Psychohistory Revisited: Fundamental Issues in Forecasting Climate Futures

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Abstract

Uncertainty in the trajectories of the global energy and economic systems vexes the climate science community. While it is tempting to reduce uncertainty by searching for deterministic rules governing the link between energy consumption and economic output, this article discusses some of the problems that follow from such an approach. We argue that the theoretical and empirical evidence supports the view that energy and economic systems are dynamic, and unlikely to be predictable via the application of simple rules. Encouraging more research seeking to reduce uncertainty in forecasting would likely be valuable, but any results should reflect the tentative and exploratory nature of the subject matter.

1. Forward the Foundation

In this issue of *Climatic Change*, Timothy Garrett of the University of Utah contends that the range of future scenarios used by the IPCC can be constrained via the application of thermodynamic principles. In essence, as we will discuss, Garret argues the future cannot depart greatly from recent history.

Readers of the late Isaac Asimov will no doubt be familiar with the notion that the long-term future of human systems can be approximated with statistical relationships drawn from the past. Indeed, this very concept was the premise behind Asimov's seven *Foundation* novels, which explored the implications of psychohistory, a fictional scientific discipline offering its practitioners probabilistic insights into the future. As Hari Seldon, the character responsible for inventing psychohistory, puts it:

> "What I have done… is to show that, in studying human society, it is possible to choose a starting point and to make appropriate assumptions that will suppress the chaos. That will make it possible to predict the future, not in full details, of course, but in broad sweeps; not with certainty, but with calculable probabilities." (Asimov 1991, p. 10)

Unfortunately, such predictive power remains a fiction today. Human systems rarely exhibit constancy over multi-decadal scales, as countless historians, sociologists, political scientists, humanists, journalists, artists, and writers can surely attest. If universal laws governing the global trajectory of human systems exist, we have not discovered them. Yet, when looking at the linkage between the energy and economic systems, Timothy Garrett reaches the opposite conclusion.

While Garrett's approach is misguided, it is not our intention to single out his paper for criticism; it contains a number of interesting ideas, and more exploratory work along similar lines might well be illuminating. Rather, we suggest that the mistakes documented below are all too common in the energy forecasting business, and that they arise chiefly from the application of honest, academic inquiry towards efforts to either project the future or assess prospective policy.

The problem, in short, is this: scientists and other analysts have an unfortunate tendency to reduce projections of future energy use to deterministic relationships that are poorly founded in empiricism, or sometimes never supported by data at all. That such mistakes occur in the peer-reviewed literature is not evidence of sloppiness or malfeasance, but rather an example of the risks of interdisciplinary work. With interdisciplinary subjects, such as forecasting energy or climate systems, it is especially difficult to know whether scientists operating in different fields or under different paradigms have examined one's assumptions in detail. For example, applying perspectives or traditions from the physical sciences directly to complex social systems carries a risk of contradicting well-established principles from the social sciences.[1]

Although such cross-pollination can challenge problematic conventional wisdom or generate novel insights, it can also fall short when it starts with an assumption that runs against the preponderance of available evidence. The larger lesson, then, is to encourage discussion among the different expert groups studying a complex system, and to adopt a more tentative tone when considering predictions of the future. While we do not claim to operate a perfect crystal ball ourselves, there is merit to critically examining the philosophical basis for predicting complex systems, and we hope this article will contribute to that end.

2. The Problem of Baselines

Garrett begins his analysis by highlighting an important problem plaguing the climate economics community: the broad range of emissions scenarios considered plausible visions of the future. This uncertainty is key, as the conventional method of calculating the cost of climate policy requires comparing a baseline scenario (a hypothetical story about a world with no action on climate) with a mitigation scenario (a hypothetical story about a world in which policy action on climate occurs) (McGarity 2010; Weyant 2000). All other things being equal, a low-emissions baseline requires less effort to achieve a mitigation target than a high-emissions baseline. As a result, uncertainty in the baseline scenario

[1] For a sharper treatment of this problem, see a recent example from Randall Munroe: http://xkcd.com/793/

drives uncertainty in the cost of climate mitigation. Even if one could accurately foresee the costs of all mitigation options—imagine a universal catalog of technologies, behavioral changes, and policy interventions available for implementation—one could not precisely state the cost of climate policy, due to uncertainty in the baseline scenario.

So long as uncertainty in the baseline scenario exists, it will be reflected in estimates of the cost of climate mitigation. And that uncertainty is large. The SRES database, used by the IPCC in subsequent assessment reports for analysis, contains scenarios ranging from negative CO_2 emissions in 2100 to those where CO_2 emissions increase by a factor of ten over 1990 levels (Nakicenovic et al. 2000, Figure SPM-2). The "illustrative scenarios" span a smaller range of emissions levels, with most falling in between a slight decrease in 2100 emissions relative to 1990 emissions, and a case in which emissions increase six-fold over the same period. As Garrett notes, if the range of plausible futures could be limited further on the basis of available evidence, it would be a great benefit to the field of climate economics, whose core analytical problem would become somewhat more tractable. Projections of climate impacts, which are muddied by the same uncertainty, would benefit as well.

In an attempt to constrain the uncertainty in climate scenarios, Garrett constructs a model linking the energy and economic systems. He supposes that the consumption of energy and creation of economic wealth obey a fixed relationship, wherein the consumption of energy leads to the generation of wealth via equations borrowed from thermodynamics. This model leads Garrett to conclude that of the four major drivers of SRES scenarios—population, per capita income, energy intensity of economic activity, and carbon intensity of energy use—one need only consider the aggregate level of economic activity and carbon intensity of energy use:

> "If civilization is considered at a global level, it turns out there is no explicit need to consider people or their lifestyles in order to forecast future energy consumption. At civilization's core there is a single constant factor, $\lambda = 9.7 \pm 0.3$ mW per inflation-adjusted 1990 dollar, that ties the global economy to simple physical principles." (Garrett, this issue, Section 8)

While we do not object to the primacy of the Second Law of Thermodynamics, Garrett's conclusion is premised on several crucial mistakes. Most importantly, it supposes a fixed relationship between energy consumption and cumulative economic output (the term λ in Equation 4). Essentially, Garrett is saying that there is a fixed ratio of energy inputs to economic outputs, and that all plausible visions of the future will follow this relationship. This perception is sorely mistaken on both theoretical and empirical grounds.

