ANALYSIS

Energy, diversity and development in economic systems; an empirical analysis

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Abstract

As economic systems develop over time they tend to become more complex with more structure and greater throughputs, assuming favorable conditions. Energy use increases as more economic sectors develop and more channels for flow are opened. Economic diversity, as measured by the number of economic sectors using energy and the equatability of flows between them, generally increases. As diversity increases the efficiency of generating outputs with a given amount of energy also increases. Development capacity, the product of system energy throughput and diversity of flows, is a measure of the potential system output and is calculated for selected countries. Capacity changes over time are shown to relate to changes in economic output in selected countries. Two distinct development strategies become evident, one which promotes energy use and one which emphasizes diversity. While most countries utilize a mix of the two, developing countries generally rely more on increasing energy use to increase output while developed countries tend to become more diverse as a means of increasing outputs. Sustainability is enhanced by strategies which promote diversity and resource use efficiency in economic systems. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Economic development is an evolutionary process that results in changes over time as economic systems self-organize in response to energy flows and information feedback (Norgaard, 1992; Gowdy, 1994, p. 127). Economies are open thermodynamic systems which extract low entropy materials and energy from the environment to create goods and high entropy wastes. Wastes, including spent products, ultimately leave the economic system and are discharged to the environment. Kauffman (1995) characterizes such systems which are far from equilibrium as on “...the edge of chaos” (p. 26) where order is at an optimum to
facilitate change through self-organization without being unstable, i.e. such systems are between inflexible order and unpredictable chaos. A portion of energy throughput builds structure thereby increasing complexity and reducing uncertainty (Muller, 1998). This behavior resembles the dissipative structures of Prigogine (1980) which consume energy while increasing complexity and decreasing uncertainty within systems. These changes can also be represented as increasing Shannon–Weaver (Shannon and Weaver, 1949) diversity (Templet, 1996a, 1998a).

Economic evolution continues over time as more system diversity leads to increased efficiency and less entropy generated at the margin, and so on as the energy flow-diversity building cycle continues. This may be an example of systems behavior characterized by von Bertalanffy (1968) as “...directedness based upon structure...”. Kauffman (1995, p. 25) characterizes the changes as “Order, vast and generative, arises naturally”. The greater the evolved diversity within a system the greater the number and types of energy uses, the more equitable the distribution between compartments and the smaller the energy flow gradients between compartments (Muller, 1998). To put it another way, as energy cascades through the compartments of the system it generates less entropy at the margin (specific entropy) if there are many compartments with only small gradients between them. Reducing marginal entropy is a system requirement for ecological evolution (Binswanger, 1993) and probably for economic evolution. This organizational strategy is also incorporated into industrial ecology (Tibbs, 1993; Andrews et al., 1994; Froshc, 1994) and used by ecosystems during development (i.e. succession and evolution) and results in more system diversity, structure and information (Odum, 1969).

Assuming isomorphism across system types (von Bertalanffy, 1968, p. 33; von Bertalanffy, 1975, p. 121), economic system diversity is also expected to generally increase during development. Having built new structure with a portion of past energy flow, an economic system becomes more diverse in structure and efficient in generating future outputs (Muller, 1998; Templet, 1998a). Productivity is expected to rise and the energy intensity of system production, i.e. the amount of energy necessary to generate a dollar of GNP, rises rapidly in early development, peaks and then declines as GNP/capita increases (Goldemberg, 1996; Templet, 1996a). Diversity is important because it relates to improvements in efficiency, productivity and output (Ulanowicz, 1986). A measure of diversity is useful because it gives us a means of tracking economic evolution and progress toward sustainability.

In an earlier paper (Templet, 1996a), I presented an empirical means of estimating diversity in economic systems using broad economic sectors as energy nodes (analogous to species in ecological systems) in the Shannon–Weaver (Shannon and Weaver, 1949) equation. The relationship of diversity (H) to GNP per capita was found to be positive, logarithmic and significant. A cross-sectional analyses over 64 countries and the 50 states of the US shows a significant and positive relationship between gross national (or state) product and development capacity ($r = 0.27$ and $0.95$, respectively). The stronger relationship between gross state product and economic capacity for the US states may be due to the fact that the states have similar governance, cultural and economic systems while countries do not. As one might expect, those countries with the highest diversity are the most highly developed and have the highest GNP/capita. There is a significant and positive relationship between average GNP/capita and average diversity for grouped countries (Templet, 1998a). However, there are hindrances to the building of diversity in economic systems. If energy is plentiful and cheap then a favored strategy is to invest in more energy procurement which yields rapid output returns rather than building diversity whose returns generally are longer term and cumulative. This introduces the concept of short- and long-term economic strategies which parallel Daly’s (Daly, 1993) ‘growth’ and ‘development’ economic stages.

