Integrated Monitoring, Modeling and Management (IM3) Methodology

Applied to Governance of Global Energy Resources and Global Energy Use

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Introduction

Persons interested in governing uses of global energy resources can be helped by research models designed to improve our understanding of how growth and stability functions are fundamental to energy use and how these functions may constrain the range of options available for governance. How to measure and/or monitor the positive feedback between energy incorporation in a subsystem and technological advancement in that subsystem is discussed as central to this effort.

Developing a learning model to explore how energy dynamics relate to the growth and stability of social systems and subsystems, the research model itself can be viewed as a growing knowledge system. Usefulness and value are key aspects in both the energetic system being studied and the knowledge system being developed. Parallels in information and energy are kept in mind, particularly as method is related to technique and technology.

The Integrated Management, Modeling and Measurement (IM3) methodology (a) translates into computer form the mental models of managers, (b) merges the formalized mental models with scientific models for explaining relationships and dynamics in gathered and/or measured data, (c) makes the merged modeling layer transparent and accessible to managers and adjustably and robustly responsive to their queries, and (d) designs the data-gathering to be flexibly and rapidly adjustable to the data needs of the modeling layer and thus to the manager's queries as the manager anticipates a decision.

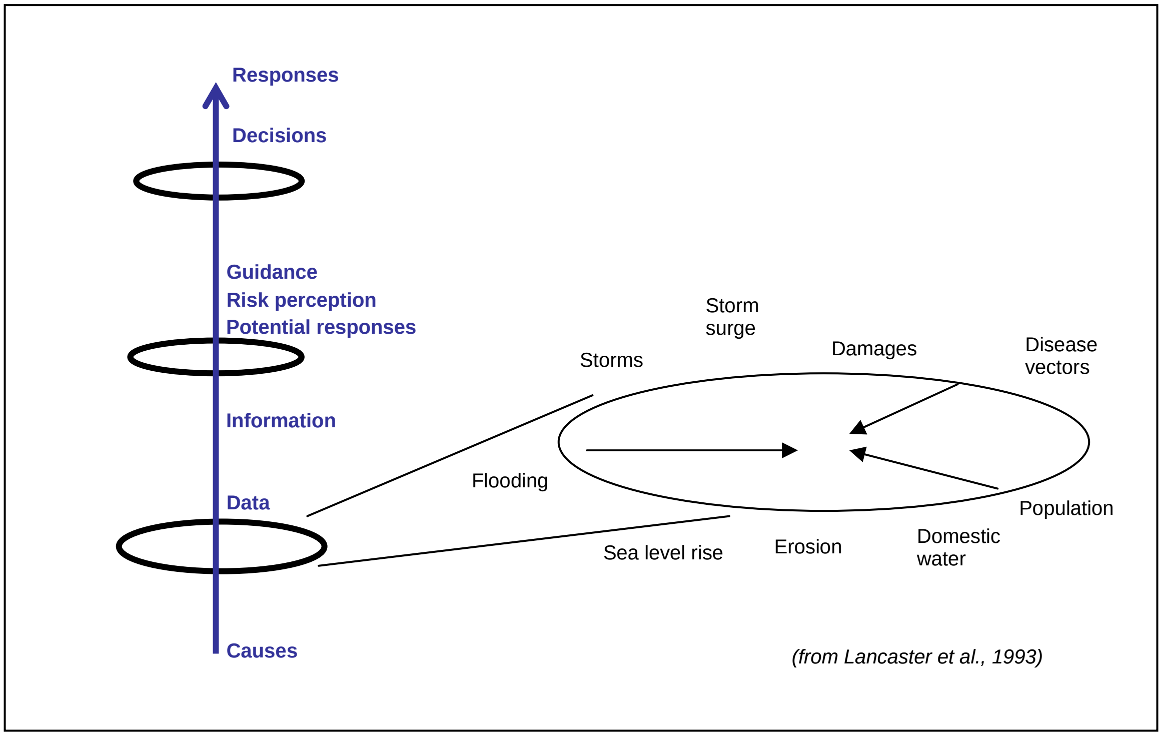
The IM3 methodology was initially applied in 1995 to enhance governance of water resources in the Charles River watershed in eastern Massachusetts (USA). The collaboration involved citizens and stakeholders from 26 cities and towns in five different counties, multiple state and federal environmental and resource agencies, science teams from eight universities, and more than five public-interest non-profits.

The IM3 methodology fostered information exchange and feedback between managers, modelers and data-gatherers, while improving understanding of the dynamic system being studied through the modeling layer. Resource characteristics, cost, stakeholder viewpoints, switching and displacement of use, value of information, utility, subsystem boundaries and nesting of subsystems are shown to be key aspects of improving analysis.

The IM3 methodology can be applied to the problem of governing energy resources, energy use and the energy industry. A combined factor of energy and utility may assist the modeling effort. This factor can be a compound function of growth and stability, including (i) switching resource flow in multiple subsystems and (ii) growth of subsystem network components through an energy-technology feedback (ETF). A non-subjective measure of usefulness is proposed that is derived from the dynamic modeling of an energetic subsystem. Network components for this modeling include nodes (actors: e.g., governments and corporations), arcs (actions: e.g., discover, extract, store, transport, process, sell, purchase, consume) and multiple physical objects related to the arcs.

The Integrated Monitoring, Modeling and Management (IM3) methodology

An interdisciplinary study sponsored by the U.S. Department of Energy in 1991-1993 examined approaches for integrated assessment of the potential impacts of global environmental change on society in service to decision-making (Lancaster et al., 1993). The many challenges of assembling multiple levels of data and models, uncertainty in measurement and modeling, value of information, human perception of risk, reduced-form modeling of complex systemic interactions were examined. As shown in Figure 1, below, two dimensions of an integrated assessment in the context of climate change can be visualized. One dimension can be thought of as a "vertical integration" that rises from studying causes and impacts through estimating risk and potential responses and then through decision-making to arrive at actual responses. Another dimension can be described as a "horizontal integration" that is related to each level of the vertical integration. This horizontal integration combines many physical and socio-economic aspects of a regional case study that can be seen to interact on a geographical scale. Regional, econometric input-output models, for example can be built for each economic sector and their interactions with each other and with environmental changes mapped through a geographic information system (GIS).



(from Lancaster et al., 1993)

Fig. 1. Integrated Assessment approach for examining Climate Change Impacts. A vertical integration causes and data, through risk and response analysis to decisions and actual responses, while a horizontal integration combines physical and socio-economic aspects interact on a geographical scale (Lancaster et al., 1993).

Adjustable data-gathering responsive to modeling layer and manager's queries

As a manager anticipates a decision, he or she gathers information upon which to predicate that decision. This information is made part of the manager's mental model or set of mental models, a process that may be assisted by incorporating the information into computer models (which may be expert systems) to derive secondary information that will guide and/or alter the manager's mental model(s). It is useful to design the data-gathering process to be flexibly and rapidly adjustable to the data needs of the modeling layer. Further, the data-gathering step can be made adjustable in response to a manager's queries: the modeling layer, in response to the manager's query, can recognize its new data needs and adjustably instruct the data-gathering process.

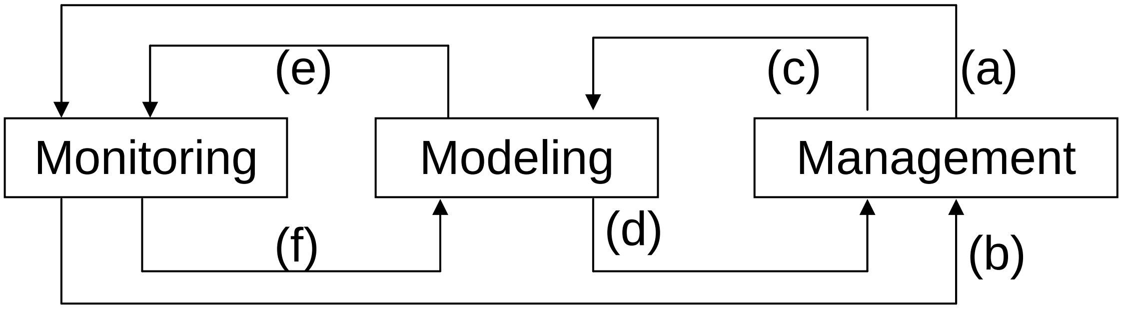


Fig. 2. Adding control steps between a modeling process and a data-gathering function (monitoring) to integrate monitoring, modeling and management in the IM3 methodology (Lancaster, 1994).

Referring to Figure 2, in a traditional method of decision-making, managers direct an information-gathering step (a), which may include monitoring or measuring, whereupon the information is returned to the managers in step (b). With the advent of numerical modeling, management began to pass the information to a modeling group (c), and the results of the modeling would be returned to managers in step (d). An Integrated Monitoring, Modeling and Management (IM3) methodology gives the modeling division and/or the modeling objects various degrees of control over the monitoring process in step (e), and brings the data back to the modeling process in step (f). (Lancaster, 1994)

In an iterative learning model, this modeling-monitoring control linkage can be connected to rules-based, guidance module, such that the data-gathering (which can be lab or field experimental, or ongoing monitoring) can be automatically redirected by the guidance module based upon the robustness of the result being created with the modeling routine. This is somewhat related to a Monte Carlo, iterative modeling exercise, where a series of parameter inputs are altered during a series of model runs to test sensitivity and robustness, except that in the IM3 approach, instead of artificial inputs the model is receiving a variation of measured and/or gathered data. In fact, the two approaches can be used together effectively, where variation of parameters yielding a range of results can, through the rules-based guidance module, determine the next-desired set of actual measurements to be obtained. In this fashion, the value of data gathered is maximized and the modeling effort is able to focus more rapidly on a particular response to a particular query.