3. Running the Numbers

We wish to emphasize that the larger issues here are the conceptual issues addressed in the next two sections (and these problems are not unique to Garret's paper); nevertheless, we must also note that Garrett does not correctly implement his ideas. Critically, Garrett errs in his calculations of economic data, resulting in an inaccurate picture of the global energy-economy link that obscures the complicated reality of energy and economic transitions.

In brief, Garrett's paper argues that human civilization can be represented by a series of equations, borrowed from thermodynamics, which relate cumulative global GDP to annual global energy consumption. One equation in particular describes this link. From Garrett's model, global economic value, C, is related to energy consumption, a, by a fixed parameter, λ (Garrett, this issue, Equation 4):

$$\mathrm{a} = \lambda C$$

Per Garrett's argument that constraining greenhouse gas emissions scenarios requires assumptions regarding only aggregate economic activity and the carbon intensity of energy, we take C to be the independent variable and a to be the dependent variable. To estimate λ (a parameter), Garrett examines the historical record from 1970 to 2005, and concludes that its value is 9.7 (±0.3) mW per inflation-adjusted 1990 USD.[2]

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[2] Curiously, Garrett says the associated uncertainty represents a 95% confidence interval corrected for autocorrelation (Garrett, this issue, Section 4). No details are given about how this calculation was performed. In any case, it seems inappropriate to assume that autocorrelation, should it exist in the data, reflects statistical noise in this instance. Indeed, the trend we observe in the data—a declining energy/GDP ratio—would seem to be the counterargument to Garrett's model formulation,

We were unable to reproduce this value, due to the limited methodological description offered in the paper. Although the precise calculations cannot be repeated on this basis, Garrett's general approach is transparent. It is also, we argue, problematic on multiple levels.

Unlike more familiar measures of the relationship between energy consumption and economic output (which typically compare annual data for both systems), Garrett's metric takes a different perspective. He compares annual energy consumption with cumulative economic output dating back to the year 1 C.E. Intuitively, this approach seems irrevocably flawed, as it presumes a relationship between two thousand years of economic output and the annual level of energy consumption. The implausibility of this type of relationship stems from the inherent problems in mapping an economic quantity (GDP) to a physical quantity (free energy potential).

If one considers the conventional link between energy and economic activity, which involves comparing metrics for both items on an annual basis, the data suggest a very different story. We analyzed world primary energy consumption country by country from 1960 to 2007, using data from the International Energy Agency (OECD 2010).[3] The same dataset also provides estimates of annual gross domestic product (GDP). We selected purchasing power parity estimates (PPP) of GDP, expressed in terms of 2000 US dollars (USD). PPP is preferable to market exchange rates (MER) because PPP more accurately measures the local level of consumption and living standards, which we believe is a better way to gauge the relationship between "civilization" and energy consumption. By contrast, MER converts local currencies to a common currency (usually US dollars) on the basis of international exchange rates. From a thermodynamic perspective, MER data are problematic because a dollar in the US buys you considerably less than the same amount of money would in, say, rural India. Therefore if one is concerned about the relationship between money and the things it purchases, PPP is the preferable metric, as it adjusts for the different prices found across the world.

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rather than a statistical artifact in need of correction. Additionally, we note that if the purity of the data is in question, then Garrett's methodology—a simple extrapolation of a linear trend based on the same data—is not particularly credible.

[3] Although national-level data are available for some developed countries going back to 1960, most data for developing countries date back only to 1971.

When we calculate the changes in the global energy/GDP (E/GDP) ratio using PPP data, we find that it falls by an average of 1.3% per year over the period 1971 to 2007 (see Fig. 1). The same ratio falls at 0.9% per year when using MER data, a slightly lower value reflecting the methodological undercounting of economic activity.

[Fig. 1 here]

But the story doesn't end there, as the global aggregate masks incredible transitions within nations. At the country level, the situation is much more complicated. Many countries' E/GDP ratios have paralleled the global trend, but some have decreased more rapidly, while others have risen over the past few decades. Fig. 2 shows the E/GDP trend for 23 representative countries in PPP terms. Fig. 3 shows the E/GDP ratios for the same countries using MER data. Note that the axes are the same as in Fig. 2, but as a result, several countries' ratios are literally off the charts. Fig. 4 presents the same information as Fig. 3, but uses a different y-axis scale.

[Fig. 2 here]

[Fig. 3 here]

[Fig. 4 here]

Whether one prefers MER or PPP methodology, it is clear that several major developing economies have experienced rapid declines in their E/GDP ratios. Those declines are magnified by MER data, which undercounts economic consumption in developing countries, and hence results in higher E/GDP ratios for the same level of energy consumption relative to the same measure using PPP data. Because the gap between PPP and MER data tends to shrink with increasing economic development, the E/GDP ratios appear to fall more rapidly in developing countries when using MER accounting.

Although by no means does a single pattern dominate all national E/GDP trends, we are confident that the role of GDP accounting for developing countries is the key to understanding the global E/GDP trend. One way to visualize this is to aggregate the nations of the world into two categories. For simplicity, we will call members of the Organization for Economic Cooperation and Development (OECD) "developed" economies, while non-OECD countries will represent "developing" economies. Using this simple (and admittedly coarse) distinction, we can see how the economic accounting of developing countries drives the global E/GDP trend. Developing countries' fraction of global GDP has been steadily rising over the last 20 years (see Fig. 5). China, in particular, stands out for its economic growth. As a result, the weight of developing countries' E/GDP ratio in determining the global ratio has been increasing in parallel.

