AIM3: Automating Research on Governance of Global Energy Resources

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Abstract

As we study problems associated with governing global energy resources, we seek research models that can improve our insight into how growth and stability functions might constrain the range of options available to managers. A positive feedback function between energy acquisition by a particular subsystem of global human society and increase of technological power within that same subsystem is discussed here as central to this learning effort. We continue to develop an automated, integrated, monitoring, modeling and management (AIM3) research methodology for examining behavior of multiple societal subsystems separately and in aggregation, in order to better show system dynamics to managers, to better articulate the most critical problems and to guide toward optimal solutions. Here, we suggest a simplified five-box, eight-parameter, energy-flow network model as a first step in designing a common modeling interface that can allow nesting of submodels at multiple levels as well as merger of geographic accounting approaches with economic sector modeling.

I. Introduction

"Houston, we have a problem."

Viewing the rotating Earth from a lofty perspective, one can marvel at the fluid dynamics so impressively swirling through our linked biosphere-ocean-atmosphere system. This picture, so powerfully driven and displayed by the Sun's light, tells us immediately where on the planet the big winds are blowing. But underneath the clouds, another dynamic has been brewing, in the bushes near Houston and on the sands in other plains and valleys where oil wells have fueled a grand eagerness and momentum in human expectation. A feedback between human energy acquisition and the acceleration of human technology that thrives on that acquired energy, has created a powerful subsystem with runaway potential. This is a human-created storm, but one invisible to the great part of human society who know it so well by so many other names of its thousand parts, too many to piece together for one view of this great, single beast.

For the many people in many places on our planet who need our abilities to manage the growth of our technology to quicken at least in pace with our abilities to alter the global environment, a growing number of environmental scientists have found it worthwhile to broaden research scope to include interdisciplinary research approaches. While becoming a generalist can lose one a large measure of traction in academic circles, the endeavor can afford a fascinating view of the changing world and its human dimensions, and it can offer stimulating opportunities to cross-pollinate methods between disciplines. Previously, this writer has been found participating in reporting observations about environmental change to government (Keeling et al., 1989), describing fundamental natural principles related to energy and human governance (Lancaster, 1989), gathering and processing geophysical and remote-sensing data to constrain modeling of the global carbon cycle (*Idem*, 1990a; 1990b), conducting early workshops on the human dimensions of global environmental change (HDGEC) (1992a), urging advances in international environmental policy formulation (1992b), developing integrated assessment methodology for HDGEC (et al., 1993; 1994), building case studies for integrated monitoring, modeling and management (IM3) methodology (1995; et al., 1995), developing software for geodynamic real-world simulation (2001), countering obfuscation of climate science by energy-industry agents (2006) and developing IM3 design for application to governance of global energy resources (2007), *inter alia*. This paper continues an incremental development of IM3 modeling for global energy resources, with a view toward designing a system to provide automated learning capability, i.e., "automated, integrated monitoring, modeling and management (AIM3)."

II. Background -- Ecological Economics

Developing some perspective on the growing fields of ecological economics and evolutionary thermodynamics is helpful for understanding that our approach suggested here follows on a large and growing literature of very able researchers who have been constructing and testing hypotheses and theories in this area for more than a century. Still, awareness of this science in the minds of those in higher levels of power in government and industry has come much more recently, generally only in the past three decades. Yet these themes and research approaches will be critical for discussing how to stabilize and sustain human development in the 21st Century.

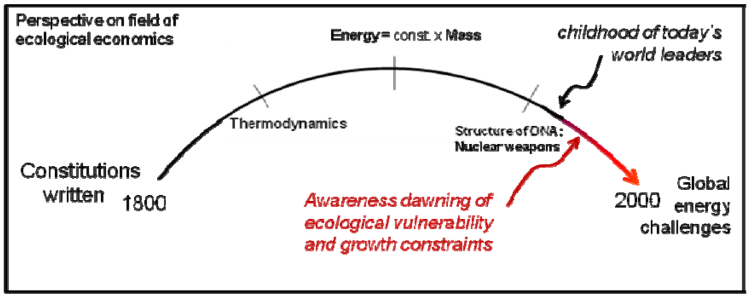

Fig. 1. Awareness of ecological economics becoming popular in last 40 years, with basic structures of government designed with limited understanding of energy and thermodynamics. Many of today's parliamentary leaders gained their early education prior to the broader emergence of ecological studies and its now widespread vocabulary.

In 1679, Antoni van Leeuwenhoek, the Dutch inventor of the microscope, published the first quantitative estimate of the Earth's carrying capacity: 13.4 billion people (Cleveland, 2003). Despite such early scientific contributions, the major structures of constitutional government created in the 18th Century in Europe and North America were set in place absent knowledge and appreciation of thermodynamics and ecology. Not until the 1800s would the science of thermodynamics emerge, with its insight that energy, mass and motion are conserved through exchanges of heat. And only in the late 1800s would oil flowing from the ground begin another industrial transformation, to be followed by the rise of modern armies with mechanized weaponry. And only much more recently has it become widely understood that global biology, chemistry and ecology could be affected so completely by human actions, with environmental changes feeding back onto our human systems so powerfully with undesired effects.

Early descriptions of the fundamental principles of evolutionary thermodynamics were presented by Boltzman (1886), Ostwald (1892), Osborn (1918), Lotka (1910, 1922) and Johnstone (1921). Lotka (1922) stated

> "To recapitulate: In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system, so long as there is presented an unutilized residue of matter and available energy. This may be expressed by saying that natural selection tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject."

and he went on to assert more strongly,

> "[. . .] the influence of man, as the most successful species in the competitive struggle, seems to have been to accelerate the circulation of matter through the life cycle, both by 'enlarging the wheel,' and by causing it to 'spin faster.' The question was raised whether, in this, man has been unconsciously fulfilling a law of nature, according to which some physical quantity in the system tends toward a maximum. This is now made to appear probable; and it is found that the physical quantity in question is of the dimensions of power, or energy per unit time, [. . .]." (Lotka, 1922).

Ho (1993) outlined a "thermodynamics of organised complexity" based on a nested dynamical structure that enables the organism to maintain its organisation and simultaneously achieve nonequilibrium and equilibrium energy transfer at maximum efficiency. This thermodynamic model of the organism is reminiscent of the dynamical structure of steady state ecosystems identified by Ulanowicz (1983, 2003).

MClare (1971) had proposed “Useful work is only done by a molecular system when one form of stored energy is converted into another,” and Ho (1993, 1995) reminded that this pertains when the conversion is “. . . in the same system.” Stored energy is thus equivalent to exergy, as both refer to energy that is available for doing useful work. But stored energy is explicitly defined with respect to a characteristic space-time, and is hence a real property of systems rather than a pseudo-property as defined for exergy (Ho and Ulanowicz, 2005).

The minimization of dissipation will result in reducing entropy production (Ho and Ulanowicz, 2005), while maximizing non-dissipative cyclic flows will increase the following: (i) energy storage capacity, which translates into carrying capacity or biomass; (ii) the number of cycles in the system; (iii) the efficiency of energy use; (iv) space-time differentiation, which translates into biodiversity; (v) balanced flows of resources and energy; and (vi) reciprocal coupling of processes. This idea is akin to systemic storage of energy through internal dynamic coordination described earlier by this writer (Lancaster, 1989).

Greater energy input does not necessarily increase productivity (Ho, 2004a,c): if the energy is supplied at a rate greater than the space-time differentiation of the system is able to assimilate, then no further increase in productivity can occur. The existence of a carrying capacity seems to be borne out in a study of multiple systems of agriculture in which a plateau of output per hectare appears around 70–80 GJ, regardless of the total input; this rate has only been exceeded in the three high-yielding, pre-industrial systems of Yunnan, China. Intensifying energy input further was seen to lead to a drop in efficiency, which was particularly sharp as inputs approached the output ceiling (Ho and Ulanowicz, 2005).

Karnani and Annila (2009) suggest that all species, abiotic just as biotic, can be viewed as mechanisms of energy transduction for the global system to evolve toward a stationary state in its surroundings. The maximum entropy state displays homeostasis by being stable against internal fluctuations. When surrounding conditions change or when new mechanisms emerge, the global system readjusts its flows of energy to level newly appeared gradients. This echoes aspects of Schneider and Sagan’s (2005) description of evolution as simply a method the universe uses to reduce gradients in energy density.

Hirata and Ulanowicz (1986) suggested shifting emphasis from deterministic, numerical simulations of ecosystems in order to consider more basic concerns about how to represent them, understanding that approximating the entities of an ecological community is a problem of aggregation/decomposition and that the more useful representations of ecosystems appear to be networks which are amenable to such techniques as input-output analysis, environ analysis, information theory and Markov chain calculations.

Materials and energy network flow analysis

Ayres (2005) has emphasized the importance of Georgescu-Roegen’s historical point that – in contrast to the standard neoclassical view – the economic system is a *materials processing* system that converts high quality (low entropy) raw materials into goods and services, while disposing of, and dissipating, large and growing quantities of high entropy materials and energy waste (i.e., waste heat). The economic system of industrial countries is driven mainly by solar exergy, much of which currently comes from solar exergy captured and accumulated hundreds of millions of years ago as fossil fuels.

Ayres (2005) also points out that environmental economics is faced with a profound dilemma: on the one hand, thermodynamics is highly relevant to environmental economics so that thermodynamic concepts seem to have to be integrated somehow to redress the deficiencies of neoclassical economics. On the other hand all approaches toward such an integration were found to be incomplete and unsatisfactory. The implications of the entropy law cannot be given due regard, and the radical alternative of an energy theory of value was even more of a failure..."(Sollner 1997).