Productivity increases were first suggested to be related to diversity in ecological systems by Darwin (1859) while Ulanowicz (1986) shows
that diversity and capacity are related. Tilman et al. (1996) investigated Darwin’s suggestion for grassland ecosystems and found the relationship of diversity to productivity to be positive and significant. Ulanowicz (1986) has developed a general theory of growth and development using energy flows, information theory and input–output techniques which he has applied to ecosystems. He defines system ‘ascendancy’ (i.e. to rise) as the product of system size (represented by energy throughput) and organization (which is related to diversity, structure, mutual information or connectedness). The first term in the formulation of ascendancy is the ‘development capacity’ which serves as an upper bound on the ascendancy since the remaining terms are negative and represent redundancy or overhead. Mageau et al. (1995) have suggested that Ulanowicz’s formulation could be used to assess economic system health but presented no data. The purpose of this paper is to empirically explore the relationship of the organizational structure of systems, which is represented by Shannon-Weaver diversity, to productivity and output.

Laitner (1995, pp. 10–11) has performed a two-sector analysis of the US where he investigated the effect of efficiency and structural changes on GDP. His measure of structural change was the change in value added of the service sector, rather than diversity, and the period of analysis was different than that used here. For the period 1970–1987 he found that efficiency improvements in the US represented 92% of the change while in the later period, 1987–1993, efficiency improvements were only 51%. Structural changes accounted for the remainder of the change in the two periods.

The energy data used in this paper is commercial energy consumption, i.e. the energy that is traded in markets. This approach neglects traditional energy use (firewood, charcoal, etc. which is collected and used by households but which does not enter markets) and which can be a substantial portion of total energy consumption in developing countries but which declines in relative importance as development proceeds and fossil fuels begin to dominate a countries’ energy mix.

2. Results and discussion

2.1. Diversity, output and development

Economic diversity can be calculated from the Shannon–Weaver (Shannon and Weaver, 1949) formula;

\[ H = -\sum p_i \ln p_i \]  

where \( H \) is the diversity and \( p_i \) is the fraction of energy flowing through compartment or sector, \( i \). Economic energy diversity calculated with Eq. (1) has two components, richness (i.e. the number of channels present, which determines the number of terms in the summation) and equability which is a measure of how evenly energy is distributed across channels. Energy data across countries is collected into six categories or channels labeled industrial, commercial, residential, transportation, agriculture and other (World Resources Institute, 1992). Agriculture is omitted from this analysis because of lack of data. Applying Eq. (1) to yearly energy sector data gives the diversity values used in this analysis. A representative set of country diversities are shown in Fig. 1 over time. The diversity in Malaysia is the lowest of the four countries but has climbed rapidly from 1971 to 1978 and has remained relatively unchanged since then. Japan’s diversity in 1971 was low for a developed country but has climbed consistently since then while the US has remained unchanged over the period. Germany’s diversity overtook the US shortly after a swift rise beginning in 1974, which was probably prompted by the oil price shock of that year, and has fluctuated but remains above the US diversity. (For more information on economic diversity see Templet, 1996a, 1998a).

Development capacity is the energy throughput multiplied by a term which is similar to the diversity formulation used here and derives from system organization (Ulanowicz, 1986). Using Shannon–Weaver diversity as a surrogate for the organizational term and multiplying by energy throughput gives a surrogate for the development capacity which, in turn, should relate to system output. In Ulanowicz’s approach, this means that diversity, as calculated by Eq. (1), is analogous to
the organizational term if one assumes a five-compartment model with single energy inputs to each compartment and no interconnections or energy outputs other than dissipation. Data availability requires this simplification of Ulanowicz’s approach for economic systems and therefore the diversity calculated here can only be a first order approximation. This first approximation to ascendency indicates a positive relationship to diversity, in agreement with Darwin’s prediction. The existence of the neglected overhead terms means that the relationship is not so straightforward and may have led to the historical uncertainty surrounding the role of diversity in the output and stability of ecosystems.