[Fig. 5 here]

Another aggregate view reinforces the importance of calculating the economic footprint of developing economies. While the difference between PPP and MER accounting has only a minor effect on developed countries' E/GDP ratios, the choice of methodology leads to fundamentally different outcomes for developing countries (see Fig. 6). The disparity in the two methodological approaches, neither of which is completely satisfactory from a thermodynamic or statistical perspective, underlies the difficulty in assessing the global E/GDP trajectory in a world experiencing rapid economic change.

[Fig. 6 here]

We now return to Garrett's model. While relatively good data measuring energy and economic consumption is available for the last five or six decades, our ability to empirically evaluate the last two thousand years of the energy-economy link is quite limited. In particular, we contend that the precise production of an annual time series of economic output dating back as far as 1 C.E. is implausible. Because Garrett's model relies on exactly such a data series, its projections cannot be considered reliable.[4]

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[4] Garrett extrapolates economic activity back to 1 C.E., driven by economic data from Maddison (2003). We believe the following discussion captures the inherent difficulty of analyzing global energy and economic trends, as well as the dangers of imprecise methods and oversimplifications.

Maddison (2003) offers nine point estimates of global GDP that extend the UN data Garrett uses to calibrate his model. The point estimates are for the years 1, 1000, 1500, 1600, 1700, 1820, 1870, 1913, and 1950 C.E.; these data are expressed in purchasing power parity (PPP) terms.

Garrett then converts these data to market exchanges rates (MER) in a highly questionable way (as discussed in Appendix C of his paper). Garrett's economic data sets contain both MER and PPP estimates of global GDP for the period 1970-1992. Using this overlap, Garrett estimates a parameter, π, that expresses the ratio of PPP to MER:

$GDP_{PPP} / GDP_{MER} = \pi = 1 + e^{[(t-1998)/73]}$, where t is the year.

Garrett applies π to his data to generate MER point estimates, which he then converts into annual data from 1 C.E. to 1969 using a cubic spline function.

To recap: Garrett translates nine admirable-but-imprecise point estimates of global economic activity stretching back two thousand years into an annual series by fitting a curve. The data are converted from PPP to MER based on relative price

Yet even if one could create perfect long-term time series, it is not clear what one is describing by adding the numbers together. If there is a strict thermodynamic relationship between economic activity and energy consumption, we are unconvinced that cumulative historical economic output plays a role. Only a fraction of GDP is invested into future endeavors; one-time consumption reflects a much larger part. There is no reason, for example, why the amount of food consumed in the year 1426 has any thermodynamic relationship to the level of energy consumption in 1984. And if such a relationship did hold, there is no reason why the cumulative economic series should be indexed starting from the year 1 C.E.

Calculating recent energy consumption poses difficulties, too. While commercial energy consumption leaves a trail of tax records and corporate expenditures, non-commercial energy is not easy to estimate. Biomass consumption is particularly vexing. National authorities supplying data to the IEA (or the United Nations and other authorities) undercounted biomass in the 1970s, or simply ignored it. Even today figures on biomass consumption are likely to be highly unreliable. In part this is because biomass use is strongly associated with rural settlement and low incomes. With rapid urbanization in the developing world and rising household incomes, the share of biomass has declined over time as more consumers have moved to commercial energy counted in energy balances, particularly petroleum products and electricity. Biomass remains a significant fraction of primary energy consumption, however, accounting for over 30 percent of total energy use in many developing countries. It would certainly need to be accounted for very carefully in an analysis of this type. We would expect that the problems with biomass data would bias a measure of the energy intensity of GDP towards higher numbers. Corrected for the

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relationships from the period 1970-1992, a decision that requires assuming that the same price relationships held over the past two thousand years. Finally, Garrett takes his annual GDP series and integrates it to produce an estimate for the term C, a measure of economic value that captures the cumulative GDP up to a given date.

This approach departs recklessly from the standard methods of converting between MER and PPP data, which themselves are so uncertain as to draw criticism from leading economists (e.g., Johnson et al. 2009). Respectfully, we hope the implausibility of the paper's calculations is apparent at face value.

expected bias over time, we would expect the E/GDP ratio to fall more rapidly than the data show.

Instead of suggesting a fixed relationship between economic output and energy consumption, the evidence firmly supports the view that the link is dynamic. We now turn to a more theoretical discussion of the issue.

4. What Do the Last 40 Years Mean for the Future?

When projecting forward to the end of this century, the period 1970 to present does not sufficiently capture the dynamics of the global energy system. It is true that energy data in general are scarce and this period may offer the richest options for analysis, but it is also remarkable for the relative constancy exhibited by the energy system.

Others who have examined the question of path dependency in energy systems have reached different conclusions than does Garrett. Keller et al. (2007) take a longer look at the historical record, employing data going back to 1700, and conclude that the range of SRES scenarios does not represent the full probabilistic range of possible outcomes. They also show that selecting shorter time periods for model calibration reduces the range of model outputs for the future. This result is particularly important because both Garrett and Keller et al. share (in the formulation of their respective models) a basic epistemological perspective: that the future energy system will continue to follow trends observed in history. What Keller et al. show is that the farther one looks back in history, the more uncertain future path-dependent projections become on the basis of that evidence.

As the example above suggests, deterministic analysis of energy systems is not new, and we believe the record bears revisiting. In the late 1970s, several scientists began to explore whether there are simple patterns in the energy system that govern the transition from one kind of primary energy resource to another. Marchetti (1977) noted that history revealed a striking pattern of energy transitions that could be described with a logistic equation, as though "[t]he whole destiny of an energy source seems to be completely predetermined in the first childhood" (p. 348). In a subsequent report, Marchetti and Nakicenovic (1979) famously observed: “It is as though the [energy] system had a schedule, a will, and a clock” (p. 15) (see Fig. 7).

[Fig. 7 here]

While the available evidence at the time of publication supported this conclusion, the historical record in recent decades has not behaved so kindly. As Smil (2010) discusses, the fractions of global primary energy consumption stagnated—especially in developed countries—and did not continue the transitions predicted by Marchetti (see Fig. 8). The lesson from this example is that even when the data strongly support a particular trajectory for the global energy system, surprises may occur.