Explicitly treating the economy as a materials processing system that evolves over time, Ayres (2005) conceptualizes this system as a chain of linked processing stages, starting with resource extraction, conversion, production of finished goods and services, final consumption (and disposal of wastes). It is understood that there are also feedbacks – reverse flows – along the chain. For instance, capital goods are manufactured products that feed back into the extraction and processing stages. He posits that that *useful work done* (or *exergy services delivered*) can be regarded as a quality-adjusted factor of production, at least in the same sense that labor or capital can be so regarded. In effect, `technical progress' can now be interpreted rather well in terms of the technical (thermodynamic) efficiency with which raw materials are converted into exergy services.

Material and energy flow analysis (MEFA) versus least-cost analysis (LCA) has been discussed recently by Schiller (2009), who states that money is far greater in coordinating the functional integration of the system than language, which translates into an incapacity to learn. He sees the theory of reflexive modernity (Beck et al., 1997) departing from this by just referring to the potential of social structures and systems to develop reflexivity. In comparison to the slow academic uptake of ecological economics, the acceptance of recommendations from material and energy flow analyses in policy seems to be better (Schiller, 2009).

A variety of approaches to materials and energy flow analysis (MEFA) in ecology has been reviewed by Suha (2005), the focus being on the linear network system introduced from input–output economics. Structural path analysis (SPA) has been demonstrated as an input–output-based technique for measuring flows in ecological and linked ecological–economic networks, where it is shown that for most linear dissipative networks, a manageable number of paths of limited length exist that cover in the order of 99% or more of total throughflow. These paths can be conveniently extracted, enumerated and ranked using SPA (Lenzen, 2007).

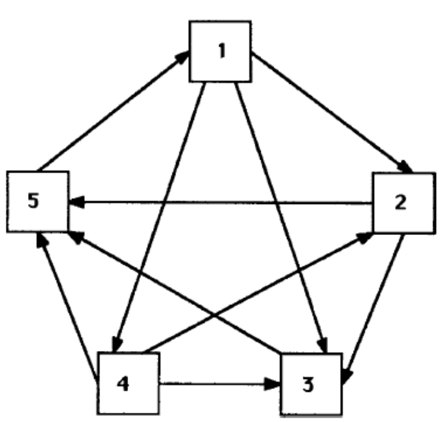

Fig. 2. A directed flow network, after Ulanowicz (2004).

Ulanowicz (2004) has suggested a quantitative method for economic network analysis (ENA), using directed flow graphs (see Fig. 2, above) and Ulanowicz et al. (2009) have combined thermodynamic, network, and information theoretic measures with research on real-life ecosystems to create a generalized, quantitative measure of sustainability for any complex, matter/energy flow system. Goerner et al. (2009) explore how this metric and its related concepts can be used to provide a new narrative for long-term economic health and sustainability. Ulanowicz (2004) illustrates mapping the web of connections into a virtual linear chain that summarizes trophodynamic performance by an ecological system. Using backtracking algorithms with pruning to identify pathways that recycle materials and energy within the system, he finds the cycling pattern(s) will often reveal modes of control or types of functions exhibited by various groups of taxa. The performance of the system as a whole at processing material and energy can be quantified using information theory. In particular, the complexity of process interactions can be parsed into separate terms that distinguish organized, efficient performance from the capacity for further development and recovery from disturbance. Finally, the sensitivities of the information-theoretic system indices appear to identify the dynamical bottlenecks in ecosystem functioning. Janssen et al. (2006) also look at ecological systems from a network perspective, seeing different types of networks as a function of 'reachability' and density.

Goerner et al. (2009) point out that today's primary measure of economic health, GDP growth, only counts the volume of monetary exchanges and ignores whether such exchanges go toward building economic capacity or paying for damages, liabilities and unproductive debt. GDP growth actually masks declines taking place in various parts of the economic web by allowing massive gains in one sector, such as hedge funds, to be conflated with health for the whole. This blindness to network health has rendered much of classical theory incapable of understanding, much less predicting, either bubbles or the kind of widespread economic instability that now threatens the global economy. On the other hand, analyzing network flow circuits can provide important insight into greater details of a systemic breakdown. Flow circuits often fall into positive-feedback arrangements in which each node has an amplifying effect on its downstream neighbor in the loop. Such autocatalytic loops often create centripetal pull, a self-reinforcing momentum that draws progressively more resources into their sway, making the circuit a centralizing hub for surrounding flows (Matutinović, 2005). A number of natural processes cause this vortex to accelerate its own efficiency and growth in a way that actively drains the broader system, which processes can be seen to include (Goerner et al., 2009):

1. Selection, a natural tendency to augment elements that increase flow through the epicenter circuit and to eliminate elements which do not;
2. Increasing efficiency honed by this selection and elimination;
3. Self-amplifying growth created by increasing efficiency, influx and pull;
4. Erosion of the surrounding network caused by the massive draw of resources into the epicenter hub;
5. Brittleness caused by the elimination of backup resilience; and
6. Rigidity cause by increasing constraints on options and behavior.

III. Management challenges for modeling efforts to consider

Scale-mismatch

One area in which an AIM3 modeling capability can serve managers relates to perceiving and anticipating scale mismatch. Cumming et al. (2006) examine the origins and effects of scale mismatches that occur when the scale of environmental variation and the scale of social organization in which the responsibility for management resides are aligned in such a way that one or more functions of the social-ecological system are disrupted, inefficiencies occur, and/or important components of the system are lost. Broad-scale versus fine-scale differences can be discerned in both societal and ecological systems; with mismatches occurring between them on spatial, temporal, and/or functional scales. Issues of scale mismatch could make a transition unstable if the replacement dynamic imposed at one level or dimension of the system cannot fit the frequency or momentum requirement of the subsystem being controlled or subsumed. Secondary cascading dynamics can be imagined to propagate disruptive effects downstream in a linked system through various network flows, and those downstream disruptions themselves can be impactful owing to secondary, local scale mismatches in particular subsystems. Many cultural rhythms in the developing world can be impacted negatively in this way by programs of development aid, which aid programs can oscillate drastically in time and degree owing to financial or political cycles in the developed world.

Resilience in systems is determined by the interactions of these few key variables that operate at different scales, e.g., slower and faster rates in time or smaller or larger extents in space. Because these variables influence the overall dynamics of the system, they are therefore of direct interest to managers, who are frequently focused on fast variables. Walker et al. (2006) identify pathologies of management occurring as stabilization of key ecological processes for economic or social goals leads to a loss of resilience. They find that efforts to deliberately enhance adaptability can (unintentionally) lead to loss of resilience. They also assert that, although social-ecological systems are self-organized through interactions among large numbers of biotic and abiotic variables, the most important changes can be understood by analyzing only a few, key variables that dominate the observed system dynamics (i.e., 3-5 variables, hence the “rule of hand”).

Mental models that managers will have typically derived from their individual histories of experience and education can be better updated by improving access of these managers to modeling results presented through strong visual illustration of flow dynamics and stability. Many participants in international governance have a wide diversity of personal mental models that they use when approaching collaborative or negotiated discussions about management problems and solutions. In relation to the dynamics and stability of social and/or ecological systems, for example, it is useful to recognize two kinds of diversity: (1) functional diversity, i.e., the number of functionally different groups, which influences system performance, and (2) response diversity, i.e. the diversity of types of responses to disturbances within a functional group, which influences resilience (Walker, 2006). Mental models drive change in social-ecological systems, and adaptability is enhanced through partially overlapping mental models of system structure and function.

Switching-costs

A key management challenge that deserves improvement in modeling and visualization relates to switching costs and resistances, and to the rate in which replacement is required. Cleveland (2003) noted that energy technologies that may be brought forward to replace oil and coal face tough challenges. First, the new energy technologies must eliminate or substantially reduce carbon emissions. Second, they must approach the abilities of fossil fuels to generate economic wealth per heat unit. The diffuse nature of incoming solar radiation requires a significant investment of energy and materials to capture, collect, and concentrate sunlight. This means that many solar technologies deliver a lower energy-surplus than fossil fuels. Equally important, the substantial "material scaffold" required to collect solar energy is made from fossil fuel inputs. Although, photovoltaics and wind turbines continue to exhibit significant technical improvements, the issue is whether a sufficient number of these solar-based renewable technologies can move from "feasible" to "viable" status in terms of their net energy return, and whether they can be scaled-up in time to offset the economic effects of fossil fuel depletion (Cleveland, 2003).

Diminishing returns

A second critical issue concerns the possibility that the energy industry could move forward in a state of denial and chase a path of diminishing returns for many years, only to come up quite short decades hence, leaving a global economy and the welfare of eight billion people, poised by then on a 20 TW flow, to find its own way down rapidly from these lofty heights (and heats). The metric of energy return on investment (EROI) is relevant to both questions.

The patterns of resource discovery are showing diminution in return for energy expended. In the Kern River oilfield in CA, the number of producing wells had increased from 500 in 1942 to 9,318 in 2007 and by then as many as 16,000 wells have been drilled in total. In this oilfield, drilling increased by a factor of twenty yet the reserves increased no more than eight-fold. Production levels of less than 1 b/d are considered likely to be below the economic or EROI limit (Laherrere and Campbell, 2009). The United States supports more than 20,000 oil companies. For the last 25 years over 60,000 pure exploration wells (new-field wildcats) have been drilled in the United States compared to 5,000 in Canada and 40,000 for the rest of the world. The average size of oil discovery is 0.3 Mb for United States, 0.9 Mb for Canada and 740 for the Middle East, 14 Mb for Africa, and 7 Mb for the world outside US and Canada (Laherrere and Campbell, 2009).

