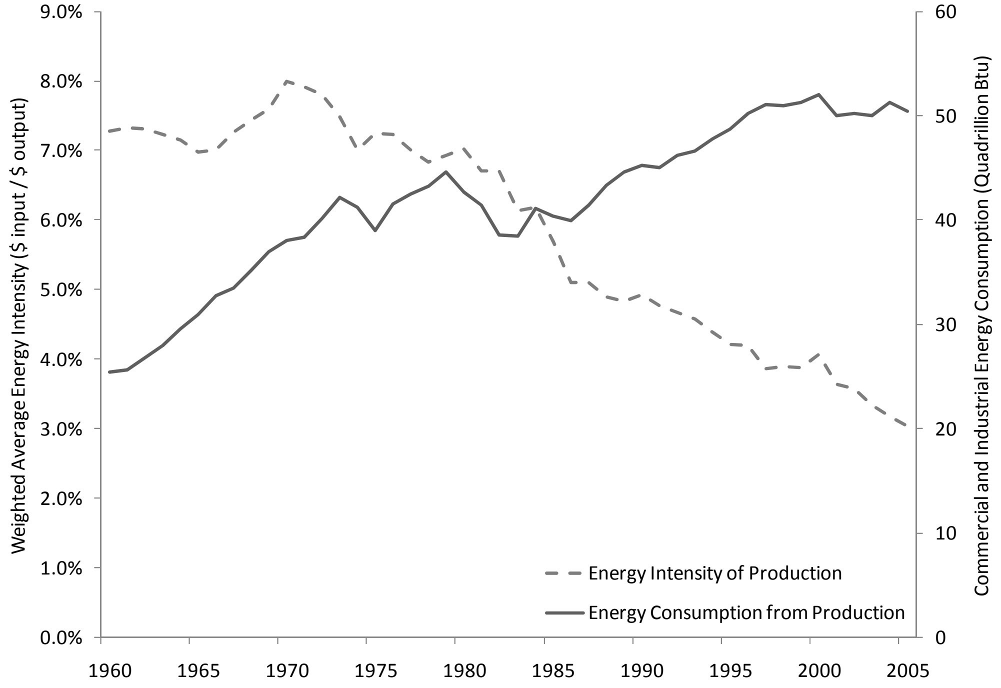
Over the past forty years, energy input as a share of US economy has consistently declined. FIGURE 5 shows a near-linear decline in the energy intensity of the aggregate economy. It also demonstrates marked differences in the intensities of growth and decline sectors. As discussed above, I expect that low-resistance processes to be added on the extensive margin (as new sectors). FIGURE 5 provides a picture consistent with this expectation. Growth sectors are dramatically less energy intensive than decline sectors. Decline sectors have continued to reduce their energy intensity over the period. Next, I juxtapose this decline in energy intensity (flow resistance) with energy consumption (dissipation rate) to assess whether an inverse relation is worth further inquiry.

FIGURE 6 reveals a pattern consistent with the hypothesis that reduced flow resistances in the economy contribute to greater flow quantity throughput and higher rates of exergy dissipation. TABLE 2 provides a detailed summary of the trends in energy intensity and throughput by industry at the start, midpoint and end of the period. FIGURE 7 summarizes the aggregate trends in energy consumption by production sector. Here we see that greater energy flows through growth sectors do not appear to have come at the expense of decline sectors, which have continued to increase their throughput.



Source: Jorgenson (2007), "35 Sector KLEM."

FIGURE 5: Energy Intensity in US Production, 1960–2005



Sources: Jorgenson (2007), "35 Sector KLEM," EIA Annual Energy Outlook.