Applying the IM3 approach in regional water-resource governance

The Integrated Monitoring, Modeling and Management (IM3) methodology has been used since 1995 to enhance governance of water resources in the Charles River watershed in eastern Massachusetts (USA). The Charles River Watershed IM3 (CRW-IM3) project was instigated as a collaboration between the Charles River Watershed Association and the Environmental Science and Policy Institute (ESPI), with funding from local, state and federal agencies. The project involved collaboration of citizens and stakeholders, multiple state and federal environmental and resource agencies, science teams from eight universities, and more than five public-interest non-profits (Lancaster et al., 1995).

Measurement – Gathering information

The measurement aspect of the CRW-IM3 project has included monitoring flow, water and sediment quality, habitat and biota; modeling hydrologic, water quality and economic conditions in the watershed and involves the cooperative efforts of CRWA staff, several university research teams, a network of over 100 volunteers, and several state and federal agencies.

Modeling

The modeling of the watershed was designed by ESPI and MIT. Researchers at MIT developed an advanced flow model of the Charles River that included inputs from tributaries and groundwater. The river was mapped into an ArcInfo® geographic information system (GIS) that included data-layers for political boundaries and land use. Together with an MS-Access® database structure, the information system allows for tracking and mapping water quality data and rapid and complete visualization of water quality within the watershed over time.

The flow modeling developed by MIT was adjustable and responsive to rainfall, groundwater flow and river-flow observations within the watershed, and the flow modeling was also integrated with a dynamic water-quality model that accounted for response in water quality depending on levels of different types of pollution in water sources entering the river.

With known flow observations and measured water quality observations, running the integrated dynamic model in reverse allowed prediction of pollution source locations. The CRW-IM3 project was designed to enable the modelers to rapidly relocate measurement points within the watershed to increase resolution spatially or temporally along the river's length, up tributaries and in response to varying source conditions (e.g., degree of precipitation, temperature variation). The wealth of data gathered over time allows high-confidence prediction of water quality at any location and at moment.

Management

Management of the water resources of the Charles River is a shared proposition at the local, watershed, regional, state and federal scales, and among government, citizen, and corporate (non-profit and profit) interests. At the local scale are 26 political jurisdictions, ranging from sparsely populated towns to the substantial cities of Boston and Cambridge. The larger towns and cities have local Water Departments tasked with delivering potable water to citizens, installing and maintaining delivery pipes, protecting sources, pumping and waste-water management. At the watershed scale are the non-profit Charles River Watershed Association (CRWA) and Conservation Law Foundation (CLF) focused on resource protection and use management. At the regional scale is the Massachusetts Water Resource Authority (MWRA), a state-spawned, semi-autonomous agency with its own taxing authority that reaches over multiple cities to manage resources, quality, delivery and waster-water management. At the state level is the Massachusetts Department of Environmental Protection (DEP), and at the federal level are the U.S. Environmental Protection Agency (EPA) and the U.S. Army Corps of Engineers (ACE). DEP and EPA are concerned primarily with resource protection, while ACE has a mixed agenda of flood-control and use permitting. Corporations also play a role in management, de facto, particularly power plants that utilize large amounts of cooling water.

Figure 3, below, illustrates the integrated monitoring, modeling and management (IM3) project in the Charles River Watershed. As in Figure 1, a “vertical integration” rises from data-gathering (monitoring) passed into a step of data aggregation and analysis (modeling), and then to a management level where decisions are taken. The “horizontal integration combines many physical and socio-economic aspects (including uses and environmental aspects) that are mapped per geographic region and which are relevant to each level of the vertical integration (Lancaster et al., 1995).

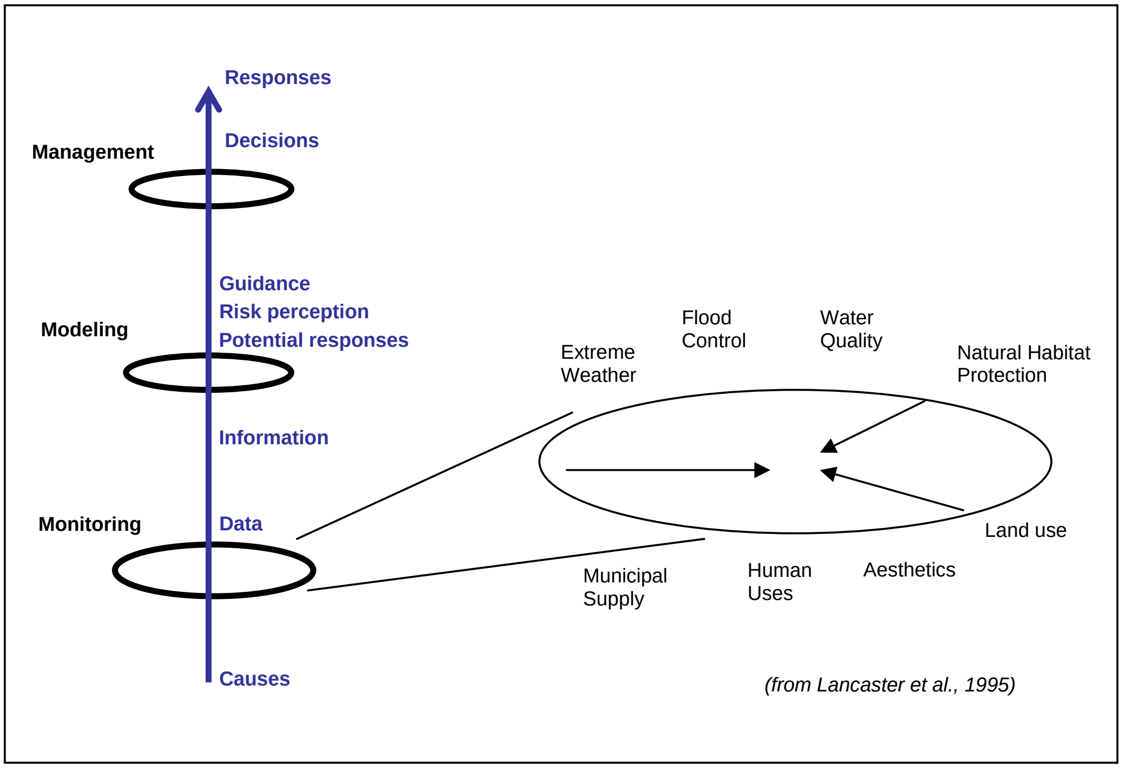


Fig. 3. Integrated Monitoring, Modeling and Management (IM3) applied to water resource management in the Charles River Watershed.

The primary challenges of this approach include translating into computer form the mental models of managers, merging formalized mental models with scientific models for explaining relationships and dynamics in gathered and/or measured data, and making the merged modeling layer transparent and accessible to managers and adjustably and robustly responsive to their queries

Enhancing information exchange and feedback between managers, modelers and data-gatherers

The CRW-IM3 program allows a very large network of data-gatherers to pass their data into a collection and modeling phase that regularly presents the information to managers. Notably, the structure of the monitoring network allows rapid response to impending rainfall and adjustable response to requests from the modelers. For example, within a few hours of a local weather forecast predicting heavy rainfall within the watershed, the modelers can redirect through monitoring coordinators the efforts of a group of 60+ volunteers, previously trained in EPA quality-controlled techniques, to a shifted time sequence and new spatial resolution for a specific sampling run. Data gathered by universities and non-profit groups is collectively organized for rapid access by government managers. The information also finds its way into the court system, where non-profit interest groups, armed with a wealth of focused and credible data, are better able to pressure responsible governmental action for resource management.

Improving system understanding through the modeling layer

Numerous dimensions (parameters) of the management and use of water resources can be pulled into a modeling layer to assist and improve the manager's analysis. These parameters can include resource characteristics, cost, stakeholder viewpoints, use, switching and displacement of use, value of information, utility, subsystem boundaries and nesting of subsystems.

Resource characteristics of the water resource within the Charles River Watershed include surface run-off, groundwater in aquifers at various depths, ponds, lakes, marshes, rivulets, streams (tributaries), and the Charles River watercourse itself. Building a modeling database of the resource includes characterizing many aspects of each of these, including amount (volume, length, flow rates), water quality, and location. The extent and location of each aspect can be mapped in a geographic information system (GIS), which couples geospatial information with multiple attributes in a relational database. Dynamic models can be written that automatically access

Cost is both a monitored quantity and a calculated quantity based on the modeling. Water is bought and sold by industry and governmental agencies, and these prices can be monitored. As well, the cost of delivering a liter of potable water to the public can be calculated through the modeling layer with respect to different management queries, e.g., by differing political boundaries (county, city, or regional water authority district). The cost of maintaining a section of the river at a certain level of water quality can be calculated. Or, the cost of improving water quality in a particular input can be discerned. Importantly, the change in cost that would be caused by a potential decision and infrastructure change can be estimated through the modeling layer.

Uses of the resource include household uses (drinking, bathing, cooking, lawns and car-washing), agriculture (crops and livestock), industrial processes, cooling water for power generation and manufacturing, recreation (fishing, boating, swimming), transportation, ecological preservation, and aesthetic (including real estate valuation). Switching and displacement of use can be mapped in terms of cost/benefit per use sector, per stakeholder group, per political unit and per geographical unit.