Hall and Cleveland (2005) focus on energy return on investment (EROI) to discern phases in industrial development and evaluate sustainability. In 1930, for example, the U.S. got 100 barrels of oil back for each barrel invested in seeking it (EROI = 100:1). In 1970, this was about 25 for 1 barrel invested. In the 1990s, it became about 11-18 barrels returned for one invested. It is now much less for finding new oil (EROI = 3:1 approximately).

Net energy of energy sources has been presented recently as an index (Emergy Yield Ratio; EYR) that must be evaluated for energy sources to better understand their potential contributions to society, but more important, as an indicator of the changes needed in the future if lower net yielding sources are to be relied upon (Brown et al., 2009). Maa and Nakamori (2009) recently explored advantages and disadvantages of three kinds of modeling practices for energy systems, using optimization models with endogenous technological change, and agent-based models. The deliberately simplified energy system assumes that the economy demands one kind of homogeneous goods (e.g., electricity), and that the demand increases over time, where existing, incremental d, and revolutionary technologies could be used to produce the goods from resources.

IV. The AIM3 Project

Know-how (KW), Material Technology (MT) and Population (P)

The function for increasing potential storage in a subsystem comprises at least three aspects: (1) know-how; (2) material technology; and (3) people. There can be overlap in the extension of these categories. Books, for instance, can fit partially both the first and second category, while teachers can fit both the first and third. Still, in broad strokes, these distinctions can be useful as we characterize the combining elements of the energy-technology feedback over many epochs in some instances, or very rapidly within a single generation when looking at other key drivers.

As Boulding (1982) so clearly put forth many years ago, know-how is a critical aspect of development, and much of the leveraging of energy invested in one moment of time to create future development finds its action through a potential residing in the system that seems very hard to place one's finger upon precisely. The valuing of intangible intellectual property, however, is an active part of business and the legal profession, so developing one or more suitable metrics for modeling the growth, density, momentum, location and operation of know-how should be seen as merely a difficult task.

Know-how (KH) is built upon experience, observation, and/or information. Being knowledge of technique, know-how is technology. An early technique in human society may have existed in one person who knew how to track a rabbit, or another who could make and control fire. These methods could be taught simply by demonstration, but as time went on such know-how would be amplified and shared through the crafted technique of language and then story, and through symbols and drawings. The evolution to scrolls and hieroglyphs and more advanced maps, together with apprentice methods and artisan guilds, allowed methods and pathways of activity and routes through the world to be widely shared, thereby enabling the technology of roads, the rise of agricultural and architectural technology. The evolution of the alphabet, mathematics, the printed word and the printing press and now the Internet have accelerated rapidly our capability to expand our knowledge of method.

For over half a millennium, patents have listed man's growing technology (a first patent in1421 was to Brunelleschi for a method of transporting marble via paddleboat), patenting being itself a focused reward method that stimulates inventive effort and disclosure, building a positive feedback in engineering achievement. Where decisions to license methods commercially are now made, specialized graphic artists have provided detailed drawings to accompany the concise language of the patent application, providing a rapidly accessible roadmap to the next inventor half-way around the world. Today, modern R&D facilities in corporations are unraveling the fabric of physics, chemistry and biology in carefully recorded detail, coded in the language of specialists, with most people in the world using tools and machines of which they have no understanding at all of the internal working mechanisms.

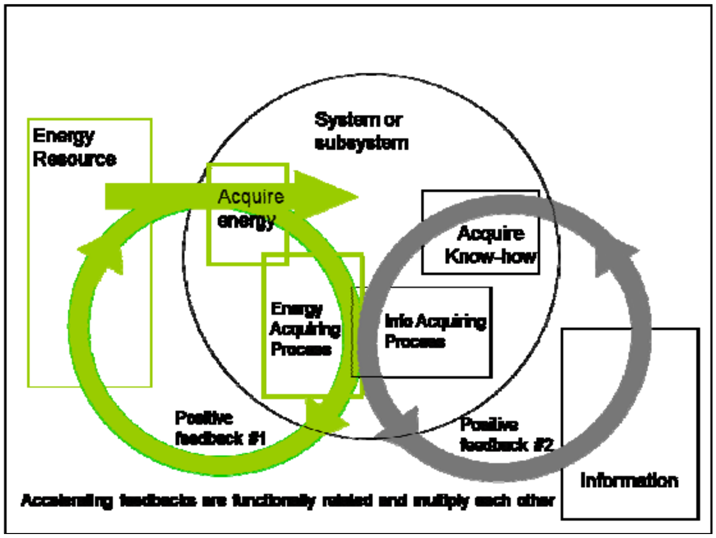

Fig. 3. The acquisition of information and growth of know-how multiplies the ability of the employees of the energy industry to wield the material technology of that industry to acquire more energy in the next time interval.

Methods for organizing groups, educating and training people, coordinating governance, taxation, and exchanging currency create dynamic structures of varying utility; this know-how creates strong, positive feedback in the growth of subsequent know-how and material technology and in acquiring energy from the environment (see Fig. 3, above). Legal incorporation, a method of organizing and focusing stored know-how, capital and collective human activity, while reducing the individual risk and social exposure of participants, both owners and employees alike, is a powerful social technology.

Control methods are technology of know-how. Armies, being comprised of methods of control, techniques of training and collective, forceful action are a know-how technology. Modern armies also combine know-how with large, complex assemblages of advanced and high-energy-density technological tools (material technology).

The energy industry/sector learns. It is a subsystem of the global human energetic system that gains knowledge, stores energy and capital, and develops its methods of control over the greater system. With or without provable intent, the force of this subsystem has moved individuals to unethical and unprincipled behavior (Lancaster, 2006). In modern times, this industry gaining control over governments and armies may be the most disheartening aspect of the energy-technology feedback. In the United States, for instance, oilman Bush and well-serviceman Cheney gained control of the executive branch of government and launched a war to secure their industry's access to oil in the Middle East. The well-service companies Halliburton and Kellogg, Brown and Root, employing a private mercenary army (Xe Corporation, formerly Blackwater), are deeply intertwined in the U.S. Iraq war operation. Other powerful corporate and financial interests closely tied to both the energy industry and governmental power, such as the Carlyle Group, have increased their corporate control of ports and shipping facilities critical to the transport of energy resources.

Material Technology (MT)

Material Technology (MT) is what many of us mean when we refer casually to technology, usually something that we can touch, hold, steer, or at least press a button to make move. In early epochs, the creation of clubs, leather cord, flint shards, and later the smelting of metals, enabled the material technology of weapons, agricultural and architectural tools: the invention of the wheel and axle, aqueducts and stone dwellings, growing to pyramids and cities; the creation of domestic animals and crop vegetables and grains; waterwheels, windmills and water-screws enabling the growth of mills. The increasing ability to take, transport and shape lumber and iron with saws, hand-drills, shovels, sluices, gears and belts, mills and plants, enabled the growth of fleets of ships, which ships themselves provided a positive feedback for the transport of further ship-building and tool-building resources. The compass and the clock broadened and sharpened ocean navigation. Quickening in the 19th century, came the invention of the steam and internal combustion engine, engineering tools and hardware (fasteners, lathes, large-scale drilling and mining machinery, the sewing machine and the chainsaw, tractors and combines, steamships and trains, the lightbulb and the generator, the telegraph, the microscope. And in the last century came the surge of war technology and weapons of mass-destruction, computing, telephony, electrical grid, skyscrapers, asphalt, concrete, plastics, cars, trucks, airplanes, biotechnology and nanotechnology. Again, evident to the observer of this history is the quickening, the positive acceleration of each layer of tool and machine built upon the layer prior.

With much of coal and oil transported by ship, if we want to examine a growth in the material technology of the energy industry, then we might start by looking at some aspects of shipping history related to coal mining in England hundreds of years ago. For example, in the period around 1750-55, an early investigation in political economy yielded the following observation of coal industry transport during the mid-18th Century in Britain: "This single branch of commerce does not employ less than fifteen hundred vessels, from a hundred to two hundred tons, […] (Nickolls, 1754)." Watson (1960) noted that coal was so abundant in Britain during the 18th Century that supply could easily be ramped up to meet a rapidly rising demand, so that circa 1770-1780 the annual output of coal in Britain was approximately 6.25 million tons, and after 1790 output soared, reaching 16 million tons by 1815. If we combine these pieces of information, calculating 1500 ships @ 100-200 tons/ship conveying 6.25 mtc/a, we arrive at a figure of an average of ~10 tons/day delivered per ship, which suggests a 200-ton shipment every 20 days per ship.