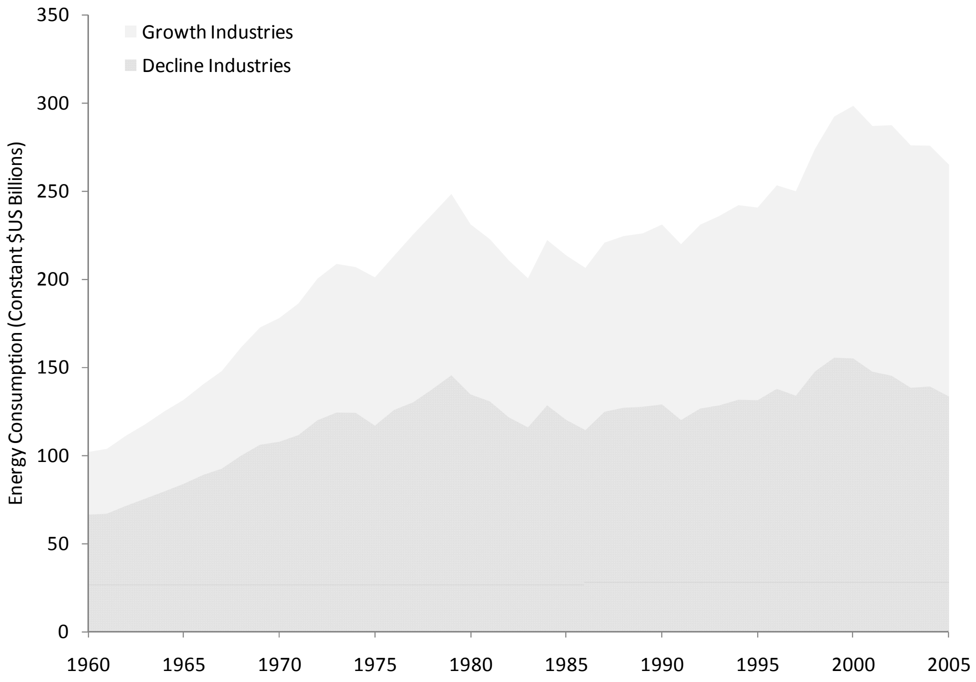
FIGURE 6: Energy Intensity and Consumption in US Production