The development capacity (C) can be written as:

\[ C = \text{Energy Throughput} \times - \sum [p_i \ln p_i] \quad (2) \]

or

\[ C = E \times H \quad (3) \]

taking the natural log of both sides of Eq. (2) gives (Eq. (4)):

\[ \ln C = \ln E + \ln H \quad (4) \]

or

\[ \text{Change in } C/C = \text{Change in } E/E + \text{Change in } H/H \quad (5) \]

where \( E \) is the annual commercial energy throughput of a country. From Eq. (5) we see that the fractional change in \( C \) is the sum of the fractional changes in \( E \) and \( H \). Table 1 gives the results of the change analysis of \( H, E, C \) and GNP for 12 selected countries, six developing and six developed by decade over two decades.

During the 1970s five of the six ‘developing’ countries shown in Table 1 had low or negative increases in \( H \) but increased their relative energy...
Table 1
Changes in diversity, energy consumption and capacity by decade for selected countries

<table>
<thead>
<tr>
<th>Country</th>
<th>1971–1980; % change in</th>
<th>1980–1988; % change in</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>E</td>
</tr>
<tr>
<td>Developing countries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>1.9</td>
<td>100.3</td>
</tr>
<tr>
<td>Chile</td>
<td>1.1</td>
<td>-5</td>
</tr>
<tr>
<td>India</td>
<td>-5.1</td>
<td>72.4</td>
</tr>
<tr>
<td>Korea, Rep.</td>
<td>-1.5</td>
<td>127.8</td>
</tr>
<tr>
<td>Indonesia</td>
<td>2.5</td>
<td>82.4</td>
</tr>
<tr>
<td>Malaysia</td>
<td>19</td>
<td>72.5</td>
</tr>
<tr>
<td>Average change</td>
<td>3</td>
<td>75.1</td>
</tr>
<tr>
<td>Developed countries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Germany, FR.</td>
<td>10.8</td>
<td>16.6</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>39.1</td>
<td>-12.4</td>
</tr>
<tr>
<td>Sweden</td>
<td>4.7</td>
<td>-0.9</td>
</tr>
<tr>
<td>Switzerland</td>
<td>7.3</td>
<td>13.8</td>
</tr>
<tr>
<td>United States</td>
<td>-0.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Japan</td>
<td>11.1</td>
<td>24.1</td>
</tr>
<tr>
<td>Average change</td>
<td>12.2</td>
<td>7.6</td>
</tr>
</tbody>
</table>

consumption considerably (Chile’s energy consumption declined slightly resulting in a small negative change in C). Malaysia is the exception, having increased both its diversity and its energy consumption significantly over the period while its GNP doubled. During the 1970s the ‘developed’ countries, in contrast, generally had larger increases in H and smaller percentage increases in E. The US did not increase diversity for the two decades but increased energy consumption instead. The US strategy is reflected in its policies which promote cheap energy prices and large energy subsidies which has resulted in one of the highest energy intensities among developed countries. Japan’s strategy of increasing H rapidly and energy consumption slowly seems to have worked, Japan’s GNP/capita is now among the highest of all countries. The author (Templet, 1996a,b) has previously shown that for ‘developed’ countries, and the US states, pollution, resource use and economic and public welfare measures generally improve only as the energy intensity declines. For the 1970s the relationship of the change in development capacity (C) to change in GNP across the 12 countries in Table 1 is positive and significant (r = 0.71).