Stakeholder viewpoints are incorporated deliberately into the methodology because the management process requires the balancing of values placed by citizens on various uses, as well as realistically accounting for the economic and political power of various stakeholders. In the CRW-IM3 project, a series of community meetings were designed to invite stakeholders to the table along with surveys designed to elicit information about valuation and political acceptance of certain, potential decisions. Stakeholders include citizens, business owners, city managers, multiple state and federal agency personnel and managers, and non-profits entities, among others.

Value of information in the IM3 methodology can be viewed from multiple vantage points. In the larger sense, the value of engaging in collecting data and gaining secondary information (derived results) through the modeling layer can be assessed in terms of how useful is the guidance to decision-makers. Reductions in political conflict (measurable as reductions in court costs all around), reductions in commercial risk contingency (e.g., related to risks failure to achieve permits), and increases in use benefits (e.g., numbers of boaters & swimmers times days of use) are examples of measurable quantities from which a value of the process can be derived. In more specific detail, the value of particular monitoring activities can be valued for how much they contribute to knowledge of the modeled system, within some degree of certainty. Once the dynamics of a flow regime in the river are understood in detail, for instance, the value of fine-resolution monitoring falls off quickly, because one or two flow measurements can serve as proxy measurements for the greater system; in other words, a reduced-form model can be created that allows estimation of any part of the greater system with a high degree of confidence.

Utility, to be discussed in greater detail below, can be related to perceived benefits of the water resource per differing uses, as well as perceived benefits of various management decisions. How useful is one liter of water? How valuable is one liter of water? For example, certain amounts of the resource are absolutely necessary to keep people alive in the watershed; are these uses, at a certain level of water quality, considered the most valuable? Metrics for the utility of a potential decision, for instance to switch use and/or reallocate resources can be very subjective as a multiple function of the perceptions of many stakeholders.

An analysis of water resources in a watershed might appear to be simplified by having a distinct watershed boundary for the physical area of study. While the watershed boundary does provide a useful constraint, very quickly the study encounters cross-boundary aspects. For instance, many political subdivision cross into other watersheds, many commercial enterprises make decisions based on resources available from outside the watershed, many state and federal decisions incorporate external factors, and economic analysis within the watershed can be dwarfed by external economic considerations, particularly where a state or federal agency make be making taxation and resource trading decisions to allocate cost and benefit across multiple watersheds. Also, nesting of subsystems becomes a challenging aspect of the analysis and management, where commercial interests within single cities can compete versus neighboring interests within the same city, and then city interests between neighboring cities can be in competition. Overlapping subsystems pose challenges, too, where a non-profit association can reach over many cities, or a taxing authority and water supply district may reach over only a portion of the watershed.

Applying IM3 for Learning about Global Governance of Energy Resources

The Integrated Monitoring, Modeling and Management (IM3) methodology can be extended to the problem of global governance of energy resources, energy industry and energy use. This undertaking is enormously more challenging than applying the methodology in a single watershed toward water resources; however, most of the basic structure of the approach can remain similar. One of the biggest challenges is the scope of the task: global energy resources include many forms, including fossil fuel resources, direct solar energy, indirect solar energy (wind, wave, hydroelectric, short-term biomass), tidal, and nuclear. The cataloging and mapping of uses is almost without limit, with many dimensions of use in human and non-human systems. And management, or governance, involves an enormous number of stakeholders at local, state, national, and international scales (Bierman, 2007).

It is important to ask "Why this exercise?" As for any research, when the goal of the study is more clearly formulated, the structure of the research project will be more likely to produce a useful result. For instance, the IM3 study for the Charles Watershed, discussed above, was desired by stakeholders to improve the local and regional management of a critically important resource that had been degraded by uncoordinated management. In the case of global energy resources, concerns about global warming have created intense scrutiny on carbon dioxide emitted from burning fossil fuels. In addition, concern exists about sustaining and/or converting a fossil-fuel-driven economy through an impending decline of oil reserves (Watkins, 2006), which may be a causative factor of recent and current wars and which will eventually require converting and substituting resources (Dasgupta, 1993; Smil, 2000; Elzen et al., 2002; Gielen and Unander, 2005). For either of these reasons, learning more about the movement of global energy resources through human society can be useful; however, for each concern the approach can be distinguished.

Integrated Assessment of Global Warming Impacts

Concerns about the build-up of carbon dioxide in the atmosphere emerged in the late 1800s, but it was a change in the modeling of the air-sea exchange in the 1950s that spawned modern global-warming research. With more carefully designed monitoring network and addition of isotopic tracer information to the global modeling effort, the movement of carbon dioxide through the atmospheric, biospheric and oceanic reservoirs could be understood more completely and subtle changes in the sources and sinks could be discerned. By inverse dynamic modeling, and redirecting monitoring efforts based on modeling needs, insight into the workings of the natural system could be gleaned (Keeling et al., 1989; Lancaster, 1990). Much as in the case of running a river flow model in reverse to detect pollution sources, the Earth's biogeochemical cycles can be reverse-engineered to detect the workings of the coupled ocean-atmosphere-biosphere system.

Building a system of integrated monitoring and modeling to improve understanding of the global carbon cycle now involves many national governments, hundreds of university and non-profit research programs, and international coordinating organizations. The ambitious effort represented by the Intergovernmental Panel on Climate Change (IPCC) grew out of many previous years of international scientific discussions within the Scientific Committee on Problems of the Environment (SCOPE), formed under the International Council of Scientific Unions (ICSU) and within the Committee for Climate Change in the Oceans (CCCO), which grew out of the Scientific Committee for Ocean Research (SCOR), as well as the first World Climate Conference (Lancaster, 1992).

To focus on the physical aspects of global warming, many levels of data collection and aggregation are now occurring in multiple branches of atmospheric chemistry, oceanography, ecology, terrestrial biology, climatology and biogeochemistry, with multiple levels of modeling in each branch of science and in aggregate. Similarly, now focused on human dimensions of global change are a large number of researchers in multiple disciplines, gathering data and modeling interactions with the biogeochemical and climate systems. In the arena of policy-setting and decision-making, the Framework Convention on Climate Change and the Kyoto Protocol represent an international dialog that is gaining resonance with legislative enactments in many individual nations at the federal and state levels. Policy-makers must grapple with CO_2 abatement and changing technology (Goulder and Schneider, 1999).

As shown in Figure 1, above, it has been understood for more than 15 years that likely consequences of global warming will impose damages through storms, storm surge, erosion, flooding, disease vectors, sea-level rise and impacts upon domestic water, among other impacts. As the Earth's climate system becomes more energetic, it is likely that storm frequency and storm force will increase. Human populations, for the most part live on the shoreline. Scenarios to assess risk in these vulnerable areas have been run in most major cities. For example, prior to Hurricane Katrina hitting in New Orleans in 2005, modeling exercises anticipating such flooding had been available to governmental managers at state and federal levels. Uncertainty in measurement and modeling, variability in human perception of risk, and avoiding costs of precautionary measures all played together to leave the city vulnerable.

In this context of global warming impacts, then, there exists today a substantial degree of integrated monitoring and modeling in the hands of decision-makers. The value of this information and the value of modeling complex climatic and social interactions is very dependent on what managers choose to do with the information system. Even with potential responses well described, managers often fail to heed the guidance.

Learning more about the movement of global energy resources through human society is not likely, *per se*, to shift managers toward reducing exposure to global warming in coastal cities. However, developing an IM3 learning model to explore how energy dynamics relate to the growth and stability of social systems and subsystems may assist those developing ideas about governance to understand why human managers, even assisted by expert monitoring and modeling systems to guide them, may still choose to leave human populations vulnerable to environmental calamity.

There is, however, an even stronger reason to build this IM3, global energy use, learning model: to study the Energy-Technology Feedback (ETF)

Global warming a symptom of a natural energy-technology feedback (ETF)

Human acceleration of a natural feedback between energy consumption and technology threatens the health of our populations and the health of many other species. This energy-technology feedback (ETF) has been discussed previously as a fundamental property of a natural, evolutionary principle (Lancaster 1989), as well as a purposeful force underlying the energy flows causing global warming, a force that governments must first recognize and understand before governance can manipulate these flows artfully (Lancaster, 1992).

Viewing the evolution of energetic systems in the context of the ETF, it can be argued that social systems are as alive as their components, with "life" re-defined as dynamic poise within a positive feedback between incorporating energy and evolving method (technology) for accessing energy. The extent to which human systems grow, gain complex self-control and maintain stability is fundamentally a thermodynamic function. (Lancaster, 1989). To examine these ideas one can build forward from earlier research in nonequilibrium thermodynamics (Prigogine, 1955), bioenergetics (Morowitz, 1978; Parsons and Harrison, 1981; Gates, 1985; Odum, 1983), self-organization theory (Eigen and Schuster, 1979; Haken, 1981; Allen, 1982; Odum, 1988), general systems theory (Lazlo, 1987) and creative integration of those fields (Westerhoff and van Dam, 1987; Wicken and Ulanowicz, 1988; Schneider, 1988).