## TABLE 2: Energy Throughput and Intensity by Industry

Energy Throughput and Intensity with Share of GDP by Industry: 1960, 1980, 2005

| Industry | | Energy Throughput ($ Billion) | | | | Energy Intensity of Output | | | | Output Share | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Description | 1960 | 1980 | 2005 | % Change | 1960 | 1980 | 2005 | % Change | 1960 | 1980 | 2005 | % Change |
| 1. | Electrical machinery | 1.3 | 3.5 | 2.9 | 117.9% | 4.5% | 3.7% | 0.5% | -88.3% | 0.8% | 1.3% | 3.5% | 362.5% |
| 2. | Non-electrical machinery | 1.5 | 4.5 | 3.4 | 124.4% | 3.4% | 3.2% | 0.5% | -84.4% | 1.1% | 1.9% | 4.1% | 255.7% |
| 3. | Communications | 0.7 | 1.8 | 2.5 | 280.9% | 1.6% | 0.9% | 0.5% | -70.0% | 1.1% | 2.5% | 3.3% | 215.1% |
| 4. | Instruments | 0.5 | 1.5 | 1.3 | 165.2% | 1.8% | 1.6% | 0.7% | -62.0% | 0.7% | 1.2% | 1.3% | 73.3% |
| 5. | Rubber and plastic products | 1.0 | 2.8 | 3.1 | 196.8% | 4.2% | 4.1% | 1.9% | -55.4% | 0.6% | 0.9% | 1.0% | 65.1% |
| 6. | Finance, insurance and real estate | 3.4 | 11.1 | 23.1 | 576.1% | 1.0% | 1.3% | 1.0% | 2.5% | 8.6% | 11.2% | 14.2% | 63.7% |
| 7. | Personal and business services | 10.0 | 27.0 | 43.5 | 333.2% | 1.7% | 2.0% | 1.2% | -26.1% | 15.2% | 17.3% | 22.2% | 45.4% |
| 8. | Wholesale and retail trade | 15.5 | 40.9 | 47.9 | 209.5% | 3.8% | 4.4% | 2.2% | -42.1% | 10.5% | 12.2% | 13.9% | 32.5% |
| 9. | Furniture and fixtures | 0.3 | 0.8 | 1.1 | 219.8% | 1.6% | 2.0% | 1.2% | -26.5% | 0.5% | 0.5% | 0.6% | 8.0% |
| 10. | Motor vehicles | 1.2 | 2.2 | 2.4 | 102.0% | 1.1% | 1.4% | 0.5% | -52.5% | 2.7% | 2.1% | 2.8% | 5.4% |
| 11. | Transportation and warehousing | 11.6 | 28.0 | 37.9 | 227.8% | 7.8% | 9.4% | 6.6% | -15.5% | 3.8% | 3.9% | 3.6% | -3.7% |
| 12. | Electric utilities (services) | 19.0 | 37.5 | 35.0 | 84.3% | 24.5% | 18.2% | 12.1% | -50.8% | 2.0% | 2.7% | 1.8% | -7.1% |
| 13. | Chemicals and allied products | 8.2 | 18.5 | 14.8 | 79.9% | 7.3% | 7.0% | 3.7% | -49.1% | 2.9% | 3.5% | 2.5% | -12.3% |
| 14. | Government enterprises | 3.4 | 8.9 | 14.0 | 310.6% | 4.0% | 4.8% | 5.5% | 38.1% | 2.2% | 2.4% | 1.6% | -26.3% |
| 15. | Coal mining | 1.3 | 3.8 | 2.4 | 78.3% | 13.7% | 19.8% | 9.0% | -34.2% | 0.2% | 0.3% | 0.2% | -32.8% |
| 16. | Miscellaneous manufacturing | 0.4 | 0.8 | 0.6 | 70.3% | 1.7% | 2.2% | 1.1% | -36.1% | 0.5% | 0.5% | 0.4% | -33.9% |
| 17. | Paper and allied products | 3.2 | 7.0 | 4.6 | 46.6% | 5.2% | 5.8% | 3.1% | -41.5% | 1.5% | 1.6% | 1.0% | -37.9% |
| 18. | Lumber and wood products | 1.1 | 2.6 | 2.1 | 96.1% | 2.4% | 3.1% | 1.9% | -21.3% | 1.1% | 1.1% | 0.7% | -38.2% |
| 19. | Food and kindred products | 3.7 | 7.2 | 6.3 | 70.8% | 1.7% | 2.1% | 1.2% | -30.8% | 5.4% | 4.5% | 3.3% | -38.7% |
| 20. | Agriculture, forestry, fisheries | 5.2 | 10.2 | 9.1 | 74.7% | 3.4% | 4.9% | 2.4% | -29.1% | 3.9% | 2.7% | 2.4% | -38.9% |