Movements by Tanker, Pipeline, and Barge between PAD Districts

Product: Crude Oil and Petroleum Products   Period-Unit: Annual-Thousand Barrels

Download Series History   Definitions, Sources & Notes

Show Data By: ○ Product ◉ Areas	2003	2004	2005	2006	2007	2008	View History
From PADD 1 to							
PADD 2	114,839	123,232	123,815	123,844	125,514	111,786	1981-2008
PADD 3	3,937	5,250	6,627	5,891	14,822	18,149	1981-2008
PADD 5		0	80	0	84	0	1981-2008
From PADD 2 to							
PADD 1	30,782	32,585	30,468	29,648	30,317	32,277	1981-2008
PADD 3	73,137	95,319	95,981	110,790	115,684	127,181	1981-2008
PADD 4	31,966	31,932	23,741	43,543	42,926	41,935	1981-2008
PADD 5							1981-2002
From PADD 3 to							
PADD 1	1,166,880	1,189,909	1,131,520	1,121,321	1,120,071	1,056,991	1981-2008
PADD 2	1,076,354	1,114,782	1,102,828	1,030,423	991,821	920,637	1981-2008
PADD 4	17,362	16,896	13,359	10,210	11,549	10,671	1981-2008
PADD 5	34,737	41,133	41,984	44,507	56,662	62,009	1981-2008
From PADD 4 to							
PADD 2	55,598	51,279	62,653	76,293	77,534	83,340	1981-2008
PADD 3	52,671	53,624	51,668	51,979	59,827	70,607	1981-2008
PADD 5	8,995	12,115	11,893	10,035	9,975	11,648	1981-2008
From PADD 5 to							
PADD 1	785	51	0	38	21	125	1981-2008
PADD 2							1981-2002
PADD 3	383	61	1,308	561	2,121	1,319	1981-2008
PADD 4		0	0	0	0	0	1983-2008

- = No Data Reported; -- = Not Applicable; NA = Not Available; W = Withheld to avoid disclosure of individual company data

Fig. 4. Modern datasets show multiple transfers to and from itemized regions. Source: US EIA Petroleum Imports/Exports & Movements http://tonto.eia.doe.gov/dnav/pet/pet_move_top.asp

Figure 4, at left, illustrates the detailed accounting now available to track resource movement from district to district. In 2005, oil tankers made up 36.9% of the world's fleet in terms of deadweight tonnage. The world's total oil tankers deadweight tonnage (DWT) has increased from 326.1 million DWT in 1970 to 960.0 million DWT in 2005, almost 300% in 35 years. The combined deadweight tonnage of oil tankers and bulk carriers, represents 72.9% of the world's fleet (UNCTAD, 2006)

Population (P)

The growth of human population is a third aspect of human society that accelerates the energy-technology feedback (ETF) and which has itself been accelerated by the ETF, through gains from the above-described acceleration of know-how and material technology. Population has provided the actors to effect KH and to construct MT, while both KH and MT have combined to support and accelerate population growth.

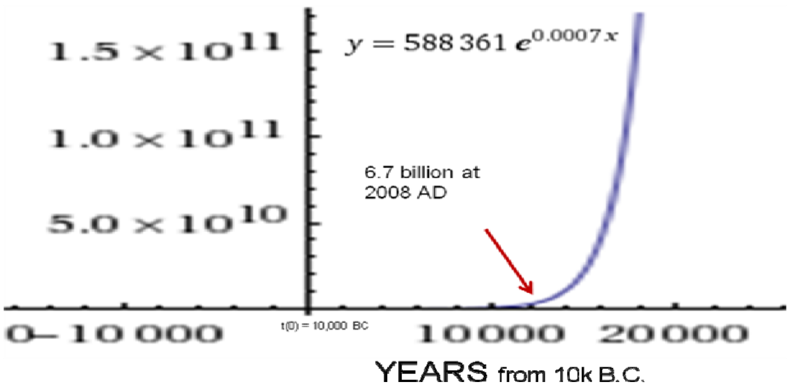

Fig. 5. Human population growth approximated as a single exponential curve,
y= 588,361 e^(0.0007x), where t(0) is 10,000 yrs B.C. It is recognized that global human population increase has now departing from this historical trend.

As shown in Figure 5, above, historically, human population exhibited exponential growth, although recent changes in human population are departing this trend. The movement of exponential growth into other aspects of human society may indicate that the growth force of the energy-technology feedback is residing in (living in?) and effecting other aspects of the larger, emerging energetic system that no longer depends on numbers of humans for its growth.

The Energy-Technology Feedback (ETF): ***ETF = f(KW, MT, P)***

Previously this writer has suggested an energy-technology feedback (ETF) as a new modeling parameter related to growth (Lancaster, 1989, 2007). Subsystems of human society that are involved in energy acquisition can be found (identified and/or defined) at multiple scales and in a wide variety of configurations geographically and conceptually. The classic structure of a global oil industry comprised of many large energy corporations, their supporting companies and the related inter-governmental regulatory structure is an obvious and most important subsystem for beginning to study the ETF. After coal and natural gas, other studied subsystems include government/corporate projects at varying scales to dam rivers for hydroelectric power and large biomass-to-fuel conversion industries, among others.

In an exponential growth curve, with *y = t(0)e^(kt)* , the exponential factor, *kt*, characterizes the "gain" property of the function, with the base constant characterizing the state at t(0). If we believe that an energy-technology feedback is or should be operating in the global human energetic system, and that such a feedback would have exponential characteristics, then it is reasonable to look for signs of this type of growth in the key contributors to the growth of the energy industry, namely in the annual gains of know-how, material technology and personnel. This is a task suggested for a next step in our research, but at this early stage we get a suggested glimpse of some exponential rates from the graphed data above:

Growth factor, *k*	Context
0.0188	(EIA, 2009; 1971-2006; estimated production)
0.035	(Boden et al.; 1750-2006; estimate emissions)
0.0007	(population, P)

Of course, each of these rates listed needs to be recomputed based on trend fits to more cleanly processed data sets, and at varying levels of aggregation. However, as we develop a measure of the ETF as some compound function of ΔKW, ΔTM and ΔP, we can expect that the ETF will itself have a compound, exponential shape, where ETF = ETF(t=0) e ^(kt). A worthwhile achievement of this research effort will be to adequately define and then subsequently describe the changing behavior of this ETF parameter. A fundamental aspect of sustainability will relate to the ability of governance to manage the ETF.

AIM3 Research System Design

Previously we introduced Integrated Monitoring, Modeling and Management (IM3) as a potential methodology to study and improve governance of global energy resources (Lancaster, 2007). We further proposed a design for automating aspects of this research in conjunction with development of a knowledge base constructed in the form of a causal network model. The Automated IM3 (AIM3) system is designed to

(a) test a research query against an accessible knowledge base to derive an information-needed gap,

(b) build and select a data-request object that can be 'run' automatically by a learning module to gather data to close the gap,

(c) loop-repetitively gather data from a series of 'outsourced' research calls to third party data repositories and/or third-party labs,

(d) automatically process the retrieved data,

(e) build and update a dynamic energy resource/use model in terms of geographic/geopolitical and utilergy functions, and

(f) test for closure of the new model output against the original query.

Constructing a Knowledge Base

A growing knowledge base includes an improving dynamic model of the system and its subsystems, accessible directly to managers, that can be utilized to test relative effectiveness of a variety of strategies to re-engineer the system dynamics through new laws, technologies, switching and exchanges.

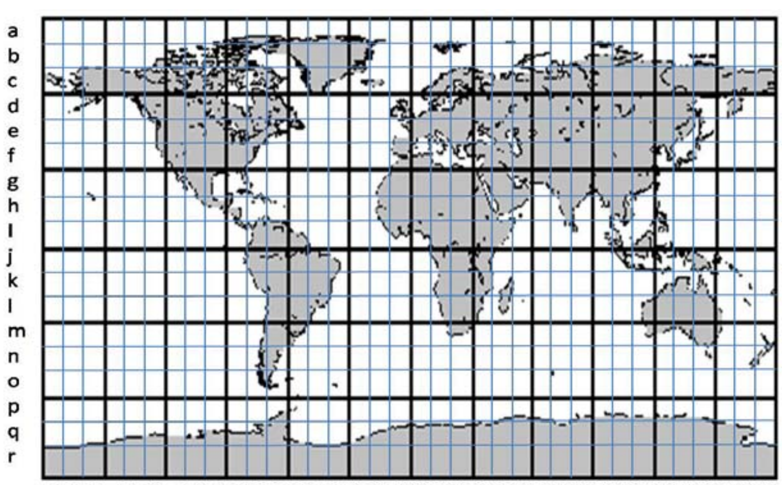

Fig. 6. 10 x 10 degree grid layout planned as basis for first AIM3 global energy resources modeling exploration.

We propose starting with a fairly simple model of the planet's surface, using an equal-area geographic projection for visualization. We take each of the 195 nations of the world (per

UNESCO 2003) as individual entities and we index them appropriately with a GIS-based surface grid, with resolution at 10-degree increments of latitude and longitude; this creates 18 latitude bands and 36 longitudinal bands, for a total of 648 geographic "boxes", labeled "a1" through "r36" (see Fig. 6, above). Countries that map across boundaries between boxes are indexed to the box in which the majority of their territory is located. Major cities on boundary lines are ascribed to boxes indexed to their nation. Note that boxes have different geographic areas, most boxes are ocean, some boxes will have more than one nation indexed to that box, while other boxes are indexed to a single nation.

A ten-by-ten degree grid is 100 times less data intensive than the 1-degree grid used for many emissions mappings currently (for instance in many aspects of IPCC modeling), which can allow an easier time initially in setting up many of the first indexing relationships in various databases and which is more realistic where much of the existing data sets are only presented as a single number per country; yet, this structure will also allow for easy aggregation of the existing 1 x 1 degree mappings and databases when appropriate. The resolution is also fine enough to provide useful visual separation for most of the major producing and consuming countries.

Causal Network Modeling

Translating monitored information into dynamic, causal network models allows further construction of dynamic linkages via Bayesian inference and reverse-engineering (see Fig. 7, below).