Building a Modeling Framework

To build this analysis, it is useful to define some terms and restate a postulated theory of growth as an inherent property of energetic systems, as follows:

- An *Energetic Structure* is an organizational process, O_{r_i}, for which there exists an organizational radius, r_i. An energetic structure may be an energetic system.
- An *Energetic System* is characterized by an organizational radius, $r_{j=m}$ and is an assemblage of energetic structures within an observed boundary, which structures are characterized by organizational radii $r_{i<n}$.
- The *Observed Boundary* is the minimum spatial boundary that will circumscribe all the components of the energetic system, as defined by inter-relationships between the energetic subsystems comprising the system and by energy and

material responsive to those subsystems, as determined by an observer.

- *Dynamic Coordination* is a process whereby kinetic energies become stored through harmonization, or non-interference.

- A *Subsystem* is a subset of energetic structures within an energetic system that share a common functional relationship to the system, which relationship differs from relationship of other subsets to the system.

Evolution can be seen as increasing the volume and energy contained by the observed boundaries of successively emerging energetic systems, where the observed boundary is the minimum spatial boundary that will circumscribe all the components of an energetic system, as defined by inter-relationships between the energetic subsystems comprising the system and by energy and material responsive to those subsystems, as determined by an observer (Lancaster, 1989). More specifically, the increasing energy in successive systems can be defined by the product of a unit energy density and an increasing organizational radius, r_i, from subatomic through biospheric scales. The "organizational radius" can be taken as a scale radius, r_i, corresponding to the spherical volume, V_i, that is defined by the total energy of an energetic subsystem, E_i, per constant energy density, $u_s = 1$ J/cm^3, such that

$$E_i = u_s \frac{4}{3}\pi r_i^3 \quad . \tag{1}$$

The change, with respect to time, in energy contained in an evolving series of emerging structures can be modeled as the product of a radial evolutionary force, F_e, and a radial evolutionary velocity, v_e,

$$\frac{dE}{dt} = F_e v_e \quad . \tag{2}$$

The force is the product of a pressure and surface area at radius *i.* The pressure is the energy density, u_s, so that the force is equivalent to the change in energy with increasing scale radius

$$F_e = u_s 4\pi r_i^2 = \frac{dE_{r_i}}{dr_i} \quad . \tag{3}$$

The evolutionary velocity is the rate at which the organizational scale radius is increasing, which rate is greater than zero

$$v_e = \frac{dr_i}{dt} > 0 \quad . \tag{4}$$

This rate is nonconstant; it will be described by a growth function or set of such functions, which may be similar to a solution for the Verhulst-Pearl equation (Jorgenson, 1988)

$$E_i = \frac{C_0}{1+e^{A_0-K_0 t}} + \frac{C_1}{1+e^{A_1-K_1 t}} + \cdots + \frac{C_i}{1+e^{A_i-K_i t}} \tag{5}$$

where C is related to energy limitation, A to the time of emergence, and K to the growth rate. From Eq. (2), with substitution from Eqs. (3) and (4), we can model the change in energy in terms of the change in organizational radius with respect to time, obtaining the differential of Eq. (1)

$$\frac{dE}{dt} = u_s 4\pi r_i^2 \frac{dr_i}{dt} \,. \tag{6}$$

Solving Eq. (1) for the scale radius as a function of energy, and Eq. (3) for the scale radius as a function of force, we can write an expression relating a system growth force, F_{sys}, and the total system energy, E_{sys},

$$r_{sys} = \left(\frac{F_{sys}}{3\lambda}\right)^{1/2} = \left(\frac{E_{sys}}{\lambda}\right)^{1/3} \tag{7}$$

where $\lambda = u_s 4\pi/3$ ($gs^{-2}cm^{-1}$). Making a further substitution, $\Lambda = 3\lambda^{1/3}$, which is numerically equal to 4.836, we can write the growth force as a function of system energy

$$F_{sys} = \Lambda E_{sys}^{2/3} \tag{8}$$

System functions, or techniques, that enhance the incorporation of energy previously external to the system, will provide a positive energy feedback to the extent that the incoming energy can be used to enhance those functions. Similarly, innovative techniques that yield more efficient work create a positive feedback by making conserved energy available for greater work. Such techniques, as well as those that reduce destructive interference and minimize degenerative transformations, will enhance the stability and evolutionary competitiveness of the encompassing system.

Dynamic coordination, while enhancing the growth and stability of an emerging energetic system, reduces the degrees of freedom of component energetic structures. Stability in an energetic system is the ability of the dynamic structure to withstand perturbations. Fluctuations in the energy flow through the system boundaries, as well as fluctuations caused by component mutation, innovation or degradation, can perturb the system. The positive energy-technology feedback (ETF), between energy storage, technique and increasing energy absorption, controls the susceptibility of the system to perturbation. Positive feedbacks in the energy flow that support a fluctuation will drive the system to a new dynamic configuration based on the fluctuation. This configuration will be relatively stable until another branch point is reached by another such fluctuation. Periodic transformations between potential and kinetic energy create oscillatory responses within the system that are a product of growth. Oscillations also result when a system succeeds in maintaining its identity against fluctuations, giving rise to the homeostatic notion of "elastic limit" (Prigogine, 1955).

Bioenergetic systems evolve both by expanding their observed boundaries and by increasing their useful energy density. The evolving biosphere converts an *increasing* fraction of the solar influx to chemical potential or structure, so that the total useful energy density contained within the observed boundary of the biosphere is an increasing function. This hypothesis predicts that the total solar energy reflected or re-emitted from the Earth's surface is a decreasing fraction of the total incoming solar energy. Further, as energetic systems, human social systems are “attracted” to energy in order to increase their energy density (Lancaster, 1989).

The energy density of the human social system is increasing in three ways:

a) the residence time of energy throughput is increasing by lengthened pathway and structural storage;

b) the amount of solar energy being channeled through the human social system is increasing; and

c) terrestrial materials, including increasingly heavier elements, are being incorporated into the human social system.

The subsystem boundary will be defined as a conceptual boundary drawn around all the subcomponents of the subsystem as defined by coordinated relationship between the subcomponents. Where subcomponents overlap in participation with adjoining subsystems, we can arbitrarily impose the definition that >50% participation shall establish the residence of the subcomponent (similar to nations declaring taxable residence on citizens

Having sketched the above modeling framework as a foundation for an IM3 learning model for studying global energy resource use, we can sharpen our focus on the research questions posed.

Research questions for the IM3 global energy resource learning model

The IM3 learning model for studying global energy resource use suggested here is aimed to tackle the following hypotheses and/or research questions:

(1) What are the changing patterns over time of energy flow through various societal subsystems, both in terms of (a) graphed node-arc subsystemic networks and (b) geographically mapped storage, transport, through-flow and use?

(2) Are there patterns of growth, stability or a combination of these that can be seen in

an analysis of multiple energetic subsystems within human society?

(3) How are these patterns seen differently by analyzing the dynamic in terms of an optimizing function wherein each subsystem follows goal-directed rules to increase useful energy density within the subsystem?

(4) What if the definition of useful energy density is "anything that increases the ETF function", how does this change analysis of question #3 above? (akin to maximum power principle, except that useful energy density can be directly stored (potential energy), indirectly structurally stored in physical or information structures (know-how, or technology)that can effect the ETF).

(5) Is human society capable of resisting (throttling) an energy-technology feedback function that may exist at an overarching system level that encompasses all existing societal subsystems?

(6) If subsystem flows are switchable and/or reducible, what instabilities are introduced by switching and/or reducing the energy through-flow?

(7) If subsystem flows are switchable and/or reducible, where are the strongest leverage points presenting smoothest control and least instability in transition?

(8) What instabilities or other difficulties are created by converting energy sources for various subsystem flows? Are there cascading effects into other subsystems?

(9) Does modeling of the growth of multiple subsystems reveal any general functional correlation between systemic growth and the amount of total energy within the subsystem boundary, or the amount of a particular portion and/or type of the total energy within the subsystem boundary?

Questions #1-4 are essentially reverse-engineering questions, where the research of the human system (or many subsystems) is trying to unravel management patterns as part of an automatic, built-in response in the system (e.g., a set of rule-based decision schemes based on very local optimization functions). Questions #5-8 are management-oriented questions that ask the modeling layer to predict outcomes based on potential governance actions. Question #9 focuses on testing theoretical hypotheses, such as that posed by Equation 8 above.

To achieve answers to the above research questions a research agenda can be outlined, as described in the following section.

Research Agenda

To achieve answers to the above research questions, the IM3 energy-resource learning model will monitor energy through-flow through various subsystems and analyze (and/or model) the impact of increases in energy density in various subsystems. This approach can include:

- Tracking and mapping a set of parameters for each subsystem, including reserves, extraction, transport, storage, processing, consumption, conversion, price and growth, among others (see Fig. 4 below);
- Deriving, through modeling, measures of "energy intensity", "energy density", "useful energy" and/or "energy usefulness" (or "utilergy") in each subsystem and the extent of feedback relationship between technology and energy through-flow and/or useful energy in each subsystem (see Fig. 4);
- Exploring multiple dynamic structures for an average subsystem using constraint-based optimization, wherein growth and stability are optimized within a set of constraints for each subsystem;
- Modeling the management component of various subsystems as a goal-directed function, where the goal is to maximize growth, stability, and/or a combination of growth and stability.