[Fig. 8 here]

Whether the past 40 years pose an exception to the general trend of technological change remains a question for future study. But what is clear is that transitions from one kind of infrastructure or prime mover in an energy system to another have taken decades—sometimes up to a century or more (Grübler 2003). Therefore, a model calibrated exclusively to a shorter time horizon might not capture the issue of long-term technological change.

Even short-term energy forecasting, which typically relies on the simple extension of energy-economic trends, has fared somewhat poorly in retrospect (Ascher 1979; Craig et al. 2002; DeCanio 2003; Koomey et al. 2003; Smil 2000, 2003). As a result, any statement that seeks to extend recent patterns into the future should be cautious of overreaching, especially when looking forward almost a hundred years.

5. Do Social Systems Obey Physical Laws?

It is tempting to ponder whether complex social systems might exhibit patterns derived from simple laws. This is especially alluring when thinking about the application of well-established insights from physical science. Who could possibly argue that social systems violate the Second Law of Thermodynamics? Indeed, all energy conversion goes from a more available form to a less available form, with a net increase in entropy. Therefore any energy conversion process—and the global economy certainly is one—depletes available energy.

We agree that if a global scenario can be shown to violate a basic thermodynamic principle, it should be disregarded by the IPCC as implausible. However, the difficulty arises in making sure that the analytical framework used to make this case is appropriate, as the models, theory, and data used in the social and physical sciences vary widely. Therefore we ask: does a scenario that departs from the observed relationship between global GDP and energy consumption in the period 1970-present violate the laws of thermodynamics? Emphatically, we believe the answer is no, for three reasons.

First, we suggest that there are compelling reasons to believe that the relationship between energy consumption and GDP is not primarily governed by thermodynamics. By this we mean that while the future of the global energy system will not violate the Second Law of Thermodynamics, other factors—such as prices, government policy, technological change, and social values—will explain more of the observed variance in the E/GDP ratio. This view is supported by the fact that the global E/GDP ratio has been declining over the last 40 years.

Second, the economic evidence surrounding the rebound effect—to what extent energy savings from efficiency or conservation are lost due to increased consumption derived from the wealth or price effects of the energy savings—is considerably more optimistic than Garrett suggests. Garrett erroneously cites a report written by Steve Sorrell to claim that the rebound effect negates the possibility for savings from efficiency, while the same document reaches a very different conclusion:

> "[T]he evidence does not suggest that improvements in energy efficiency lead to economy-wide increase in energy consumption. At the same time the evidence suggests that economy-wide rebound effects will be at least 10% and often higher. Rebound effects therefore need to be factored into policy assessments." (Sorrell 2007, p. viii)

As Sorrell discuses in a related paper, the question of the rebound effect gets to the heart of heated disputes over the nature of economic growth (Sorrell 2009). These perspectives are worth briefly noting here, as they convey the extent to which a total understanding of the energy-economy link remains an active element of debate, both within and between focused expert communities.

Conventional economic thought, as expressed by proponents of both neoclassical growth and endogenous growth theory, asserts that increases in energy inputs play a relatively minor role in economic growth. Because energy expenditures account for only a small fraction of total economic costs, these camps tend to argue economic growth is primarily due to increases in the productivity of capital and labor (including technological change). Ecological economists have disputed this position, however. Some have argued that increased availability of "high quality" energy inputs is a prerequisite of economic growth. Quality can include both a thermodynamic component (e.g., exergy, which Garrett's paper explores) as well as a consideration of relative economic value of different energy inputs (i.e., some energy resources are more valuable than others, on a per unit energy basis). For some ecological economists, concerns about the scarcity of high quality energy suggest a growing role for energy as a driver of economic growth; for others, the remaining room for technical efficiency increases and price responses in the energy sector suggests that the economy is decoupling from its thermodynamic base (see Sorrell 2009 for a review of the literature).

Each of the above perspectives has been developed in great detail. We raise them here not to seek resolution, but rather to note that more sophisticated treatments of the energy-economic link have been published elsewhere.

Third, even if one believes that the thermodynamic analogy used by Garrett is an appropriate constraint on global scenarios, one has to be concerned with the limitations of available data. As discussed in the previous section, the best data describing global energy and economic activity stretch back only four decades or so; one can look back farther in time, but at the cost of significantly decreasing precision. Moreover, precision isn't a problem that is readily resolved by third-party verification. Unlike physical systems—in which scientists reasonably presume a joule is a joule, no matter where or when it is measured—social systems are typically described using historical data that most third-parties cannot independently validate. Because the data are more uncertain the farther back in time one looks, quantifying aggregate uncertainty becomes more difficult, but no less important. Therefore, it seems inappropriate not to spend considerable time quantifying uncertainty in an analysis of the link between the global energy and economic systems.

Finally, we take issue with the oversimplification of civilization, which, Garrett suggests, "is most commonly quantified in purely fiscal terms" (Garrett, this issue, Section 3). When an analyst uses GDP as a proxy for civilization, he or she leaves out an incredible list of things, including all non-market activities, goods, and services. Outside of developed economies, the informal sector—including the production of household goods and services, as well as transactional markets conducted outside the official scope of the law—can account for an additional 20% to 50% of regional GDP numbers (Charmes 2006). Similarly, leisure and family time, while particularly valuable activities to those who participate in them, do not contribute to GDP.

When GDP is employed as a proxy for human welfare, it is done so with the caveat that some of the things that we as humans care about are not captured by the measure: for example, art, spirituality, value systems and ethical conduct are ignored alongside non-market transactions. Focusing on GDP, we tend to forget that quality of life and happiness are not easily compared with income, especially in wealthier societies.

Even if we maintain a clinical focus on the relationship between measures of economic output and resource consumption, it is impossible to separate values from technical analysis. Most fundamentally, this is because GDP itself is a value-laden construct. The prices people pay for goods and services depend not only on the physical reality of those goods and services, but also—and perhaps more importantly, in advanced economies—on the subjective importance individuals place on the objects of their consumption.