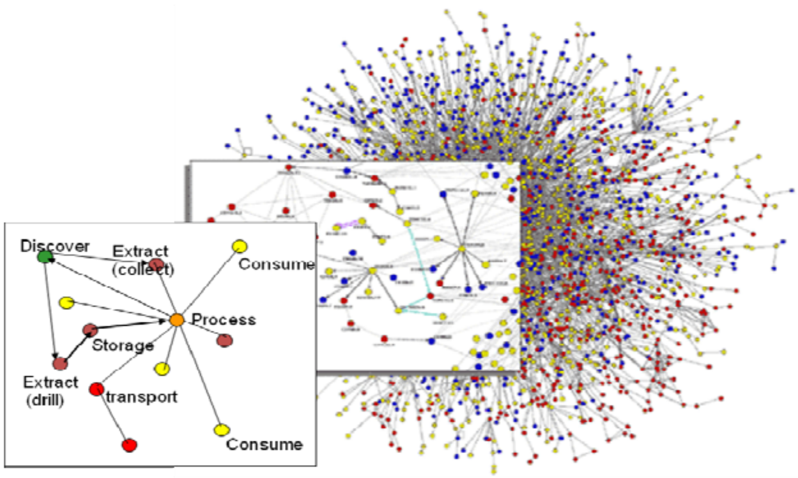

Fig. 7. Depiction of a network graphic visualization of a nested set of causal statements that describe relationships and exchanges between components and actors in the human system, planned as basis for first AIM3 global energy resources modeling exploration.

AIM3 Project Research Questions

We continue to hold forth and pursue the following research questions:

(1) How do patterns of energy-flow within various societal subsystems change, in terms of geographically mapped storage, transport, through-flow and use?

(2) What patterns of growth and/or stability can be seen in differing subsystems?

(3) Assuming subsystem flows can be modified, what instabilities in the energy through-flow per subsystem are introduced by such modifications?

(4) What subsystem leverage points present most responsive and/or most stable ongoing control (including presenting least instability in transition)? and

(5) Given instabilities or other difficulties created by converting energy sources for particular subsystem flows, how do these effects cascade more broadly through other subsystems?

Building simple models of energetic systems with minimal parameters

In order to develop a modeling approach that will (i) encourage participants to contribute parameter measurements, (ii) promote cooperative standardization of database structures and data access and (iii) entice valuable interdisciplinary collaboration into the learning effort, it is important to develop a modeling approach that is accessible and useful to a broad range of researchers, managers and observers. The complexity of many large-scale ecological economics models, similar to global-climate general-circulation models, limits their use to a small group of specialists and further limits the ability of the larger research community to leverage their many other skills and talents in a larger, collaborative effort. To be accessible, a model must be easily understandable, e.g., it should first map readily in the newcomer's or audience imagination as a straightforward mental model. With this in mind, we begin with as simple a model of an energetic system as we can describe.

A relatively simple model of a single organism is shown in Fig. 8, below, where a food resource external to the organism is captured, perhaps transported a distance, then eaten and converted internally to energy used immediately for the animal's purposes, or stored as sugars or fats and with the animal venting heat to the environment and likely excreting some waste.

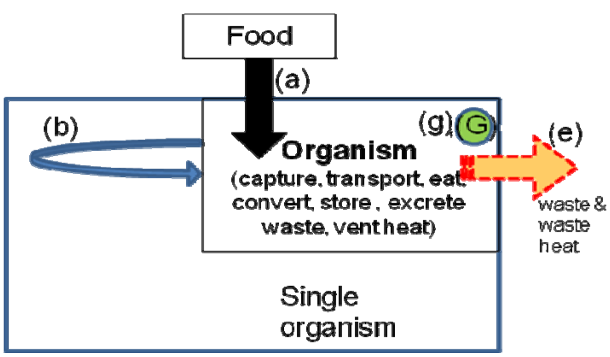

Fig 8. A simple model of system growth for a single organism, where food capture rate, a, will equal storage or growth rate, g, plus the disposal rate (waste material and heat emitted from work done by the organism). The use of resources for internal purposes, such as conversion (digestion) for energy and/or fat storage can be depicted by direct internal use rate (b). G represents stored resources (energy and/or material).

In Fig. 8, this simple model shows external food is captured by the organism at rate a and used internally and for the organism to do external work on the environment. The food capture rate, a, will equal the rate of resource use, g, to achieve storage or growth, plus the disposal rate, e (waste material and heat emitted from work done by the organism). The use of resources for internal purposes, such as conversion (digestion) for energy and/or fat storage can be depicted by direct internal use rate b. The energy use rate b can be partitioned into the energy used to create stored resource or growth, sb, and the energy for other living processes, including excreting waste materials and emitting waste heat, *wb*, and the combination of these will equal $g + e$, such that

$$a = e + g \text{ and}$$
$$b = sb + wb = g + e.$$

Note that although we can use parameter b, it is fairly well captured by knowledge of g and e, so that we essentially have a three-box model (environment, organism-in-process, and storage) and three flow parameters (a, g and e).

Now we can make the model a little more complex by adding more component participants to our energetic system, such as a parent organism plus children.

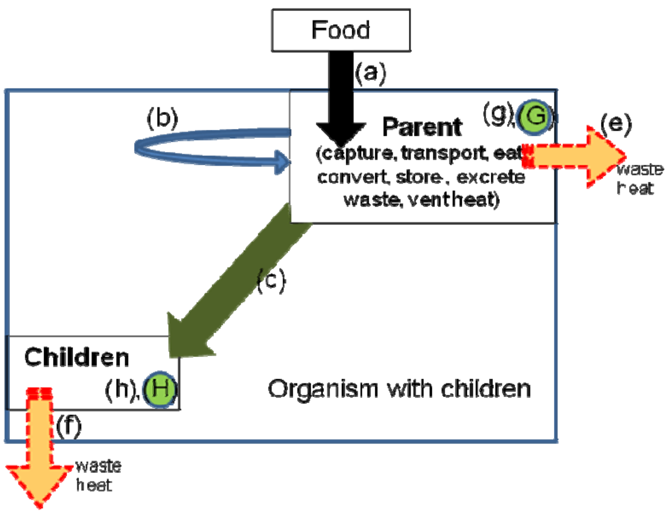

Fig. 9. Adding children components to our simple organism model of system growth. Food capture rate, a, will equal the sum of waste and waste heat for the parent, e, and for the children, f, plus the resources used for storage or growth by the parent, g, and for the children, h, respectively. Resources distributed to the children at rate c will equal waste f plus storage h. Parent's direct use rate (b). G and H represent stored resources (energy and/or material) for parent and children, respectively.

In Fig. 9, above, we have added components (children) to our simple energetic system model. Again, as in the single organism model, food capture rate, *a*, will equal the sum of uses to create growth and excrete waste, but now we have a rate for waste heat from the parent, *e*, and for the children, *f*, and for the resources used for storage or growth we have a rate for the parent, *g*, and for the children, *h*, respectively, or $a = (e + f) + (g + h)$. Resources distributed to the children at rate *c* will equal waste *f* plus storage *h*, so that $c = f + h$. Again, the parent's direct resource use can be described by rate *b*, which in our growing conceptual model might be expanded to include more activities of the parent in maintaining the family unit. ***G*** and ***H*** represent stored resources (energy and/or material) for parent and children, respectively. Also we can see that

$$c = a - g - e$$
$$= f + h$$

and

$$e = a - g - c.$$

The number of parameters and relationships are fairly few, so that knowing values for some of the parameters can allow others to be calculated by simply balancing flows. Counting G and H as separate storage boxes, we have a five-box model, with six flow parameters. A seventh parameter, *b*, can be useful in summarizing a process that is composed of flows *g* and *e*.

What if the children provide help to the parent in the household tasks, for example helping the parent to gather or capture food? To illustrate this, as shown in Fig. 10, below, we can add a return feedback flow, *d*, representing energy and/or materials that the children contributed back to the parent's sector. To maintain simplicity here, we will assume that the feedback does not draw down the children's storage, H.

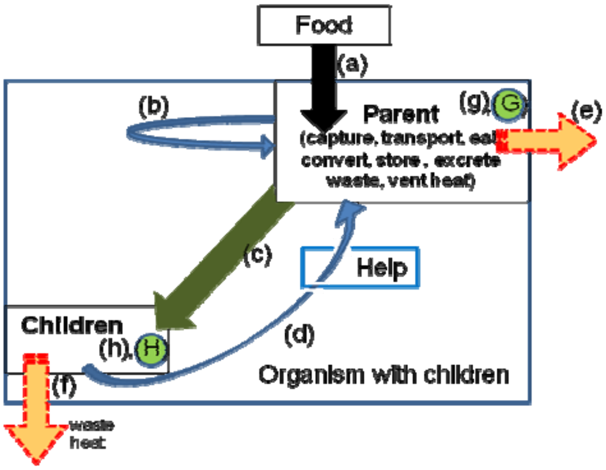

Fig. 10. Same as Figure 9, above, except now the children components provide help to the parent sector with feedback, d.

In Fig. 10, at left, with feedback, *d*, we still have resource capture rate, *a*, equal to the sum of uses to create growth and excrete waste, where $a = (e + f) - (g + h)$, and we have only a slightly more complicated task to do the arithmetic to calculate one or another parameters that are hard to discern from the other quantities that we may be able to measure more easily. For example,

$$c = (a + d) - (g + e)$$
$$= f + h + d$$

and

$$e = a - g - c + d.$$

Now, with another slight step-up in complexity, we can transition from our system model at the scale of related, interacting organisms to a similarly structured model for the whole of human society, with a prominent focus on the global energy industry and with all other sectors of society grouped into a single additional box (see Fig. 11, below). We bring into this picture also some key aspects of the energy-technology feedback, namely the dimensions of currency and capital and of useful information and technology (summarized in this picture as "know-how").