| 21. | Fabricated metal products | 2.2 | 4.4 | 4.1 | 85.7% | 2.2% | 2.6% | 1.7% | -22.5% | 2.6% | 2.2% | 1.5% | -40.5% |
| 22. | Other transportation equipment | 0.8 | 1.7 | 1.8 | 115.7% | 0.9% | 1.2% | 0.9% | -8.5% | 2.2% | 2.0% | 1.3% | -41.5% |
| 23. | Stone, clay and glass products | 3.3 | 5.8 | 4.7 | 41.6% | 7.5% | 8.6% | 4.5% | -39.8% | 1.1% | 0.9% | 0.7% | -41.7% |
| 24. | Printing and publishing | 0.7 | 1.7 | 1.6 | 115.4% | 0.9% | 1.2% | 0.8% | -5.5% | 2.1% | 1.9% | 1.2% | -43.5% |
| 25. | Petroleum refining | 75.3 | 154.9 | 140.4 | 86.3% | 85.0% | 90.2% | 76.1% | -10.5% | 2.3% | 2.2% | 1.2% | -48.4% |
| 26. | Construction | 7.9 | 10.9 | 15.7 | 98.7% | 1.6% | 1.8% | 1.6% | -3.2% | 12.3% | 8.0% | 6.3% | -49.1% |
| 27. | Non-metallic mineral mining | 1.0 | 2.1 | 1.5 | 46.1% | 10.7% | 14.8% | 7.7% | -27.7% | 0.3% | 0.2% | 0.1% | -49.9% |
| 28. | Textile mill products | 1.6 | 2.8 | 1.3 | -22.9% | 4.6% | 4.4% | 2.1% | -54.4% | 0.9% | 0.8% | 0.4% | -58.0% |
| 29. | Primary metals | 9.0 | 15.7 | 9.0 | -0.7% | 6.7% | 8.7% | 4.5% | -32.1% | 3.5% | 2.4% | 1.3% | -63.7% |
| 30. | Metal mining | 0.7 | 0.9 | 1.4 | 96.8% | 8.9% | 10.7% | 12.9% | 45.3% | 0.2% | 0.1% | 0.1% | -66.4% |
| 31. | Crude oil and gas extraction | 49.3 | 49.6 | 15.2 | -69.1% | 38.7% | 26.7% | 10.0% | -74.3% | 3.3% | 2.4% | 1.0% | -70.2% |
| 32. | Apparel and other textile products | 0.8 | 1.1 | 0.3 | -56.8% | 1.9% | 1.7% | 0.9% | -50.9% | 1.0% | 0.8% | 0.2% | -78.2% |
| 33. | Gas utilities (services) | 38.8 | 66.0 | 23.5 | -39.3% | 67.0% | 60.1% | 49.8% | -25.7% | 1.5% | 1.4% | 0.3% | -79.7% |
| 34. | Tobacco manufactures | 0.1 | 0.1 | 0.1 | 11.2% | 0.4% | 0.5% | 0.6% | 61.8% | 0.7% | 0.4% | 0.1% | -83.0% |
| 35. | Leather and leather products | 0.3 | 0.4 | 0.1 | -61.5% | 1.6% | 2.5% | 1.7% | 11.3% | 0.4% | 0.2% | 0.0% | -91.4% |
| Output-Weighted Mean: | *Overall* | 118.3 | 211.5 | 132.1 | 165.7% | 7.3% | 7.0% | 3.0% | -25.5% | N/A | | | |
| | *Growth* | 2.0 | 5.7 | 6.9 | 2.0 | 3.1% | 2.7% | 0.7% | -70.7% | | | | |
| | *Decline* | 10.8 | 17.7 | 11.7 | 0.3 | 13.8% | 13.7% | 9.9% | -16.6% | | | | |
| Mean: | *Overall* | 8.1 | 15.4 | 13.7 | 111.8% | 9.6% | 9.6% | 6.6% | -28.9% | 2.9% | 2.9% | 2.9% | -1.4% |
| | *Growth* | 3.5 | 9.6 | 13.1 | 2.3 | 2.5% | 2.5% | 1.0% | -50.5% | 4.2% | 5.1% | 6.7% | 112.7% |
| | *Decline* | 10.0 | 17.7 | 13.9 | 0.6 | 12.4% | 12.5% | 8.9% | -20.3% | 2.3% | 2.0% | 1.3% | -47.0% |
| Median: | *Overall* | 1.6 | 4.4 | 3.4 | 86.3% | 3.4% | 3.7% | 1.9% | -30.8% | 1.5% | 1.9% | 1.3% | -38.2% |
| | *Growth* | 1.3 | 3.2 | 3.0 | 2.0 | 1.7% | 2.0% | 0.9% | -53.9% | 1.1% | 2.0% | 3.4% | 64.4% |
| | *Decline* | 3.2 | 5.8 | 4.6 | 0.7 | 4.6% | 4.9% | 3.1% | -27.7% | 2.0% | 1.9% | 1.0% | -41.7% |
| 25th Percentile: | | 0.8 | 1.8 | 1.6 | 46.3% | 1.7% | 1.9% | 1.0% | -50.8% | 0.7% | 0.8% | 0.5% | -49.5% |
| 75th Percentile: | | 8.1 | 13.4 | 15.0 | 144.8% | 7.4% | 8.6% | 5.0% | -13.0% | 3.1% | 2.6% | 3.1% | 6.7% |