This subtle distinction has significant ramifications over longer time horizons, across which broader social changes might take place. Consider a future in which large, single-family suburban homes send forth two working adults every day, each driving a heavy, gasoline-powered personal vehicle 30 miles each way to work. That world would be a very different place than another that focuses on mixed-use land use development, public transit, and telecommuting. The laws of economics and thermodynamics will be present in both futures, but the corresponding energy impacts of everyday living would be remarkably different. Yet the question of which world is more likely—or more valuable and desirable—cannot be separated from one's value system and preferences.

6. Conclusion

In the absence of overwhelming evidence, it is a mistake to assume that the future of complex human systems will obey simple deterministic relationships. As discussed in this paper, there are compelling theoretical reasons to believe that a thermodynamic constraint is not a limiting factor governing the relationship between energy consumption and economic activity. Furthermore, the evidence to date shows that the global E/GDP ratio has been steadily declining over the last 40 years; the available data do not support the theory that the ratio has been constant. This finding is especially important for decision-makers (and the public at large) because the fallacy that the economy can only grow with a corresponding increase in energy consumption has been employed as a public relations tool at least as far back as the 1970s (Schipper 1976). The fear that the economy cannot grow absent increased energy consumption is simply inconsistent with the facts.

Despite its incorrect conclusions, Garrett's analysis turns on the fulcrum of a creative analogy between the physical work done by a system on itself and economic productivity. In interdisciplinary work, the tendency of researchers to draw analogies and metaphors between concepts in two different fields is the source of both fertile ideas and occasional misunderstandings. We suggest Garrett's paper is an example of both.

Looking forward, the integration of thermodynamic and economic perspectives continues to be an important area for future research. Economic systems may indeed be understood as physical systems constrained by thermodynamic laws. However, regarding global GDP as a linear map of civilization size in a thermodynamic sense is unrealistic. The demand for energy in the economy will in general be related to economic value in a complicated, subjective, and largely unpredictable way. That relationship will be modulated by the state of technology, resource scarcity, and our capacity to plan for the future—as well as by dynamic human preferences.

One important lesson to draw from this discussion is the need to be humble when facing questions of long-term forecasting and policy analysis. The projection of deterministic rules in the form of "if A, then B" statements can be a very useful tool for exploration of possible futures, but such an approach should only be used to craft definitive perspectives with great caution. Constraining the uncertainty of the future remains an important task for many important areas of inquiry, but scientists should be meticulous and open-minded when making such arguments. Quite simply, our quantitative understanding of social systems falls far behind that of physical systems.[5]

Then there is the matter of human agency. Asimov was aware of this problem, too:

> "If a psychohistorical analysis is made and the results are then given to the public, the various emotions and reactions of humanity would at once be distorted. The psychohistorical analysis, based on emotions and reactions that take place *without* knowledge of the future, would become meaningless." (Asimov 1991, p. 12-13)

One can get tied up in philosophical knots trying to sort out whether determinism and foresight can coexist peacefully. For our purposes, suffice it to say that one need only weakly believe in free will in order to doubt the precision of deterministic social forecasting. Whether global society is capable of or willing to make new choices about energy consumption in the face of climate change is another matter, but it is not a problem exclusively for the physical sciences.

Perhaps in the future a particularly brilliant scientist will discover a robust and verifiable means for deterministically predicting energy system dynamics. Until that time, however, the evidence suggests we should err on the side of humility and uncertainty in making projections about the future. After all, the track record to date is full of mistakes, and very few success stories.

Acknowledgments

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5 Others, such as Scher and Koomey (this issue) argue that accurate forecasting of economic systems may not be possible, due to the inherent structural inconstancy over interesting time scales.

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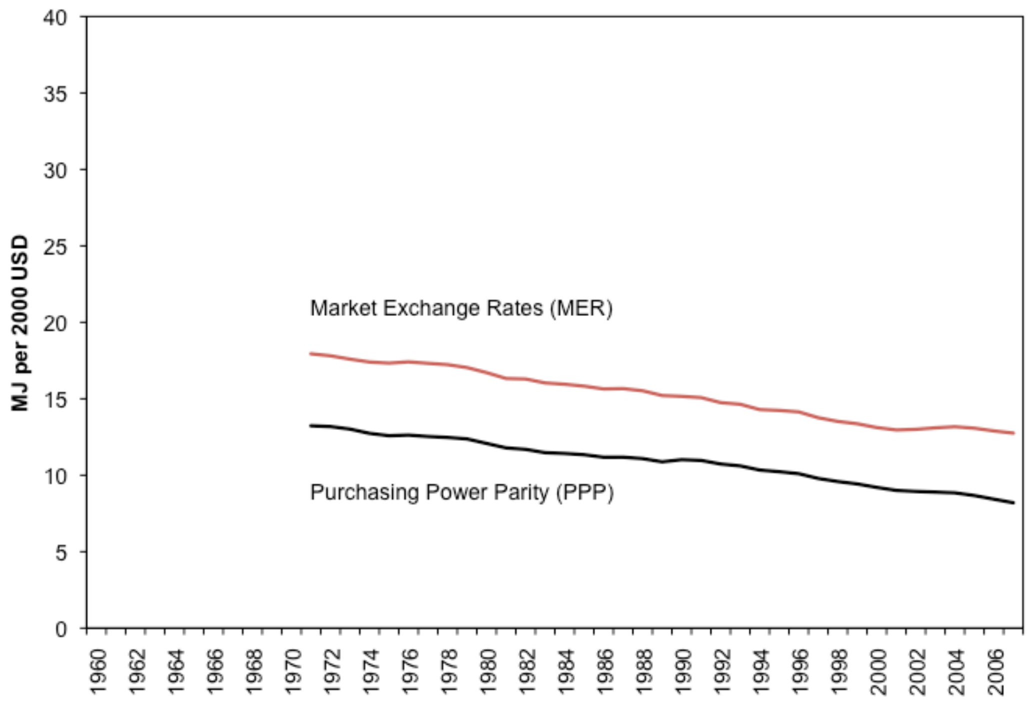

Fig. 1 The ratio of global primary energy supply to global economic output (E/GDP) has been declining steadily for the last forty years. Economic data are from the Organization for Economic Cooperation and Development and energy data are from the International Energy Agency (OECD 2010).