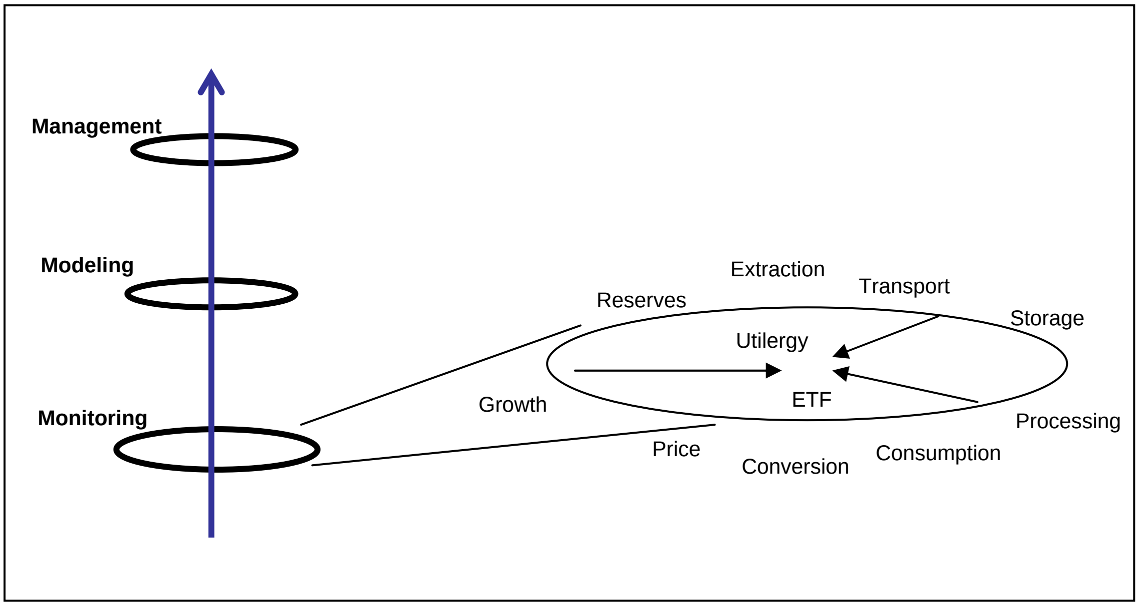


Fig. 4. Integrated Monitoring, Modeling and Management (IM3) approach for studying human use of global energy resource

Utilergy

As we study how energetic subsystems grow and self-organize to form successively emerging energetic systems, we are challenged to improve our definitions of incorporated energy, usefulness, useful energy and usefulness of energy. A concept of "util-erg" is proposed, to be formed from a multiplication of dimensions of utility and energy; utilergy carries the dimension of "usefulness of energy" in an energetic system.

Utility defined in terms of system service

Much in the way that "usefulness of information" to the process of decision-making can be modeled within an IM3 structure, the usefulness of energy can be modeled within an energetic subsystem. At least two approaches should be explored initially for creating the utility scale, one being based on growth and the other based on stability.

A utility scale based on growth can be developed simply from the effectiveness of any particular component in increasing the useful energy density of the subsystem of interest over time. Objective rules for determining this effectiveness can be created that have no human subjective element of valuation. In other words, how useful is a particular energetic investment (or structural change) in terms of an objective system function that causes, governs or contributes to growth? Differing metrics for growth should be explored, with energy through-flow, system energy density, size/reach/control extension, and other measurably increasing functions being initially favored for research.

We can formulate a "utilergy" hypothesis: a positive feedback occurs as increasing energy consumption amplifies techniques for extracting useful energy from the environment (the energy-technology feedback, or ETF). For instance, an amount of energy (or a form of energy, or a particular flow-path through the subsystem) that cannot increase the ETF can be defined as having little or no usefulness, thus 0 utilergy. A form of energy that can increase the ETF will have a higher usefulness, say x utilergy if ETF is enhanced by 10%.

Similarly, stability can be tested as a metric for building a utility scale with a subsystem of interest. Here, the lack of oscillations, or lack of substantial departures from a mean flow (or mean energy density) with the system, beyond some threshold during some time interval, can be considered useful; hence stability can be ranked on the utility scale.

Further, a combination of factors for growth and stability could be developed, where an increasing multiple of the two functions could be scaled as increasing utility in the context of the ETF.

Creating a scalable parameter for modeling and calculating “usefulness of energy”

A simple measuring stick seems trivial to us now, but at one time it did not even exist as a human concept. “Distance” was created as a dimension long ago by comparing two points that are not the same, taking the gap between them and dividing it into 100 parts, or 12 parts, and giving the gap and the part a label.

“Time” is created as a dimension by taking the moment “now” and taking another moment “after now” and dividing the difference into a scale of 60, or 24, and giving the demarcations a label. Early measuring devices were sunrises, then sun motions, and then shadow motions (sundials). Sand-dials, water clocks and finally spring and flywheel clocks came thousands of years later.

A “temperature” is merely a relative comparison of something hot (say, boiling water) and something cold (say, frozen water), and a division of the difference into 100 parts. It took until the 1500s before Galileo and others created a way to measure temperature.

“Energy” is a quantity related to being able to do work (say, to heat water or to lift an object), versus not being able to do work, and then partitioning that difference into equal units and labeling them. One calorie, a measure of energy, is the heat energy required to move one cubic centimeter from one rung on the Celsius temperature ladder to the next rung. A calorimeter was eventually developed to measure energy content.

Three “foot-pounds” equals either one pound raised three feet, or three pounds raised one foot. A force of one pound exerted through a distance of one foot provides a unit of energy or work, where 1 ft-lb equals 1.356 joules (one joule is 10**7 ergs).

Following the above line of developing measurable, dimensional parameters, it should be feasible to measure usefulness: we must merely detect a gap between something that is not useful and something that is useful to be 100 units of usefulness and then each equal unit within that gap can be defined as one “util”.

The “utile” historically

In economics, the "utile" was developed by Bentham as a unit measure of relative satisfaction, based on pleasure and pain (Clough, 1964). One would suffer the negative utility of working to earn income to buy goods and services into which sellers embody utility to be extracted by the paying consumers through end use. Bentham presumed a technical device capable of measuring units of pleasure/pain without a human present – akin to a scientific instrument. However, when this presumption could not be technically satisfied, pleasure and pain were replaced by money as a principal metric. This led to equating value to society with its dollar price in the marketplace and fostered development of the marginal utility theory of value. (Chartrand, 2006; Blaug, 1997).

Defining one “util-erg”

For our purposes in the IM3 energy-resource modeling, we will depart substantially from previous subjective measures of utility (such as simply equating with dollar value) in order to develop a new line of definition. Instead, we will compare usefulness of ergs insofar as these ergs and their usefulness have objective relation to the ETF within each and any energetic subsystem, as this relation is derived and measured from inverse dynamic modeling of each subsystem. For instance, in a particular subsystem, one util-erg might be associated with an erg available in the form of electrical potential, while in this same subsystem a volume containing one erg of radiant heat might be scaled at zero util-ergs. In another subsystem, however, an erg of radiant heat might be found (through modeling) to have usefulness if it causes an enhancement of the ETF. Interestingly, then, waste heat of combustion, on its way to venting to space through the atmosphere, if cleverly routed to extract usefulness within some subsystem, could be found to have a positive utilergy measure attributable to that portion of the energy through-flow, even as that waste heat is associated in many mental models as “dissipated energy” and/or “entropic loss.”

It is desirable to build the utilergy definition within a prescribed set of processes, such as increasing the ETF through storage, dynamic coordination, switching-energy, etc. A combined factor of energy and usefulness can then be identified as a compound function of, *inter alia*, (i) switching resource flow in multiple subsystems, (ii) growth of subsystem network components through the ETF, and/or (iii) stabilizing energy flows and relationships between subsystems. These modeled energy-resource network components include nodes (actors: e.g., governments and corporations), arcs (actions: e.g., discover, extract, store, transport, process, sell, purchase, consume) and multiple physical objects related to the arcs.

With a relative scale of usefulness of energy available to us, we can associate utilergy with useful energy density and we can improve our ability to analyze energetic processes within a self-organizing and growing system. Any utilergy present in the system, by its initial definition, causes increase in the energy-technology feedback. Utilergy causes either increase in the technology that is useful directly (and/or indirectly) for acquiring energy or it causes increase in the energy through-flow that contributes to creation of such technology. Utilergy in the system will operate to increase utilergy within the system, and monitoring the degree of this increase, its relative causes and relative contributions from particular energy flows will give us a way to examine better the ETF mechanism, its force and its acceleration in the presence or absence of constraining and/or resisting factors.

Utilergy as mathematical product of usefulness and energy

An evolving system, then, may see an increase or decrease of energy within the observed boundary of the system, where that change in energy flow may in either event have associated with it a positive, negative or neutral utilergy, depending on the effect of the changed energy flow upon that subsystem’s ETF. The multiple of the change in a particular portion of system energy, E_x, times the attendant change in utility, Φ_x, yields the change in utilergy, Π_x, for the system.

$$\Delta E_x \ (ergs) \times \Delta\Phi_x \ (utils) = \Delta\Pi_x \ (util\text{-}ergs) \tag{9}$$

The coupled monitoring of changes in energy flow with changes in technology can provide information about a percentage change in the energy-technology feedback, ΔETF. From the modeling step, a percent change in the ETF can be derived based on an increase in this portion of energy (or these portions) that operates to promote the ET feedback (versus those portions of energy through-flow or energy in structure or technology that are neutral or degrading to the ETF), so that

$$\Delta \mathrm{ETF}_x = f_1(\Delta E_x) \tag{10}$$

A percent change in the ETF might also be derived (measured) from monitoring the change in energy-acquiring technology and the energy required to make and operate this technology. Alternative methods for measuring an ETF may be chosen (and should be explored); but, any one of a number of methods should be effective so long as the method is able to be applied consistently across many energetic subsystems and across many different types of energetic subsystem.