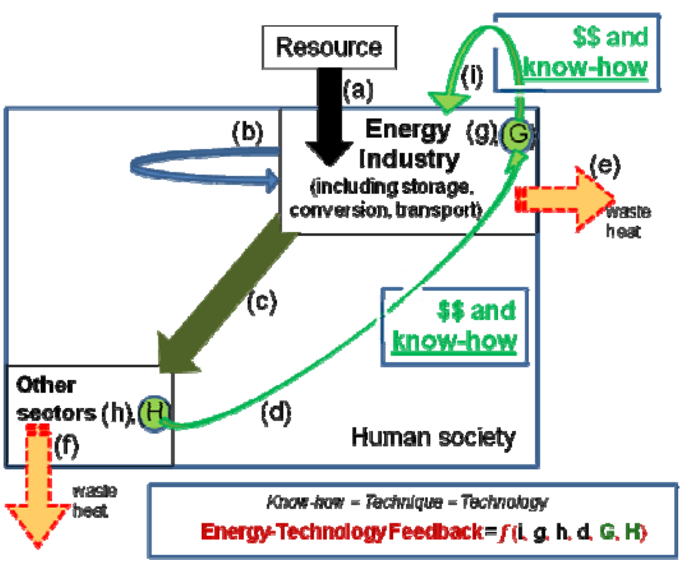

Fig. 11. A simple model of energy flow into the global energy-industry sector with resource capture rate, a, storage or growth rate, g, energy-industry waste (dissipation) rate, e, resource distribution to other sectors, c, growth in other sectors, h, and dissipation in other sectors, f. A feedback, d, from other sector's stored potential, H, runs to the energy-industry sector's potential storage, G, and the energy industry can draw upon this potential at a feedback rate, i. Resources distributed to the other sectors from the energy industry at rate c will equal the aggregate dissipation or waste rate of those sectors, f, plus storage rate, h, . The energy industry's direct energy use rate b can partition into g and e. G and H represent storage or increased potential in the energy industry and other sectors, respectively.

In Fig. 11, our energy flow model for human society depicts an external energy resource from which the energy industry captures at rate a and used internally at rate b for that sector's purposes, where b will partition into increasing potential at rate g and dissipating heat through work, e. The rate for dissipated heat from the other industrial and societal sectors to whom the energy industry distributes resources is f and the energy goes into potential or growth in the other sectors of society at rate h. Resources distributed to the other sectors of global society at rate c will equal waste f plus storage h, so that $c = f + h$. Note an important modification distinguishing Fig. 11 from Fig. 10, where here we have placed the inter-sectoral feedback d to draw from the storage H and deposit in the storage G, where an internal feedback i within the energy sector can draw down from G. This adds a complexity to calculating the flow balances.

Here, similar to the above organism examples, the energy industry's direct resource use can be described by rate b, which can include multiple activities of the energy industry in maintaining and growing its presence in the marketplace. G and H represent stored potential, but we now expand our concept of this stored potential to include the many aspects of energy incorporation in a growing energetic system (or subsystem), as described by this writer earlier (Lancaster, 1989). These aspects relate to the growth of the subsystem and the increasing energy density of the subsystem, which generally can be categorized under one or more of three modes:

(i) the residence time of the energy through-flow increasing by lengthened pathway and structural storage;

(ii) the amount of energy being channeled through the subsystem increasing; and

(iii) materials, including increasingly denser and/or energy-intensive elements, being incorporated into the subsystem.

Thus, this growth in every sector, G and/or H, may include lengthening of the energy pathway through the sector by adding and dynamically coordinating various growing subsectors incorporating of material (servicing, R&D, transportation, public relations, strategic security, lobbying, for example). Stored potential can include not only the direct storage of energy recently extracted from the environment (such as oil, gas, or coal), but can include the growth of people and/or employees in this sector, the growth of buildings, equipment, vehicles and/or vessels, the growth of invented methods (know-how) in every way employed by the sector, the growth and storage of capital that can be used to purchase work and materials from the other sectors, the lengthening of the through-flow pathway by increasing any and every way that energy can be found to reside within the definable boundaries of the subsystem associated with each sector. Additionally, as will be discussed further below, this storage/growth function for the energy industry, G, particularly, may be considered to include the extension of the power of this sector by its control and/or essential ownership of other sectors that may have originally developed independently for other purposes and functions. From Fig. 11, we can see that

$$e = a + i - g - c$$

so that

$$\begin{aligned} a &= e - i + g + c \\ &= b + c - i \end{aligned}$$

And then

$$\begin{aligned} c &= a - g - e + i \\ &= h + f. \end{aligned}$$

Finding numbers for estimating the flow parameters

Putting this model into service requires associating numbers that we might discern from various measurements that we may hope to find in existing databases. For the purposes of creating a simple illustration of the modeling approach in this paper, we will allow ourselves to take various numbers from the literature without making detailed adjustments and corrections for differing capture rates that may pertain for oil, coal and gas resources, respectively, while still allowing ourselves to use other metrics for other parts of our exercise that might include some renewable energies. The point here is not yet to obtain a sharply accurate, quantitative result in a dynamic model, but rather to explore the concepts in more gross detail in order to test the logic and instruct about which particular resource parameters and measurements will be important to include accurately in the future. It is not efficient as a research approach to spend enormous effort in making a model extremely complex and accurate in minute detail, if one is to perhaps soon learn that the current approach contains conceptual flaws. The path chosen here, then, is to get something simple working quickly that many people can test and augment themselves with further data refinements, with this collaborative effort giving guidance as to the eventual detail and accuracy required. Capture rate a, then can initially be considered to be the gross oil, coal and gas production, which may be in tons of oil equivalent per year, as in Fig. 12, below..

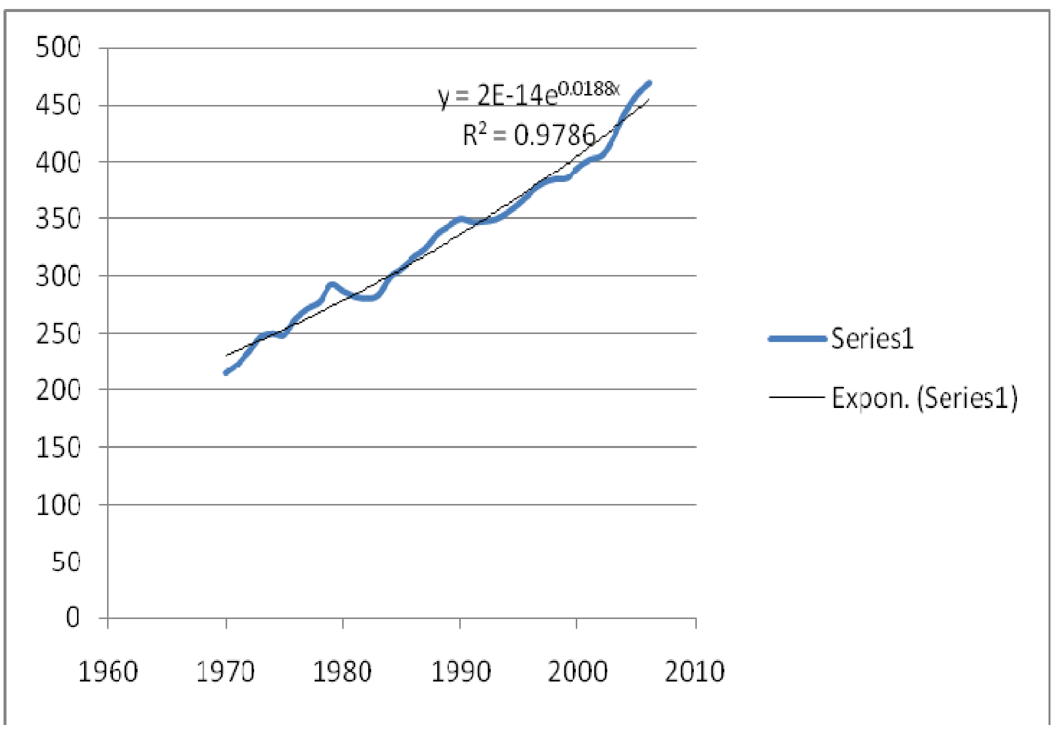

Fig. 12. World Primary Energy Production, 1970-2006, in Quadrillion Btu, including Coal, Natural Gas, Crude Oil, Plant Liquids, Nuclear Electric Power, Hydroelectric, Geothermal and Other. (Source: Energy Information Agency. DOE/EIA, June 2009. Exponential trend line to data is y = 2E-14e^(0.0188x).

An exponential trend-line fits well to the world energy production curve in Fig. 12, above, reflecting aspects of growth in the energy acquisition process that may be self-reinforcing, i.e., which may derive from positive feedbacks between energy acquisition, technology growth, population and/or investment in the sector. With good accounting at the national levels, the global production and consumption modeling can be integrated with higher-resolution, nested, submodels. For example, In Figure 13, below, the total energy consumed in the U.S. circa 2001 from various domestic sources and from imported sources is shown partitioned in multiple downstream flows for various economic sectors. Note that the two major downstream paths, “Rejected energy” and “Useful energy”, would map appropriately to flow parameters *e* and *g*, respectively, for a national-scale, reduced-form, energy-flow model as shown in Figure 11, above.