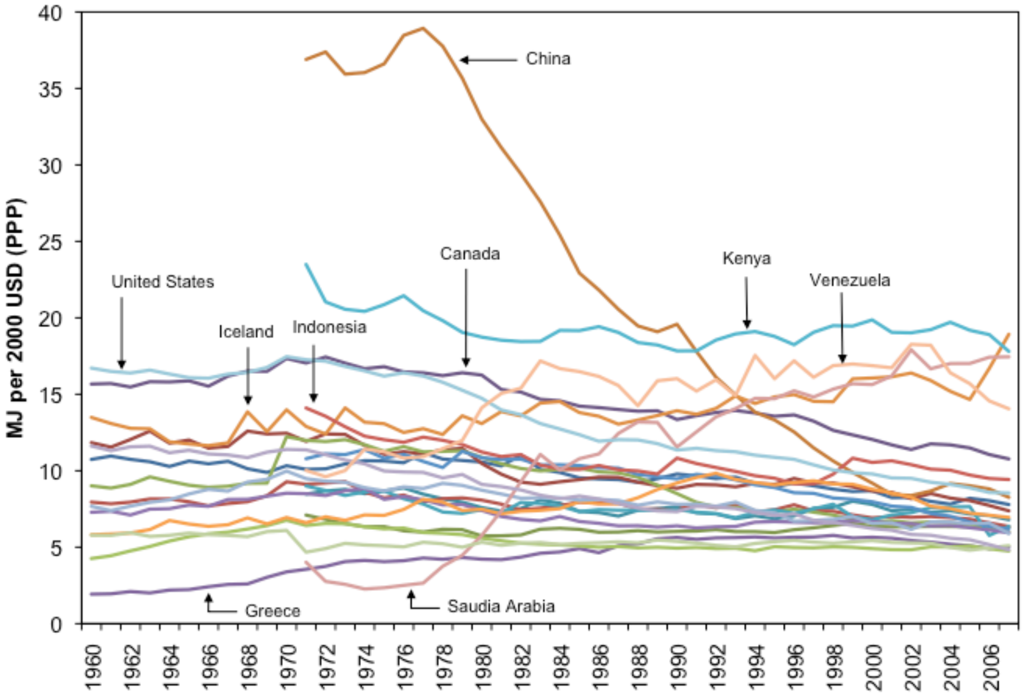

Fig. 2 At the national level, the trends in the ratio between primary energy supply and gross domestic product (E/GDP) are more nuanced. Here, E/GDP is calculated in PPP terms. The majority—but not all—of the countries shown here experienced trends comparable to the global pattern. Some, such as China, experienced a more rapid decline. A few, such as Kenya, have maintained a more or less constant ratio. Others still, such as Greece, Iceland, and Saudi Arabia, experienced an increase in the E/GDP ratio. This figure shows data for the following 23 countries, based on OECD (2010): Australia, Belgium, Brazil, Canada, Chile, China, France, Germany, Greece, Honduras, Iceland, India, Indonesia, Italy, Japan, Kenya, New Zealand, Norway, Saudi Arabia, Turkey, United Kingdom, United States, and Venezuela.

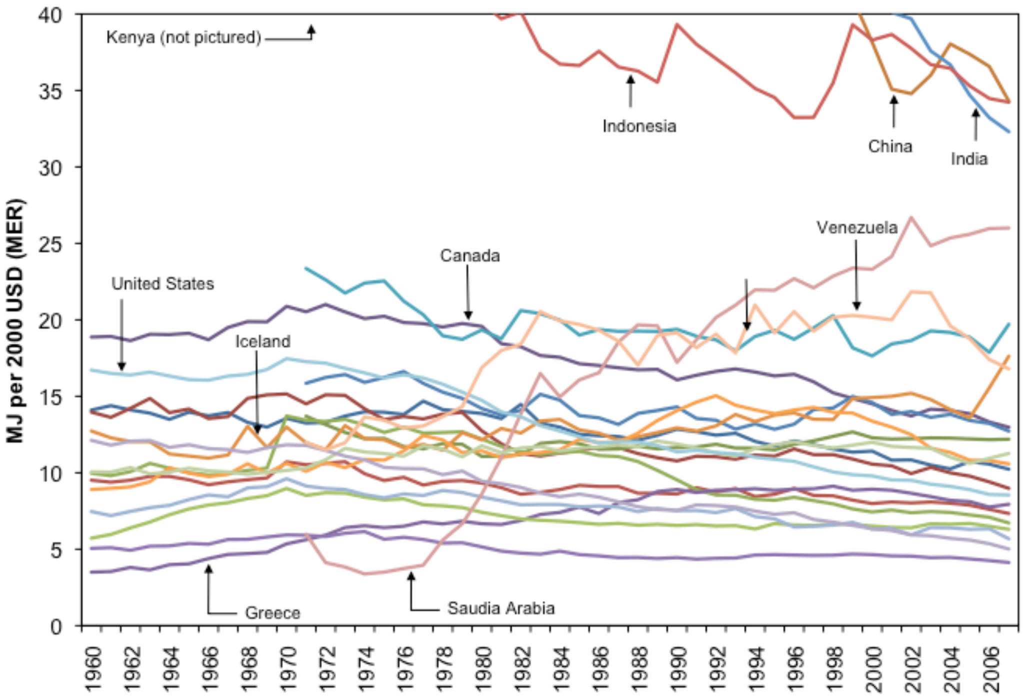

Fig. 3 The E/GDP ratio for the same 23 countries is shown in MER terms. Note that the y-axis scale is the same as in Fig. 2 for ease of visual comparison.