For the 1980s the picture is similar to the prior decade in ‘developing’ countries which had low or negative increases in H and fairly large percentage increases in energy. The ‘developed’ countries, with the exception of Luxembourg and Japan, also had small or negative increases in H but negative or only small percentage increases in E. Luxembourg had the largest increases in H and decreases in E in both decades while GNP increased significantly. The US exhibited little change in H over both decades with moderate percentage increases in E and GNP. However, US energy consumption is so large that moderate percentage increases mask large absolute increases. Germany and Sweden decreased energy use during the 1980s with little or no improvement in H which resulted in decreases in C. Consequently, their GNPs rose more slowly than in the previous decade. Declining energy use with a rising GNP results in a lower energy intensity and a ‘decoupling’ of GNP from energy consumption. The decoupling is defined by the nature of the energy to GNP...
relationship which changes from positive to negative as illustrated by the 1980s data for Germany, Luxembourg and Sweden. The decline in capacity for the three countries is related to the fairly large declines in energy consumption and is reflected in lower, but still positive, rates of GNP growth. This suggests that improvements in \( H \) are cumulative, i.e. they continue to yield dividends for future years even if the increase in \( H \) slows, as it must eventually. The relationship of changes in \( C \) to changes in GNP is positive and significant (\( r = 0.76 \)) across the 12 countries for the two decades (pooled data), thereby affirming Ulanowicz’s formulation. Since the changes in \( C \), and thus GNP, are the sum of the changes in \( H \) and \( E \) (from Eq. (5)) the reasons for the increase in GNP are easily traced in Table 1. For ‘developing countries’ the average change in \( H \) are small for both decades while the changes in \( E \) are much larger. For ‘developed countries’ the converse is true, the average change in \( H \) is higher than the average change in \( E \) across both decades. Figs. 2 – 5 show plots of the development capacity (\( C \)) and GNP by year for Malaysia, Japan, the US and Germany, respectively. As expected GNP tends to follow the development capacity but there is variation in capacity over time in the case of the US and Germany. The capacity analysis could be improved if more detailed energy data for countries was available which would allow a more realistic model of an economic system. Then Ulanowicz’s ascendancy ‘redundancy’ terms could presumably be used to make the analysis more realistic, accurate and predictive.

2.2. Policy implications

Changes in diversity and energy consumption over time determine the direction for economic evolution (‘becoming’ in Prigogine’s (Prigogine, 1980) terminology), i.e. a country’s economic policy can choose to focus more on diversity or energy throughput to drive increased output. However, continually increasing energy consumption without increasing diversity does not necessarily result in positive long-term change because efficiency, or productivity, is not enhanced, and predicts that the choice of energy policy is important for a sustainable society. The strategy of increasing energy consumption is not sustainable in a finite world, especially when
energy stocks, i.e. fossil fuels, are consumed rather than renewable energy flows.

It is apparent from Eq. (3) that changes in development capacity can occur by two distinct means: increasing energy consumption (growth) or increasing system diversity (development). In actuality most countries use some combination of the two. Because increasing energy throughput increases pollution levels, and causes other impacts this strategy for growth is self-limiting. For example, pollution levels, as measured by toxic chemical releases (US EPA, 1991) across the US states, are positively and significantly related to total energy use and industrial energy use ($r = 0.84$ and $0.93$, respectively). Global warming and acid rain are two obvious examples of feedbacks due to high energy use which can have a negative impact on economic capacity. On the other hand, improving diversity does not have apparent negative feedbacks although there are costs. One such cost is the energy required to maintain the system diversity although this development cost should be less than the costs of energy growth strategies.

Decision makers at any level of development adopt strategies depending upon existing conditions, e.g. the price and availability of energy, timing (i.e. their stage of economic evolution), the desire for rapid growth and political conditions. Maintaining low prices for energy would tend to slow the development of diversity and sacrifice efficiency in favor of increased energy throughput as is the case with the US and some other developed western countries (e.g. Canada and Australia). Low energy prices also result in more externalities which generate subsidies for energy intensive industry and those already well-off while those less-well-off bear the costs leading to higher income disparities (Templet, 1995a). Industrial energy prices are significantly and negatively related to income disparity ($r = -0.35$) across the 50 US states (Templet, 1996a). Low industrial energy prices across the US states also lead to lower efficiency and higher energy intensity ($r = 0.44$). The US, with one of the highest energy intensities among developed countries, has a high income disparity and it is rising, something not usually seen in a developed country. Louisiana, the state with one of the lowest industrial energy prices and the highest energy intensity also has the highest level of income disparity, by far, among states.
(Barancik and Shapiro, 1992), one that ranks it among developing countries.