Utility, then, will associated with a particular change of energy in the system, ΔE_x, and will be a model-derived measure associated with a portion of energy (a) flowing through the system, (b) dynamically held in the system (dynamic structure), and/or (c) partially captured or invested as informational content in the know-how of technology. The change in utility, $\Delta\Phi_x$, will be a function of the dimensionless, percent change in the ETF

$$\Delta\Phi_x = f_2\,(\Delta \mathrm{ETF}_x) \tag{11}$$

IM3 Utilergy Research Scheme

A reduced-form modeling framework for describing relations between environmental state, energy-flow, utilergy and uses/benefits is illustrated in Figure 5 below. Many relations will have a dependence on geographically referenced energy-region attributes, such as topography, stratigraphy, land use or soil type, so that integrated modeling designed to interface with GIS tools will be advantageous. The modeling framework can be transferred and utilized by researchers in neighboring energy resource regions, either directly or by adjustment from look-up tables based on a menu of regional characteristics commonly available. To build the relationships the research can be guided by field investigations and/or by previous studies of energy regions.

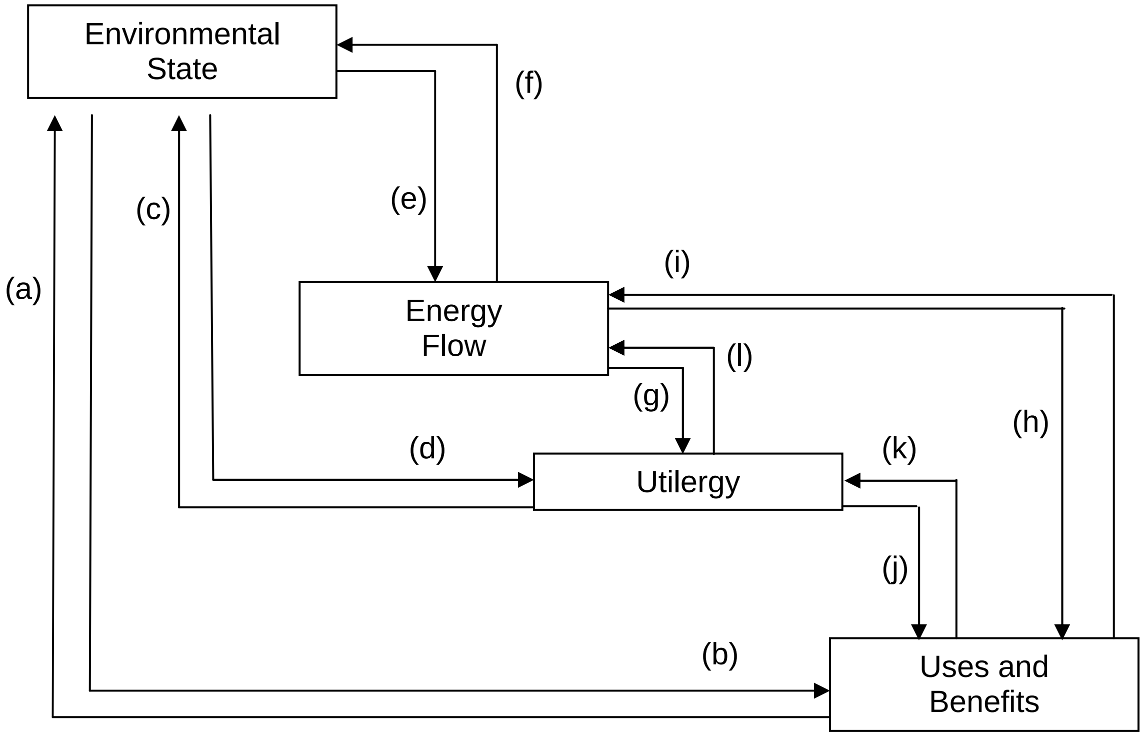


Fig. 5. Developing a combined factor of utility and energy in a reduced form modeling exercise based on environmental state, energy flow, uses and benefits

Building an integrated model in a GIS-based framework that is able to calculate and simulate the relationships shown in Figure 5 requires wrapping submodels objects with an interface and coordinating modeling routine (controller object). FORTRAN, C, and Visual Basic modeling objects, for example, can be controlled by C++ and/or Java routines. The relationships can be described and assembled in a comprehensive matrix, or set of relational databases, as follows:

(a) Relations of human uses to environmental state.

Various uses that directly affect subsystem (urban, transport, infrastructure) condition, energy storage levels, infrastructure and surfaces (transport) are described in these relationships. For instance, building a settlement or a city may cause an energy-resource region to become reduced in some measure of quality. Or pumping oil may reduce a reserve by some measure of usefulness. Environmental impacts of economic decisions can be included (Abler et al, 1999). These relations are likely to vary geographically and can be specified as a function dependent on a GIS theme.

(b) Relation of environmental state to human uses and benefit

Ecosytem diversity and wildlife abundance of some measurable degree leads to an environmental use at some measurable rate, which may vary from zero to some maximum rate. Energy-resource condition in a region, specified by utilergy (as related to energy “quality”) or energy abundance metrics for cities, energy and transport can lead to environmental use at some rate. Energy resource/reserve condition allows a certain degree of human use. Benefits of these uses may be specified by market and/or non-market valuations. Some of these relations may be specified independent of geographical location

(c) Relation of utilergy (usefulness of energy) to environmental state

Human habitat degradation or enhancement can be made a function of utilergy at the entry point of energy flow into the subsystem and/or region of interest. These relations are specified per utilergy constituent (e.g., subsystem growth, economic value, accessibility, etc.) and may be geographically specific. Relation of utility (as relating to available energy quality) to local energy reserve condition (resource utilergy) may be described as a function of mining or pumping (exploitation) operations (geographically specified). Relationships of utilergy to ecosystem species, health and abundance, and human environment, may be based on observations and/or literature descriptions; e.g., energy flows causing high carbon emissions that lead to global warming and potential negative ETF consequences in some subsystems can be docked with negative utilergy points. Feedbacks may need to be described here as environmental impacts degrade social conditions, which in turn alters the ETF (and hence utilergy) further. Some of these relations may be specified independent of geographical location, but others may depend on mappings of cities and other energetic subsytems.

(d) Relation of environmental state to utilergy (usefulness of energy)

Utilergy may be modified by retention or movement of energy through a subsystem or multiple subsystems by measurable degree, per constituent of energy flow and per residence time. Presence of human infrastructure may degrade (lower) utilergy by some degree per population density if it impedes the ETF, whereas presence of other subsystem processes may increase the usefulness of energy if they enhance the ETF. Climate state, for instance, can be directly related to fossil fuel use, with fossil fuel use having a demonstrably positive effect on ETF in most subsystems. At a global level, many of these relations do not need geographic specificity to be usefully studied in a learning model.

(e) Relation of environmental state to energy flow

The condition of the resource region affects energy flow. Stratigraphy and resource/reserve levels affect flow. Climate state affects flow through feedbacks that affect solar, wind and tidal energy production, as well as through weather events that affect transportation. These relations are likely to be geographically sensitive.

Further field observations are useful for calibrating parameters in the models that encompass numerous interactions in the natural system that are difficult to observe directly, either because we are ignorant of their mechanism or because they are too expensive to measure in detail. For instance, a single parameter for energy production in one aspect of supply may be derived, even though it is likely that field investigation in elaborate detail could discover differing rates of production depending on subtle characteristics within a single energy-production region.

To help explore and describe this relation, researchers must develop a GIS-based energy production/supply model (i.e., production, transport, storage and losses), which can be linked to modules from various “off-the-shelf” models. Examples of various such models can be found, such as models that develop linkages between ecological modeling and economic modeling in terms of equilibrium models (Tschirhart, 2006), scaling (Chave and Levin, 2003; Dopfer et al., 2004) and externalities (Crocker and Tschirhart, 1992).

(f) Relation of energy flow to environmental state

Environmental state includes the condition of physical and biological resources and standing cycles or patterns in those resources, including aspects of ecological stability and/or resiliency owing to diversity and multiple inter-relationships between species. Reduced energy flow through a subsystem can impact the natural and human environment in some describable measure. One of the chief concerns about future climate change, for instance, is how resilient is the environmental state to fluctuations in flow that could accompany fluctuations in raw energy supply and/or supply disturbance. Research in this area must include measuring, cataloging and describing these relationships.

(g) Relation of energy flow to utilergy (usefulness of energy)

This is a key relation to be derived from field observations in local energy supply and use regions (or relevant subsystems), where possible, and from literature values where flow impact coupled to resource use contribution can be extrapolated from other studies. These relations may also be model-derived, e.g., for those constituents of utilergy that are related to rate-changes in subsystem characteristics only detectable through modeling. These relations are likely to be highly geographically specific (e.g., doubling energy flow through a specific urban subsystem can yield a different impact than doubling flow through a non-human subsystem. Obvious examples include low-flow stagnation leading to loss of vitality in a region, or excessive overbuilding and activity that can become counterproductive in terms of human health and social benefit.

(h) Relation of energy flow to human uses and benefits

Energy flow allows multiple uses to occur at some rate dependent upon amount or delivery rate, e.g., electrical production, industrial manufacturing, mineral conversion and refining, up to some maximum per use type. Some of these relations are geographically dependent, some independent. These are direct relations, whereas indirect relations through energy quality follow the functional path (g) + (j). Benefits are based on market and non-market valuations. A preliminary survey of energy use and users can serve as a starting point for developing a comprehensive survey of energy resource users. Following this step, an energy allocation model can serve as a submodule to integrate these relationships with other aspects of the integrated assessment model.