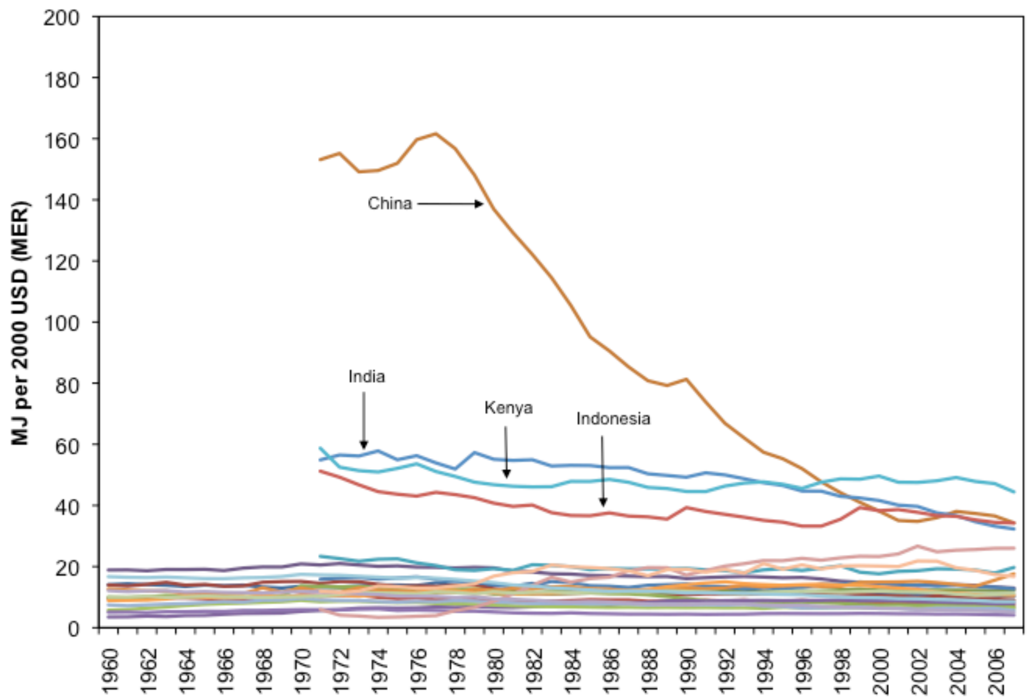

Fig. 4 Here we see the same data as in Fig 3, except that the y-axis scale has been adjusted so as to fit in the extreme E/GDP levels seen in several countries (expressed in MER terms).

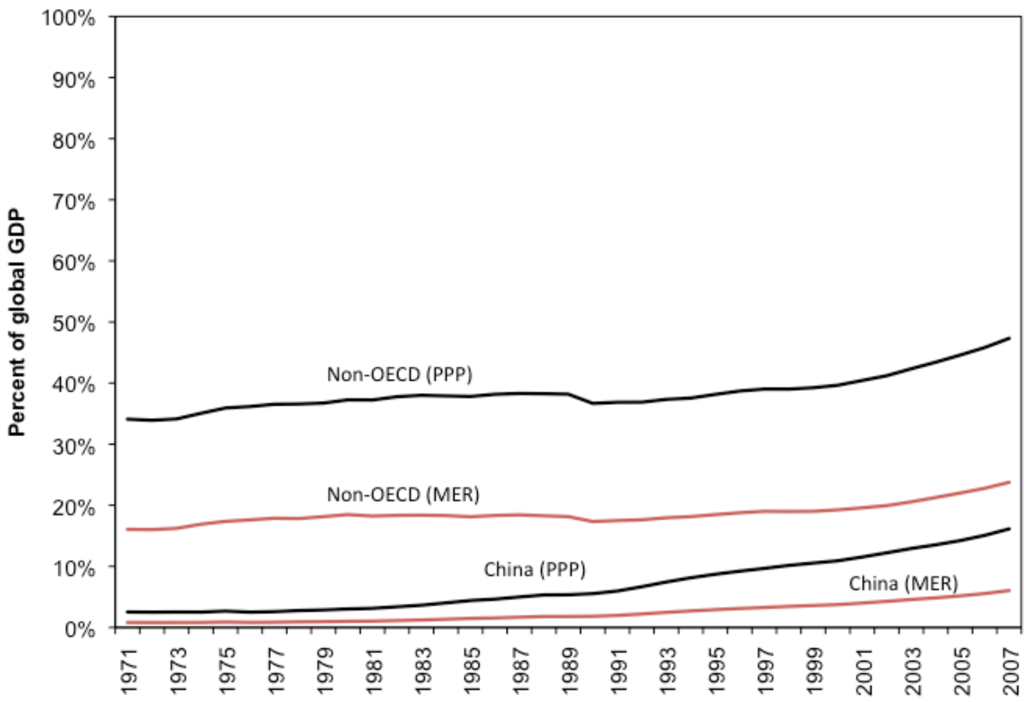

Fig. 5 Developing countries' share of global GDP increased noticeably in the last 20 years. As a result, the weight of developing country E/GDP ratios in determining the global ratio has grown. Data from OECD (2010).