Economic systems in early development generally tend to increase energy throughput rapidly while efficiency slowly increases (analogous to Lotka’s (Lotka, 1922) ‘maximum power’ principle in ecosystems). Economic systems in later development exhibit higher diversity and efficiency with stable or declining energy throughput. This behavior results in a peak in energy intensity and, in ecological systems, in ‘r’ and ‘K’ type development strategies, respectively (Odum, 1969). The ability of a society to choose different development scenarios implies an important role for government in promoting sustainability with policies which emphasize system diversity and de-emphasize rapidly increasing energy consumption as a means of capacity building, at least in the more developed countries. Examples are the energy tax policies of most European countries which drives their price of energy upward relative to US energy prices. As a consequence their diversity and energy intensity have improved over the last few decades which, according to this analysis, improved their economies and resulted in higher income and improved public welfare while reducing negative environmental impacts per unit of output. This linkage of more efficient energy use to improvement in both economic and environmental conditions may help explain the positive relationship between a sound economy and a healthy environment which the author, and others, have found for countries (Templet, 1996a) and the US states (Meyer, 1992; Cannon, 1993; Hall, 1994; Templet and Farber, 1994; Templet, 1995b). In addition, the Organization for Economic Cooperation and Development (OECD, 1993) found that environmental policies “...may spur innovation, improve efficiency and confer competitive advantage...” (emphasis added).

Efficiency gains brought on by increased energy prices seem to play an important positive role in system improvement. For example, in contrast to the usual economic predictions, a higher energy price across the US states results in improvements in pollution and welfare measures due to declining energy use (Templet, 1996a). In those countries whose governments have imposed large energy taxes on the market (e.g. Japan and the European Community) energy intensity has declined and diversity has in-
increased. Those countries which follow the US model of low energy prices generally have lower diversity and higher energy intensity. There are empirical indications that higher energy prices are 'positively' related to production output. For example, the rate of gross state product growth (for 1982–1989) across the US states is 'positively' related to higher energy prices ($r = 0.67$), not negatively as some economic models might predict.

One other interesting energy relationship is that of environmental regulation and its effect on energy intensity. This study indicates that environmental regulation generally plays a positive role in improving sustainability and competitiveness because pollution prevention strategies like waste reduction require more cooperation, integration and diversity of industry, i.e. they increase diversity and efficiency. To test this statement further we can examine the relationship between environmental policies and energy intensity. There is a positive and significant relationship across states between the Green Indexes’ policy score (Hall and Kerr, 1992) and a state’s energy intensity ($r = 0.62$), i.e. as a state’s environmental policies improve the energy intensity declines (the relationship is positive because a higher green policy score means poorer policies). The relationships do not determine the direction of causation but good environmental policies are clearly compatible with lower energy intensity and higher economic growth rates (Templet, 1998b).

3. Conclusion

Diversity in economic systems, as calculated here, is low in early development and increases during development. As diversity rises economic systems generally are capable of making more efficient use of energy inputs and energy intensity declines, i.e. the more diversity the higher the economic output for a given level of energy throughput. Development capacity is a reasonably good predictor of output and Ulanowicz’s formulation appears useful. It also provides two distinct paths to influence output, increase diversity or increase energy use. Of course both can be changed simultaneously.
Policies guiding economic development can utilize different energy strategies to maximize economic output. These strategies generally involve the manipulation of energy flows. One type of policy merely results in increases in energy flows through sectors, the other affects the distribution or allocation of energy across economic sectors or the development of new sectors. Because energy use in economic systems can cause negative impacts to other related systems, e.g. ecosystems, the essential resource source and waste sink services provided by ecosystems to economies may be reduced by high energy consumption. Sustainable development policies should stress diversity creation and minimize the emphasis on increasing energy consumption. Government must play a role because policies which minimize energy consumption and encourage diversity represent the best long-term sustainability strategy and such strategies do not appear to emerge from markets alone. Policies which maximize energy use by holding energy prices artificially low through subsidies epitomize short-term strategies and are unsustainable since more energy use increases the risk of impacts and a diminished environment which then increases risks to development (Templet and Farber, 1994). In addition, cheap energy policies diminish system incentives to build diversity. Government taxing policies which increase energy prices to high energy use sectors appear to result in long-term improvements to public welfare and economic competitiveness. The measurement of changes in diversity, energy flows and development capacity used in conjunction over time can be useful tools for predicting whether a country’s development strategies and policies are promoting or hindering sustainability.

A sustainable policy relies on increasing the diversity of the system which results in fewer externalities and cumulative economic efficiency gains. The environmentally acceptable level of economic outputs is higher when system diversity is higher for a given energy throughput but still remains constrained by system scale considerations (Daly, 1992). At a minimum, the path of economic sustainability requires efficient systems with moderate consumption and high diversity, all maintained with renewable energies.

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