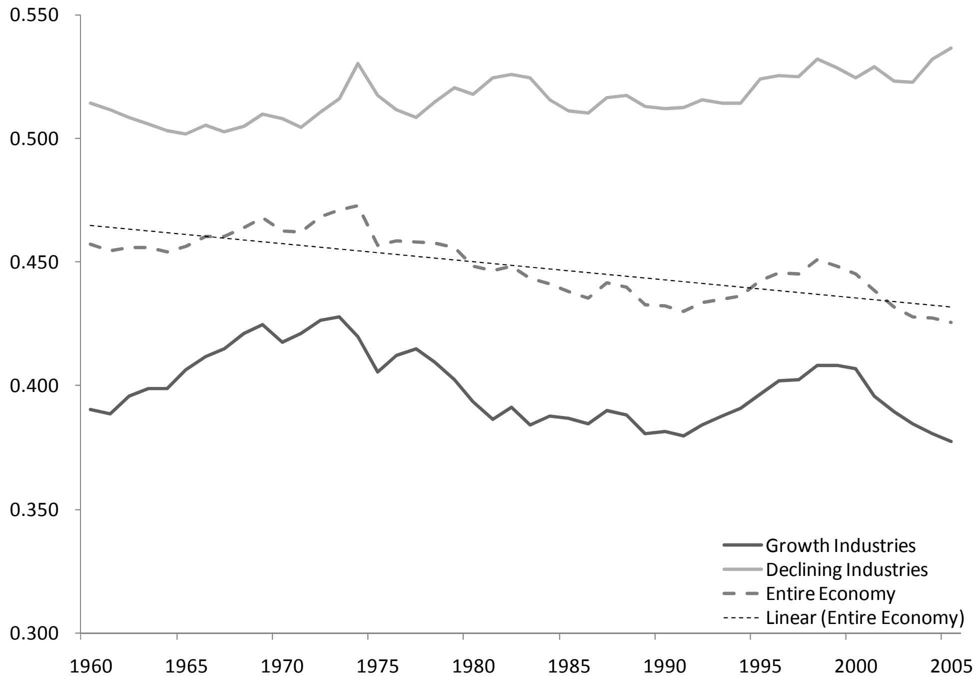
Source: Jorgenson (2007), "35 Sector KLEM."