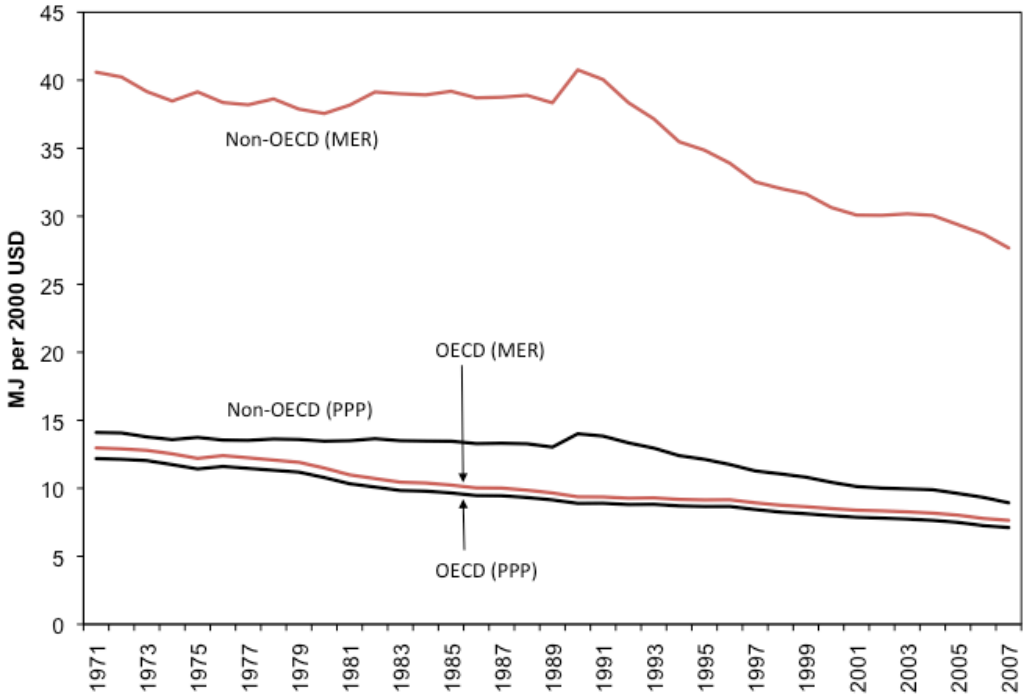

Fig. 6 The E/GDP ratio for developed (OECD) and developing (non-OECD) country aggregates. While there is almost no difference between MER and PPP methodology for developed countries, the difference for developing countries is huge. Under either MER or PPP accounting, developing country E/GDP ratios fell in the last 20 years. This, along with the increased prominence of developing countries' GDP in the global total, helps explain why global E/GDP has been falling. However, the magnitude of the change turns on the determination of global activity in the developing world, a notoriously tricky problem. Data from OECD (2010).

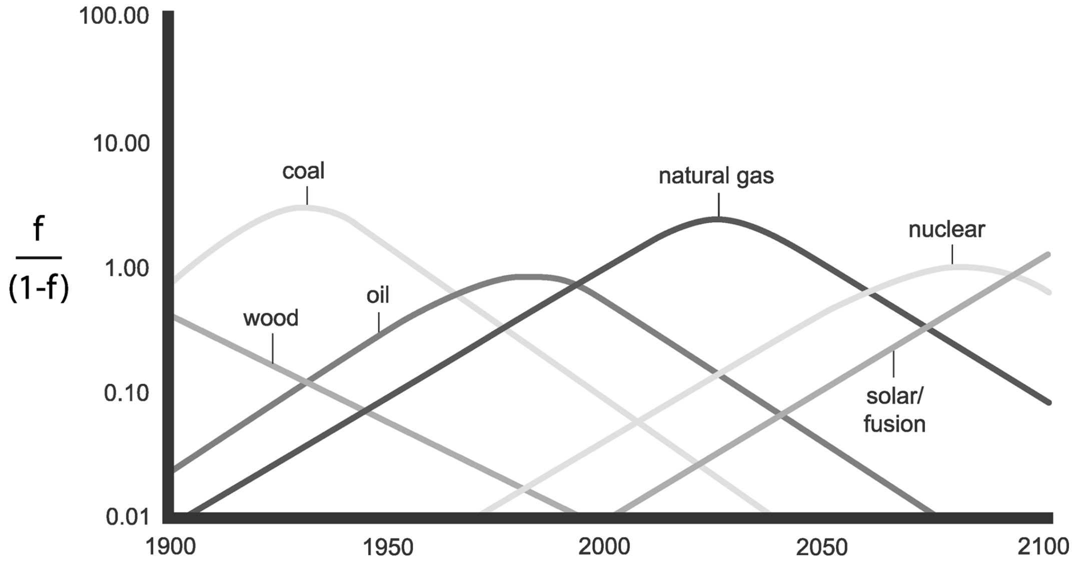

Fig. 7 Marchetti (1977) forecasted the trajectory of global primary energy resource consumption based on a logistic growth model. The model projections are shown here in a Fischer-Pry plot, where *f* represents the fraction a particular energy resource holds of the global total at a given point in time. Marchetti predicted an imminent peak for oil, a rapid decline of coal and wood, as well as an increasing role for natural gas, nuclear, and eventually a new energy resource (described as "solar/fusion" to suggest two possibilities). Based on Smil (2010) and used with permission from the author.

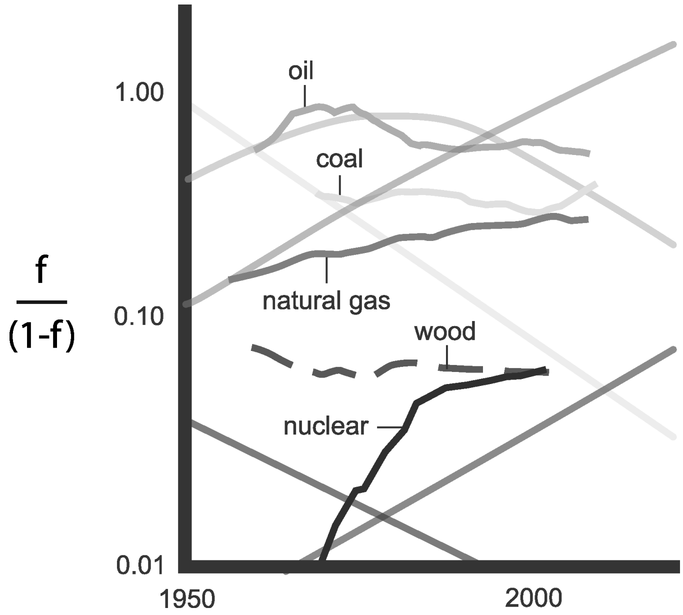

Fig. 8 Although Marchetti's model fit the data available at the time of writing, actual global energy resource consumption trends diverged significantly from their predicted levels in recent decades. Coal and wood use have remained at remarkably consistent levels, while nuclear became prominent more quickly than predicted (before reaching an apparent plateau). Natural gas use has increased much more slowly than anticipated. Only oil consumption has followed a trajectory close to that predicted by the model. The lesson from Marchetti's famous model is that even when data appear to suggest a deterministic relationship in complex social and technological systems, one cannot be certain the relationship will hold into the future on this basis alone. Based on Smil (2010) and used with permission from the author.