Observed physical impacts on energy usefulness (utilergy, and/or energy quality), on energy resource regions, cities and society will be translated into economic impacts in an analysis that can build upon new observation and historical data. Costs and benefits relating to energy resource use can be evaluated for relevant economic sectors and indexed to geographical location in the subsystem region of interest. Economic impacts can be weighed against costs of differing strategies to protect energy flow and reduce negative impacts at key sites, with conclusions drawn about which institutional strategies would best protect natural and human communities and the value of human uses. The research must aggregate results at various scales, from very local to regional, utilizing

GIS tools to contrast the environmental and economic effects of centralized versus distributed institutional strategies.

(i) Relation of human uses to energy flow

Uses (withdrawals) impact flow directly through demand functions. Energy extraction, storage and transport regulations affect flow rates. Changing political control and exploitation patterns in a resource region can affect flow. Human energy use may also indirectly affect energy flow patterns through the complex mechanism of CO_2 increase, global warming and consequent environmental changes (or events) that then impact energy flow rates (e.g., increased storm force and frequency affecting oil platforms in the Gulf of Mexico). Some of these relations are location-dependent and some too diffuse for specific regional modeling. Researchers must explore to what degree information from specific, local studies can be extrapolated to anticipate broader impacts.

(j) Relation of utilergy to human uses and benefits

This set of relationships, which are paramount to the research proposed, comprise a matrix, with utilergy parameters as one dimension and a series of potential uses and benefits as another dimension. Lowering utilergy will limit the use of that energy flow by some measure, to be determined by observation or by extrapolation from other studies (e.g., switching from high-grade oil to biomass in some locations could increase cost of transportation and hence reduce use of transportation. Form of energy relates to its use. Again, benefit functions must build on market and non-market valuations.

(k) Relation of human uses to utilergy

Processing, conversion and transport impact energy usefulness within a subsystem. Human-induced cloudiness, for instance, can reduce available solar energy in a region. Water use upstream can reduce hydroelectric production downstream. Distilling, concentrating and refining, on the other hand, can increase energy quality, making energy more useful for more different applications. Increasing flexibility of use can allow innovation and movement. Liquid fuels, for instance, are more portable and more easily injected into engines, and can have higher BTU/gram ratios and higher combustion rates, thus allowing airplane and jet transportation.

(l) Relation of utilergy to energy flow

Liquid fuels can be transported more easily through pipelines. Electricity can be transported even more easily along wires suspended above the ground. The increase in energy usefulness represented by conversion of oil to electrical energy can be modeled by seeing its relation to increasing the ETF (e.g., by counting the reduced costs of implementing the transport of so many ergs from one location to another, or by counting the added benefits of having the more flexible, electrical energy source to build and maintain new energy-acquiring technologies, such as computers being useful for controlling nuclear reactions or enabling deep-sea drilling operations).

Developing the Learning Model and the process of Knowledge Assembly

Building the learning interaction between data-gathering and the modeling process can be characterized as knowledge assembly. This is an iterative, growing process, where information fed into the process can be more or less useful depending on the ability of the results (or know-how) developed from that information to generate (a) new, useful hypotheses and (b) accelerated data-gathering. Figure 6, below, illustrates research modeling components for the IM3 energy resources learning model. The knowledge-assembly engine includes data about the energy resource network stored in a library database. Associations among data parameters are mined and reverse-engineering modeling components (Bayesian classifiers and inverse modeling components) interoperate with a simulation engine that is capable of forward simulation of system dynamics based on network parameters in the library.

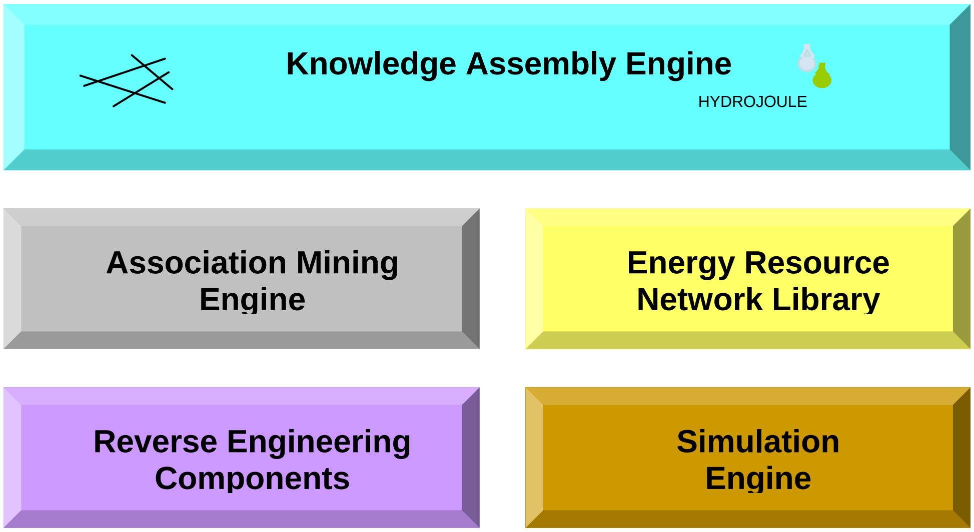


Fig. 6. Research modeling components for the IM3 energy resources learning model.

A knowledge-assembly cascade can be described that brings together (a) a reverse-engineered, energy-resource network model and (b) a literature-based, energy resource system model/map (see Figure 7, below). The reverse-engineered model is derived solely from data, and is essentially a set of hypothetical models of varying likelihoods to explain the data. This data-derived model set is likely to contain "unknown unknowns", i.e., novel causative structures not previously discerned.

The literature-based mapping is a set of models based on the existing collective wisdom of prior research on energy metabolism in human society and dynamic modeling of energy flow in the economy, topics which have been addressed in numerous studies (see for example: Worrell, 1994; Wilting, 1996; Fischer-Kowalski, 1998; Fischer-Kowalski and Huttler, 1998; Battjes, 1999; Haberl, 2001a; 2001b;Worrell et al., 2004; Schenk, 2006). Energy modeling can be relevant in a regional context (De Vries et al., 2001), examining power exchange between countries (Van Asseldonk, 2004), examining energy storage (Jensen and Sorenson, 1984), energy supplies (Messner and Schrattenholzer, 2000) and energy technologies (McFarland et al., 2004). The collective wisdom may explicitly describe unknown areas and connections, as well as characterizing uncertainties in these and other areas; but, the literature-based models will be blind to the unknown unknowns.

The knowledge-assembly module involves iterative fitting of the two input model sets, using congruence-testing and parameter variation. Many possible causative relationships inferred in the reverse-engineering will fall away when merged with very certain known models, but in more uncertain areas the reverse engineering will fill in gaps and enlarge the current view. A resultant best-fit model is then passed into a simulation module where perturbations to the system can be simulated to test effects on internal subsystem dynamics and dynamics between subsystems nested within an overarching system. The perturbation testing creates new hypotheses that direct another round of data-gathering.

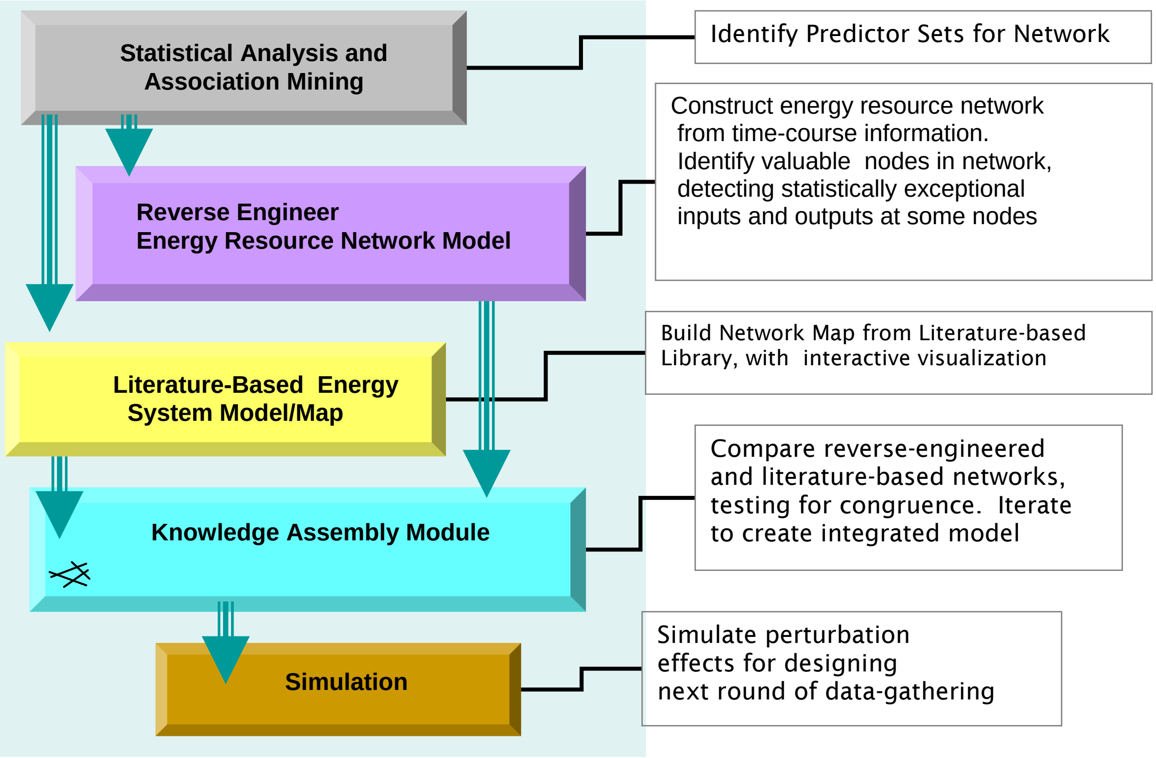


Fig. 7. Knowledge-assembly cascade brings a reverse-engineered energy-resource network model and a literature-based energy resource system model/map into the knowledge-assembly model