Source: Jorgenson (2007), "35 Sector KLEM."

FIGURE 7: Energy Throughput of US Production

Trends for materials intensity are less dramatic than for energy. As is evident in FIGURE 8, materials intensity has declined slightly over the 45 years ending in 2005. Consistent with the relations for energy, growth sectors are dramatically less materials intensive than decline sectors, which exhibit a slight positive trend in intensity. Aggregate materials use shows a considerable increase over the period, particularly for growth sectors, which exhibit an inflection point in the 1990s (FIGURE 9). The rise in aggregate materials usage for growth sectors does not appear to have “cannibalized” the aggregate materials use of decline sectors, which has continued to increase at a relatively slow, but steady rate. TABLE 3 provides a detailed summary of the trends by industry at the start, midpoint and end of the period.



Source: Jorgenson (2007), "35 Sector KLEM."

FIGURE 8: Materials Intensity of US Production, 1960-2005

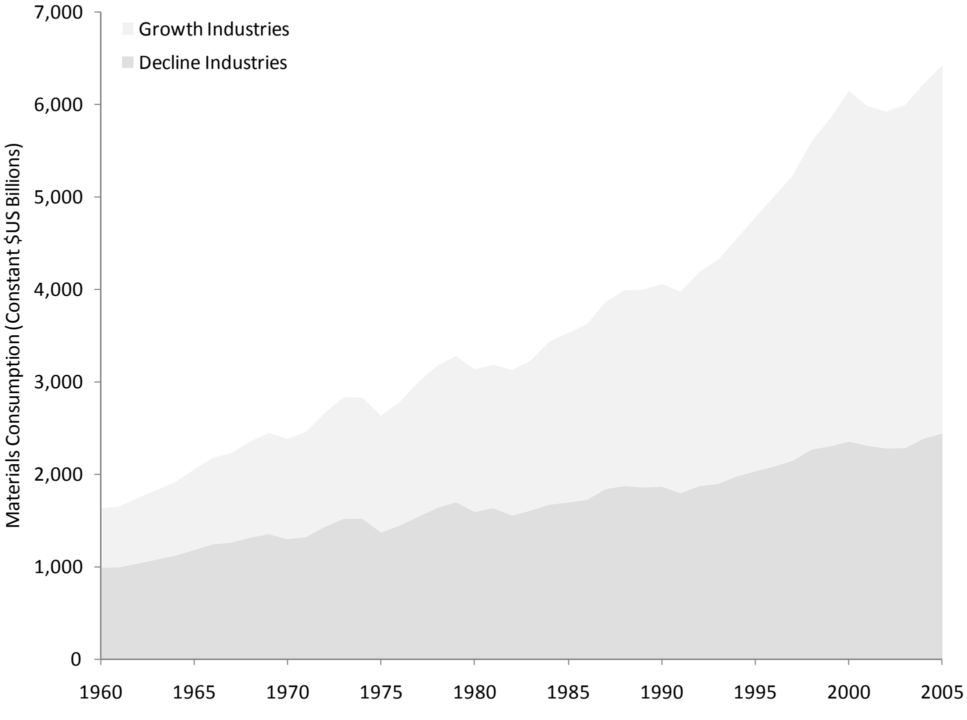


FIGURE 9: Materials Throughput of US Production, 1960-2005

## TABLE 3: Materials Throughput and Intensity by Industry

Materials Throughput and Intensity with Share of GDP by Industry: 1960, 1980, 2005