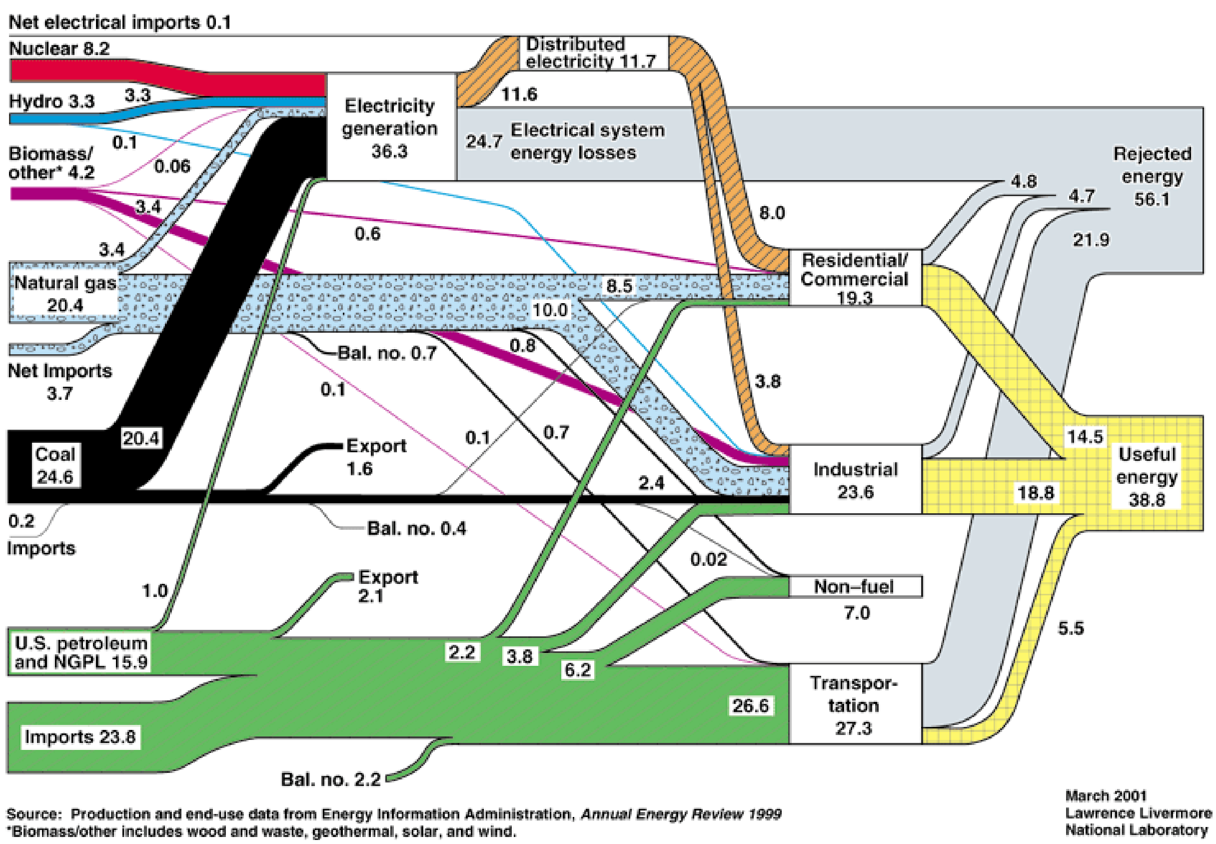

Fig. 13. Example of detail available in energy accounting between sources and uses in various sectors of the economy in the U.S. circa 2001. Quadrillion btu.

Relating GDP to energy consumption

Many researchers and commentators have pointed out that the close association of gross domestic product (GDP) and energy consumption allows the former metric to stand in for direct measurements of the latter. For example, Narayan and Smyth (2007) find that a 1% increase in energy consumption increases real GDP by 0.12–0.39%, while a 1% increase in capital formation increases real GDP by 0.1–0.28%. In Figure 14, below, we can see that the lower curve for production related to CO_2 emissions has matching shape and fine-scale structure to the upper GDP curve.

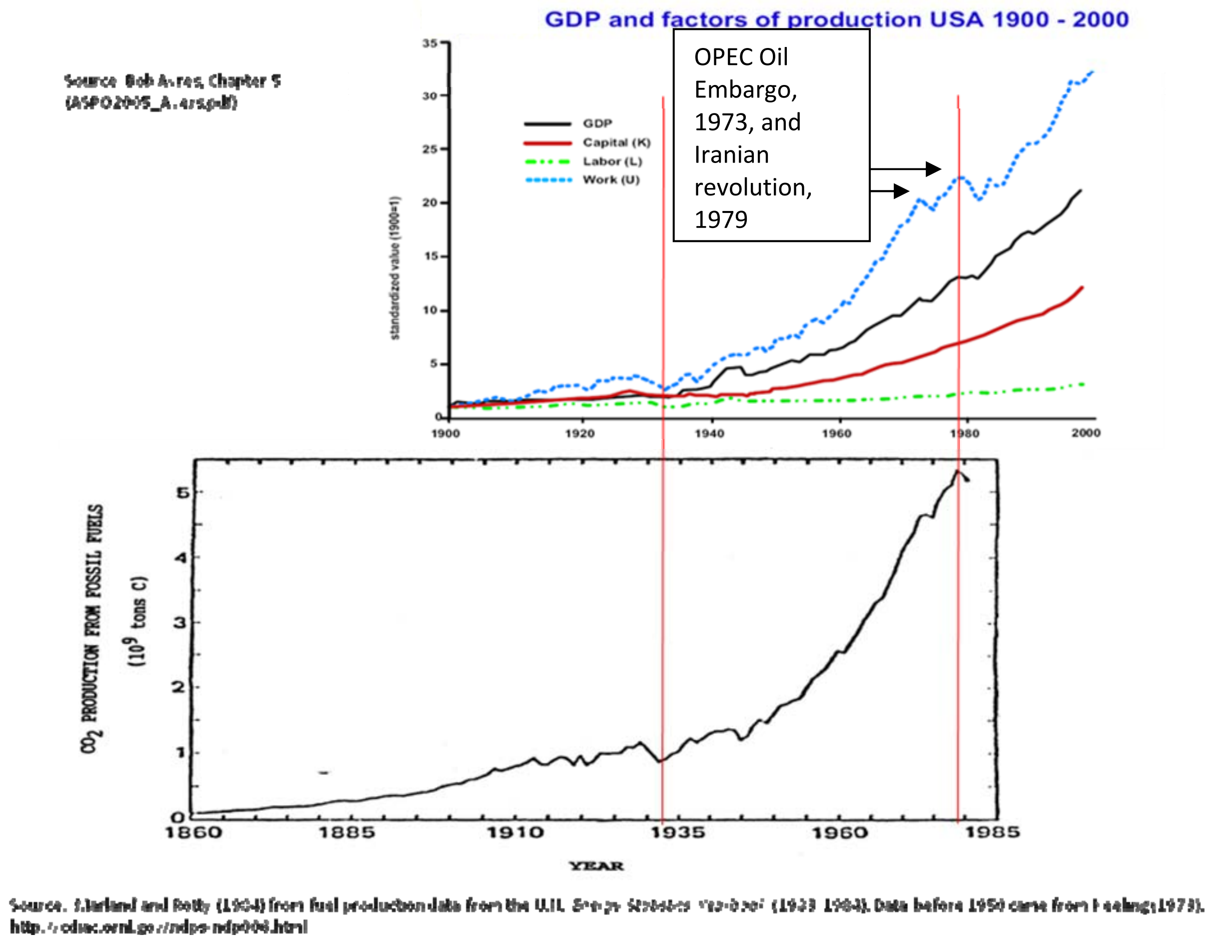

Fig. 14. The exponential growth of oil production, which tracked closely with the growth of GDP, was dramatically altered by shifting politics in the middle east in 1973 (OPEC oil embargo) and 1979 (deposing of the Shah of Iran, which led into the Iran-Iraq war in the early 1980s.

In a coarse sense, we can take money expended for a product and a service to represent the energy delivered, such that the revenues derived by the energy sector can give us an approximation of flow *c*. To get this number quickly here, we can start by assessing the aggregate revenues of the supermajor oil companies for whom access to financial information is most readily available to us, together with making some looser assumptions about what % of the overall market this group represents. Using an average ratio of enterprise value to revenues of 1.0 (approx. +/- 0.15, based on only four supermajor oil companies reporting revenues), the revenues of seven supermajor O&G companies appear to total approximately 1.44 trillion USD. Estimating these supermajors to represent about 5% of the resource power of the oil and gas industry would yield an estimate of 28.8 trillion USD for the overall oil and gas sector. If the group represents 10%, then the total revenues are about 14.4 trillion USD. This may be too high.

A recent commercial market report of total global energy industry revenues for 2008 puts this as 10.273 trillion USD in 2008, with a compound annual growth rate (CAGR) stated to be 25.5% for the period spanning 2004-2008. The Americas and Asia-Pacific industries reached respective values of $3.4 billion and $2.8 billion in 2008. Oil, gas, and consumable fuels sales generated total revenues of 10 trillion, equivalent to 97.6% of the industry's overall value (DataMonitor, 2009). The global coal market grew by 20.7% in 2008 to reach a value of $338.6 billion (Energy Business Report, 2009).

Using an average of approximately $90 per barrel ($/bbl) price for 2008 (see http://www.ioga.com/Special/crudeoil_Hist.htm), we can ask if the revenues of the energy industry can be reverse-calculated to derive the distribution flow *c* by dividing this 2008 average price into 10.273 trillion USD in 2008 revenue for the industry; this yields 114 billion boe for our estimated flow *c*, which is equivalent to about 15.6 billion metric toe or 6.618 x 10^17 BTU (661.8 quadrillion btu). However, quickly we can realize that this number is too high, given that the total energy production in Fig. 12, above, had yet to reach 500 quadrillion btu by 2006. This indicates that either our average price is incorrect, i.e., the revenues derived by the industry must be weighted toward the periods of higher prices in 2008, or that the industry revenues compensate a value-add over the direct price of the resource alone, or that energy production and distribution leaped enormously in 2008 (probably not the case). We can check the production in the following dataset from BP that covers through 2008, showing about 11.3 billion toe for global consumption in 2008 (See Fig. 15, below).