| Industry | | Materials Throughput ($ Billion) | | | | Materials Intensity of Output | | | | Output Share | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Description | 1960 | 1980 | 2005 | % Change | 1960 | 1980 | 2005 | % Change | 1960 | 1980 | 2005 | % Change |
| 1. | Electrical machinery | 35.1 | 75.4 | 181.6 | 417.2% | 119.4% | 78.5% | 33.1% | -72.3% | 0.8% | 1.3% | 3.5% | 362.5% |
| 2. | Non-electrical machinery | 37.6 | 100.2 | 269.0 | 615.0% | 84.3% | 70.2% | 42.1% | -50.1% | 1.1% | 1.9% | 4.1% | 255.7% |
| 3. | Communications | 18.9 | 85.7 | 213.6 | 1029.0% | 45.8% | 44.8% | 40.7% | -11.1% | 1.1% | 2.5% | 3.3% | 215.1% |
| 4. | Instruments | 13.3 | 34.7 | 85.8 | 545.0% | 46.8% | 36.7% | 43.2% | -7.7% | 0.7% | 1.2% | 1.3% | 73.3% |
| 5. | Rubber and plastic products | 17.1 | 40.8 | 81.0 | 373.9% | 68.9% | 60.6% | 49.0% | -28.8% | 0.6% | 0.9% | 1.0% | 65.1% |
| 6. | Finance, insurance and real estate | 104.2 | 269.4 | 754.9 | 624.1% | 30.8% | 31.3% | 33.8% | 9.7% | 8.6% | 11.2% | 14.2% | 63.7% |
| 7. | Personal and business services | 168.3 | 426.4 | 1,255.8 | 646.3% | 28.2% | 32.1% | 35.9% | 27.3% | 15.2% | 17.3% | 22.2% | 45.4% |
| 8. | Wholesale and retail trade | 162.1 | 380.3 | 757.9 | 367.5% | 39.4% | 40.7% | 34.5% | -12.5% | 10.5% | 12.2% | 13.9% | 32.5% |
| 9. | Furniture and fixtures | 11.3 | 19.4 | 45.9 | 306.7% | 55.0% | 49.2% | 51.4% | -6.6% | 0.5% | 0.5% | 0.6% | 8.0% |
| 10. | Motor vehicles | 72.6 | 109.6 | 332.3 | 357.9% | 68.6% | 67.1% | 74.0% | 7.8% | 2.7% | 2.1% | 2.8% | 5.4% |
| 11. | Transportation and warehousing | 62.0 | 121.3 | 229.3 | 269.9% | 42.0% | 40.8% | 40.0% | -4.7% | 3.8% | 3.9% | 3.6% | -3.7% |
| 12. | Electric utilities (services) | 12.8 | 34.0 | 66.5 | 417.8% | 16.6% | 16.5% | 22.9% | 38.2% | 2.0% | 2.7% | 1.8% | -7.1% |
| 13. | Chemicals and allied products | 63.3 | 137.6 | 209.8 | 231.3% | 55.8% | 51.8% | 52.3% | -6.3% | 2.9% | 3.5% | 2.5% | -12.3% |
| 14. | Government enterprises | 19.2 | 30.2 | 69.8 | 263.5% | 22.4% | 16.5% | 27.4% | 22.3% | 2.2% | 2.4% | 1.6% | -26.3% |
| 15. | Coal mining | 1.9 | 6.4 | 8.1 | 328.3% | 19.5% | 33.3% | 30.8% | 58.1% | 0.2% | 0.3% | 0.2% | -32.8% |
| 16. | Miscellaneous manufacturing | 12.7 | 20.3 | 29.1 | 129.0% | 59.5% | 58.7% | 51.2% | -14.1% | 0.5% | 0.5% | 0.4% | -33.9% |
| 17. | Paper and allied products | 34.0 | 67.8 | 75.9 | 123.4% | 56.4% | 56.6% | 50.3% | -10.8% | 1.5% | 1.6% | 1.0% | -37.9% |
| 18. | Lumber and wood products | 24.3 | 52.0 | 67.0 | 175.2% | 54.3% | 62.1% | 60.0% | 10.4% | 1.1% | 1.1% | 0.7% | -38.2% |
| 19. | Food and kindred products | 166.4 | 245.7 | 336.9 | 102.5% | 78.4% | 72.0% | 64.3% | -18.0% | 5.4% | 4.5% | 3.3% | -38.7% |
| 20. | Agriculture, forestry, fisheries | 105.6 | 157.7 | 189.9 | 79.9% | 68.8% | 75.5% | 50.2% | -27.0% | 3.9% | 2.7% | 2.4% | -38.9% |
| 21. | Fabricated metal products | 53.6 | 87.8 | 130.9 | 144.1% | 52.8% | 51.7% | 53.8% | 1.8% | 2.6% | 2.2% | 1.5% | -40.5% |
| 22. | Other transportation equipment | 37.5 | 63.9 | 104.1 | 177.8% | 43.2% | 42.6% | 50.9% | 17.8% | 2.2% | 2.0% | 1.3% | -41.5% |
| 23. | Stone, clay and glass products | 20.9 | 31.5 | 48.8 | 133.7% | 46.6% | 46.7% | 46.3% | -0.7% | 1.1% | 0.9% | 0.7% | -41.7% |
| 24. | Printing and publishing | 32.4 | 54.8 | 71.4 | 120.5% | 39.0% | 38.2% | 37.7% | -3.3% | 2.1% | 1.9% | 1.2% | -43.5% |
| 25. | Petroleum refining | 17.4 | 51.8 | 75.1 | 330.6% | 19.7% | 30.2% | 40.7% | 106.9% | 2.3% | 2.2% | 1.2% | -48.4% |
| 26. | Construction | 181.7 | 292.3 | 657.1 | 261.6% | 37.8% | 47.6% | 66.6% | 76.2% | 12.3% | 8.0% | 6.3% | -49.1% |
| 27. | Non-metallic mineral mining | 3.1 | 3.7 | 7.8 | 150.8% | 31.6% | 26.3% | 39.2% | 24.1% | 0.3% | 0.2% | 0.1% | -49.9% |
| 28. | Textile mill products | 32.9 | 44.1 | 31.4 | -4.6% | 93.7% | 70.3% | 52.8% | -43.6% | 0.9% | 0.8% | 0.4% | -58.0% |
| 29. | Primary metals | 82.4 | 115.9 | 130.9 | 58.9% | 60.6% | 63.8% | 65.9% | 8.7% | 3.5% | 2.4% | 1.3% | -63.7% |
| 30. | Metal mining | 3.3 | 2.8 | 9.5 | 186.3% | 40.4% | 33.5% | 85.4% | 111.4% | 0.2% | 0.1% | 0.1% | -66.4% |
| 31. | Crude oil and gas extraction | 8.4 | 34.4 | 75.0 | 788.1% | 6.6% | 18.5% | 49.1% | 640.3% | 3.3% | 2.4% | 1.0% | -70.2% |
| 32. | Apparel and other textile products | 28.9 | 36.4 | 18.6 | -35.5% | 70.7% | 58.6% | 51.8% | -26.7% | 1.0% | 0.8% | 0.2% | -78.2% |
| 33. | Gas utilities (services) | 1.9 | 7.2 | 11.6 | 525.6% | 3.2% | 6.6% | 24.5% | 665.6% | 1.5% | 1.4% | 0.3% | -79.7% |
| 34. | Tobacco manufactures | 11.0 | 10.9 | 14.9 | 35.1% | 39.5% | 36.8% | 77.7% | 96.6% | 0.7% | 0.4% | 0.1% | -83.0% |
| 35. | Leather and leather products | 9.6 | 8.2 | 3.4 | -64.4% | 57.4% | 53.8% | 59.1% | 2.9% | 0.4% | 0.2% | 0.0% | -91.4% |
| Output-Weighted Mean: | *Overall* | 864.2 | 1,582.7 | 3,035.8 | 4347.3% | 42.6% | 42.5% | 42.2% | 44.7% | N/A | | | |
| | *Growth* | 43.1 | 112.0 | 287.6 | 6.0 | 78.1% | 60.5% | 38.7% | -37.6% | | | | |
| | *Decline* | 36.6 | 58.6 | 88.4 | 1.8 | 45.0% | 44.2% | 53.1% | 102.8% | | | | |
| Mean: | *Overall* | 47.7 | 93.2 | 190.0 | 291.8% | 48.7% | 46.3% | 48.2% | 45.2% | 2.9% | 2.9% | 2.9% | -1.4% |
| | *Growth* | 64.1 | 154.2 | 397.8 | 5.3 | 58.7% | 51.1% | 43.8% | -14.4% | 4.2% | 5.1% | 6.7% | 112.7% |
| | *Decline* | 41.1 | 68.8 | 106.9 | 2.0 | 44.7% | 44.4% | 50.0% | 69.0% | 2.3% | 2.0% | 1.3% | -47.0% |
| Median: | *Overall* | 28.9 | 52.0 | 75.9 | 261.6% | 46.6% | 46.7% | 49.1% | 1.8% | 1.5% | 1.9% | 1.3% | -38.2% |
| | *Growth* | 36.4 | 93.0 | 241.3 | 4.8 | 50.9% | 47.0% | 41.4% | -9.4% | 1.1% | 2.0% | 3.4% | 64.4% |
| | *Decline* | 24.3 | 44.1 | 69.8 | 1.5 | 43.2% | 46.7% | 50.9% | 8.7% | 2.0% | 1.9% | 1.0% | -41.7% |
| 25th Percentile: | | 12.8 | 30.9 | 38.7 | 126.2% | 34.7% | 33.4% | 38.5% | -11.8% | 0.7% | 0.8% | 0.5% | -49.5% |
| 75th Percentile: | | 62.7 | 112.8 | 211.7 | 395.6% | 60.1% | 59.7% | 53.3% | 25.7% | 3.1% | 2.6% | 3.1% | 6.7% |