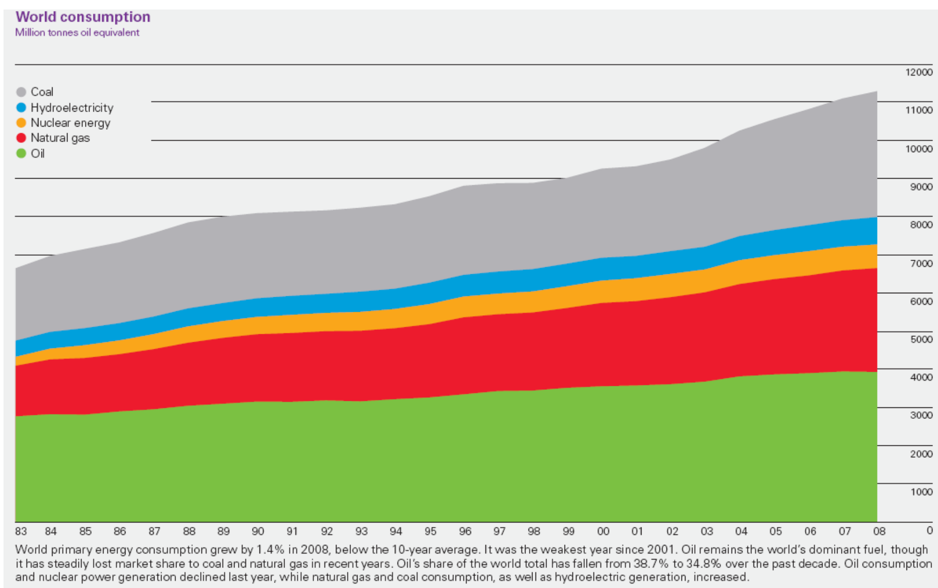

Fig. 15. Total world energy consumption of major fuel sources, 1983-2008, in million toe. BP Statistical Review 2009.

Sales of energy equipment and service generated revenues of $251.6 billion in 2008, equating to 2.4% of the industry's aggregate revenues (DataMonitor, 2009). Being related to the expenses of the oil and gas companies, these numbers contribute to flows *g* and *e* in Fig. 11, above.

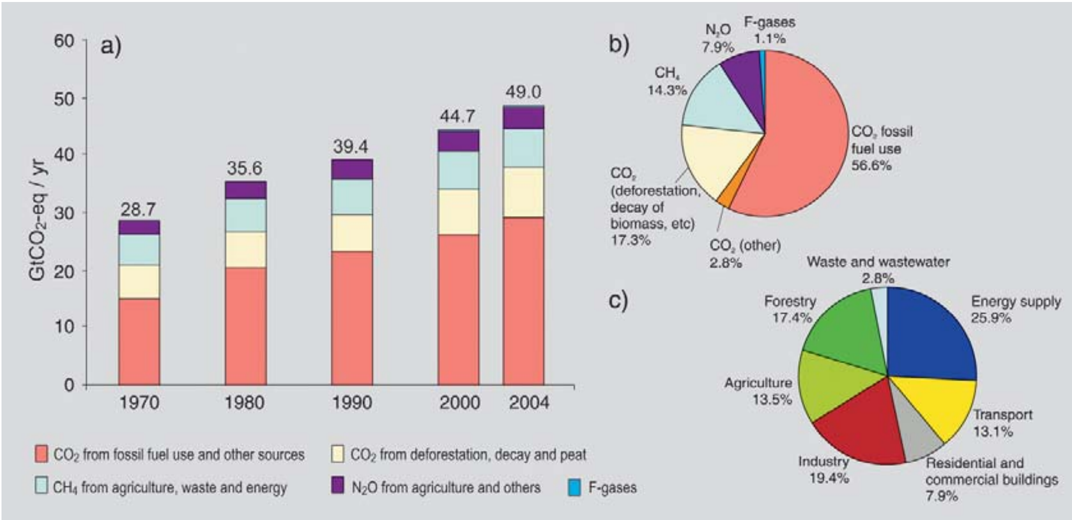

Fig. 16. Energy use by societal sector, suggesting about 30% of energy used is associated with energy supply activities. Intergovernmental Panel on Climate Change. http://www.ipcc.ch/graphics/syr/spm3.jpg.

In Figure 16, above, the percentage of energy used by the energy supply industry itself, which would include the equipment and service subsector together with the energy expenditure of industry operations, amounts to about ¼ of total energy consumption. This seems a rather large percentage, suggesting verification of this interpretation is warranted; however, once this fraction can be measured or estimated with confidence, then we will have our flow rate *c* in the reduced-form model of Fig. 11, above, which here would suggested to be $c = 0.25 \times a$.

The overall consumption of energy at the global scale, if we consider *g* and *h* to be small in Figure 11, above, should be equivalent to the emitted, dissipated energy, which can be approximated from CO_2 emissions monitoring and reverse calculations. One problem we encounter here, however, is that some of the estimates of CO_2 emissions are actually made by estimating back in the other direction, i.e., by aggregating the energy consumption derived from accounting by various sectors and countries of the distribution *c*. This makes it very hard to discern *g* and *h*.

Production and Consumption related to Emissions

Consumption numbers can be associated with changes in carbon emissions data (Forster et al., 2007; Boden et al., 2009). For example, from 1990 to 1999, the emission rate due to fossil fuel burning and cement production increased irregularly from 6.1 to 6.5 GtC yr^{-1} or about 0.7% yr^{-1}. From 1999 to 2005 however, the emission rate rose systematically from 6.5 to 7.8 GtC yr^{-1} or about 3.0% yr^{-1}, representing a period of higher emissions and growth in emissions than those considered in the 2001 Third Assessment Report (TAR).

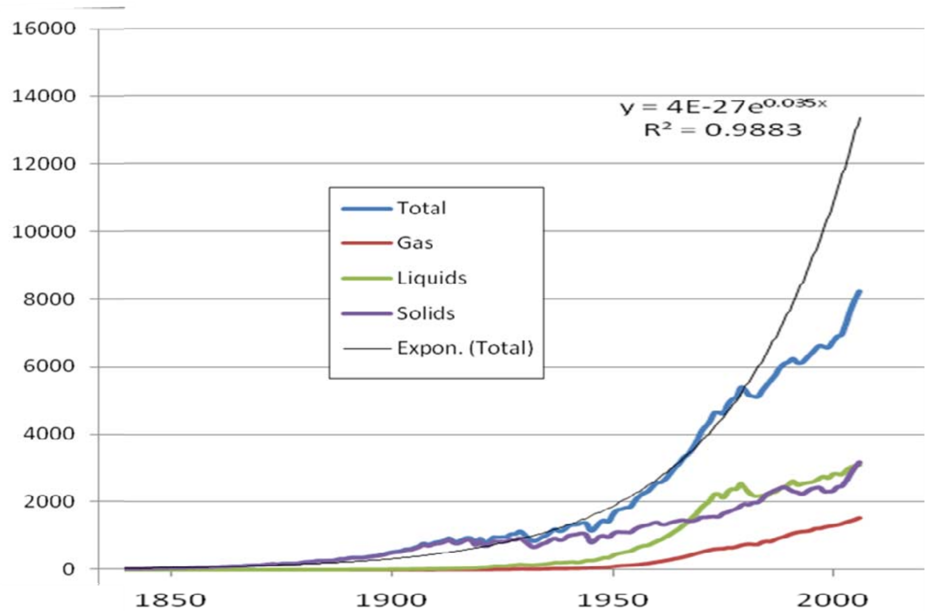

Fig. 17. Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2006. Emission estimates expressed in **million metric tons of carbon**. (Boden et al., 2009). Exponential trend line y = 4 E-27e^(0.035x) is fit to global total

CO_2 emissions owing to global annual fossil fuel combustion and cement manufacture combined have increased by 70% over the last 30 years (Forster et al., 2007), as shown in Figure 17, above). Globally, liquid and solid fuels accounted for 76.6% of the emissions from fossil-fuel burning and cement production in 2006. Combustion of gas fuels (e.g., natural gas) accounted for 18.5% (1521 million metric tons of carbon) of the total emissions from fossil fuels in 2006 and reflects a gradually increasing global utilization of natural gas. Emissions from cement production (348 million metric tons of carbon in 2006) have more than doubled since the mid 1970s and now represent 4.2% of global CO_2 releases from fossil-fuel burning and cement production. Gas flaring, which accounted for roughly 2% of global emissions during the 1970s, now accounts for less than 1% of global fossil-fuel releases (Boden et al., 2009).

Next steps

Important next steps include developing logically balanced and interrelated datasets that can easily be accessed and utilized to study more subtle aspects of particular subsystem growth relative to larger, aggregated regional, national and/or global values. For example, a recent inventory assessment by Valero et al. (2009) provides an inventory of the natural capital on earth in terms of exergy, which includes not only renewable and non-renewable energy resources, but also non-fuel minerals.

The power of the human energy industry to resist control upon its own growth is staggering, yet also profound is the commitment of those who believe that such control must be achieved and that it can be accomplished, with care and with positive effect. Along with these persons, this writer remains committed to making these next incremental steps toward creating know-how and material technology that could help reach such a positive effect.

* * *

"... with every right time,
Dagan rises,
Giving energy for Trigonometry
Jacobian fundamentals
& Jacquerian fasciculae."
~ J.M., 1963

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[Notation penned in the margin at p. 273: Akademos Decahedral octuple illuminating radially, reviving Junto's baroque forgathered Joubert genre; PM,BF,SirJP,LJPdeD,LXVI; Cannot Judge friend's reasons Hastily DaVinci's Immortal Illustrated Journal republished, 1767; "Joint optics Jostling fluxions intriguing Volta," DAlembert reasoned. "Holbach's Identity Doubtless Cubic Jurat; incept Smith Thiry, unitary Divergent geometric three Dimensional operators." TJ.VA.1826]

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