Source: Jorgenson (2007), "35 Sector KLEM."

*Summary*

Trends in the materials and energy use of US production are broadly consistent with the hypotheses generated from the thermodynamic theory developed early in the paper. In aggregate, the economy is evolving toward greater energy and material efficiencies, indicating lower flow resistances. Concomitant with this trend, energy and materials flows through the economy have increased markedly. The new processes that have emerged on the extensive margin are dramatically less energy and materials intensive than process in relative decline, and have helped to reduce the aggregate energy and materials intensity of the economy (cf. Sue Wing 2008). As expected, greater efficiency (lower flow resistance) has not prevented these sectors from facilitating substantial shares of energy and materials flows, rather it has increased their capacity to do so.

Though the patterns are consistent with the expectations of the thermodynamic theory I developed early in the paper, they are by no means supportive of causal claims. As mentioned above in the discussion of general equilibrium effects, causal arguments at this degree of complexity are exceptionally difficult to specify and are well beyond the scope of this work. The primary purpose of examining the case of US production has been to indicate whether predictions from thermodynamic theory bear any resemblance to the empirical reality of economic phenomena. By this modest measure, the theory has achieved some success.

## IV. POLICY IMPLICATIONS

Energy efficiency is often considered a critical climate policy tool for reducing greenhouse gas emissions. The presumption of such policy is that energy efficiency gains offer long-term reductions in energy consumption on which we can rely to reduce carbon emissions. The results of this work suggest that reliance on efficiency will produce illusory gains. At very least, energy efficiency seems to confer a rapidly depreciating carbon mitigation asset. Better understanding the lags in efficiency rebounds can give some indication as to how rapid that depreciation is.

Regardless of the duration of the short-term carbon mitigation gains, efficiency improvements generate a long-term carbon liability if the carbon profile of sources remain fixed. This implies that the carbon intensity of our energy sources must be the primary policy target for climate policy. Efficiency improvements with long-lag rebounds are valuable to the extent that they defer consumption to a source base with lower carbon intensity, but it must be appreciated that the carbon intensity improvements must also compensate for the increased energy demand they will generate.

As Dimitropoulos (2007) summarizes, “energy efficiency policies ought to be considered as short-term policy instruments that cannot, in any case, substitute for long-term policies that promote carbon-free or carbon-neutral energy sources” (p. 6361). Moreover, while it may carry less policy allure, similar dynamics hold for materials. Here we are indirectly concerned with carbon, and the impact of additional pollutants from increased materials use must also be factored when examining efficiency gains.

## V. CONCLUSION

In this work I have attempted to leverage physical principles to predict the evolution of biological and technological phenomena. The approach comes from embracing the embeddedness of human phenomena in the physical world to posit that, with sufficient objectivity, we ought to be able to discern continuities in the behavior of physical, biological and technological processes on Earth.

Several interesting results emerge from this approach. First, the combination of the extant literature and the specialized example of river flow considered herein indicate that there is substantial support for employing entropy maximization as a modeling principle in a remarkably wide cast of settings. Second, the strong linkage between entropy minimization and maximization principles sheds valuable light on the relationship between efficiency and growth in physical, biological, and technological systems. The case of the US economy reveals little inconsistency with the hypotheses that follow from the thermodynamic theory I develop in the first half of the paper. This has potential to offer new perspective on theories of economic progress and growth. It also poses a challenging dilemma in coping with how our geophysical constraints bind our economic prospects. Somewhat dismally, the results of this work imply that there are fewer prospects for win-win climate and economic outcomes than we may have previously hoped.

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