More details of the IM3 Learning and Knowledge-Assembly layer are shown below in Figure 8, below. Statistical analysis, association mining steps, and network reverse engineering steps are shown on the left, while the literature-based model assembly is described on the right. The existing literature can be text-mined and parsed and autoassembled into XML database structures. Ontologies allow sorting and sifting of the input text based on objects (nouns), interactions (verbs) and context, as well as resolution of ambiguous terms. The acquired information is assembled into a set of energy flow-paths for multiple subsystems, where these pathways are structured into networks having nodes (objects/nouns) and arcs (interactions/verbs). Systems and subsystems are formed at differing levels of organization, with the sets of nodes and arcs being mapped in the particular context of a particular level system. For example, a movement of oil may be mapped as shipping transport from one port in one country to another port in another country. At another level of organization, a movement of oil may be mapped as a piped transport from a corporation’s underground tank to an electrical generator. a reverse-engineered energy-resource network model and a literature-based energy resource system model/map into the knowledge-assembly model.

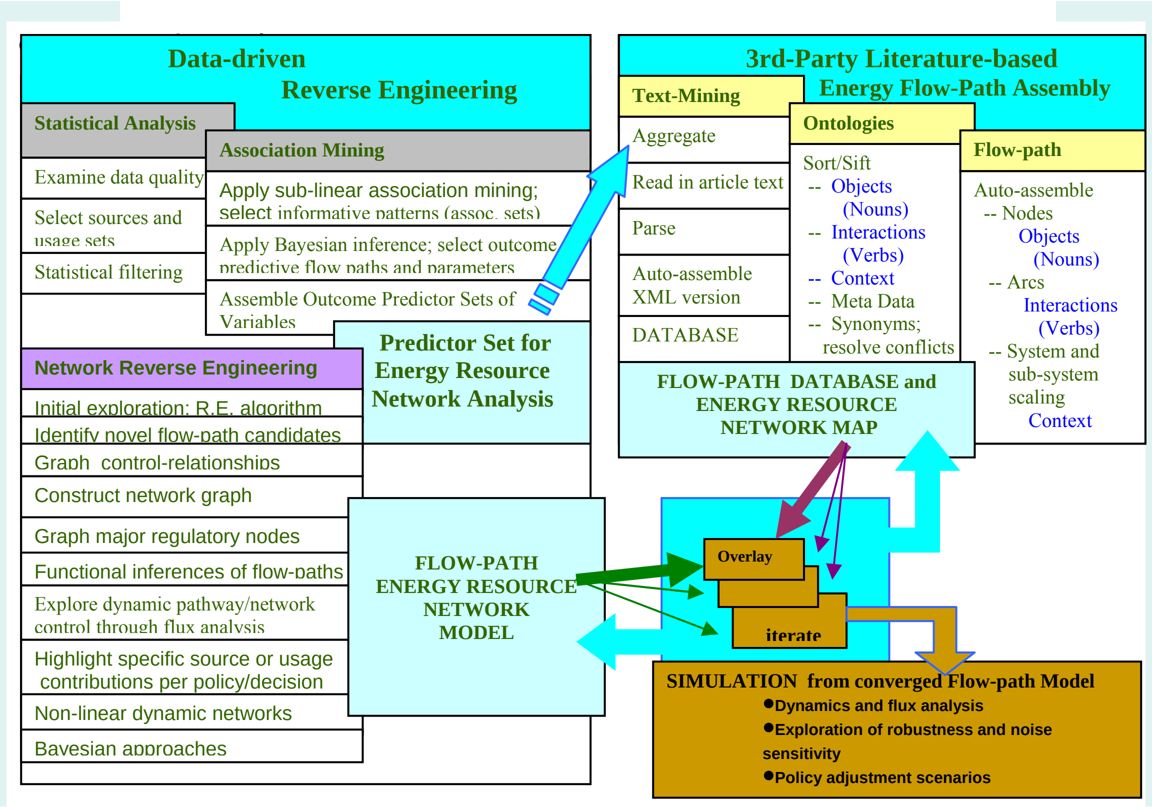


Fig. 8. More details of the IM3 Learning and Knowledge-Assembly layer.

Parameters for each subsystem will include energy reserves, extraction modes, extraction rates, transport modes and rates, storage mode and volumes, processing steps and rates, uses, consumption rates, conversion efficiencies, switching/conversion pathways, price and growth (in each of many of the parameters), as well as other parameters. In both modeling approaches, deriving and mapping measures of “energy intensity”, “energy density”, “useful energy” and/or “usefulness of energy (utilergy)” for each subsystem and geographically is an important step. Deriving through the modeling the extent of feedback relationship between technology and energy through-flow and/or energy usefulness in each subsystem is another important step.

In the simulation module, dynamics and flux analysis can be tested to explore robustness and noise sensitivity in the network model. Policy adjustment scenarios can be tested for effect on multiple parameters and particularly the model-derived parameters, such as the ETF, utility and utilergy. Previous work on scenario formulation and models (Gritsevskyi, 1998) and energy policy models (Frei et al., 2003) can be compared with the updated simulations.

Query Manager connecting Knowledge-Assembly and Automated Experimental Design

To automate the growth of the IM3 knowledge assembly, linkage is made to a module that manages queries (programmed as rules-based routines) and optimizes the research progression by mapping particular classes of queries to experimental programs needed to gather data for the continued modeling and iterative fitting of the integrated energy use and resource model (see Figure 9, below). In the IM3 methodology, this interface can be connected with visualization for supervised learning in the hands of the modelers, and/or the interface can allow managers to access and modify the query process directly.

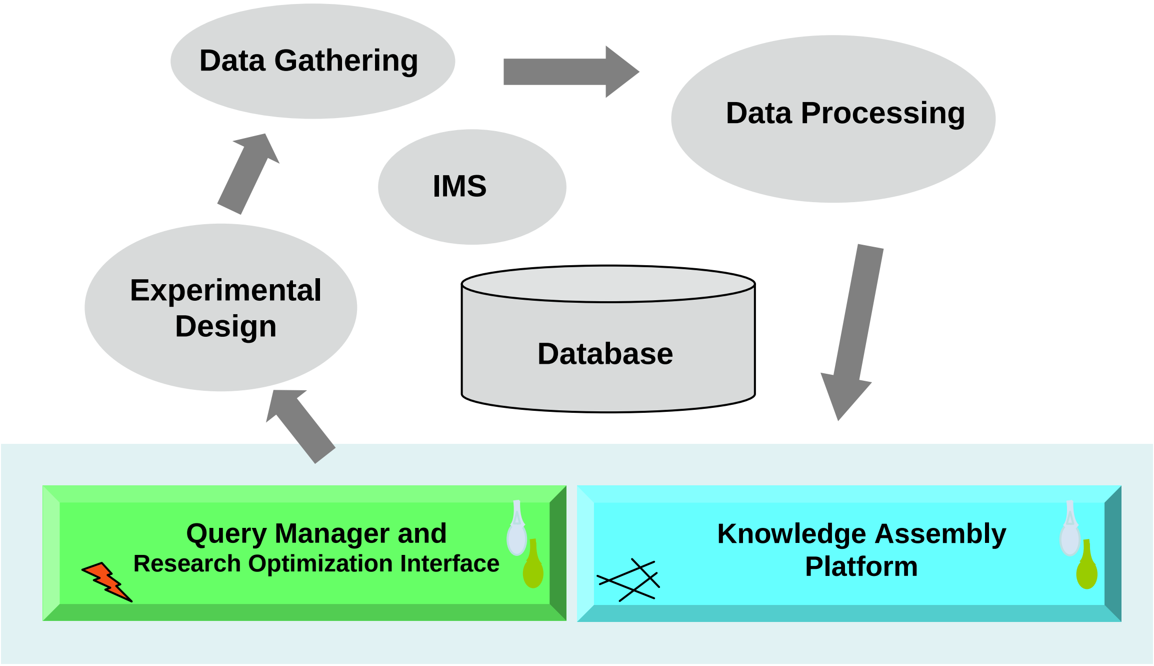


Fig. 9 Linking the Knowledge-Assembly platform to a Query Manager and Research Optimization Interface to generate experimental design and data-gathering, with the information management system (IMS) including a database and automated data-processing that feeds back into knowledge assembly.

The research optimization component can explicitly treat the question of value of information and usefulness of a potential data-gathering step to the desired modeling goal and/or the likelihood of gaining a robust answer to a query. As will be discussed below, defining a “util-bit” can be applied in the context of an information-knowledge feedback (IKF) process, where information-flow into the knowledge assembly module can enhance and accelerate the gathering of more useful information, and where usefulness of information can be defined as a function of the acceleraton of the knowledge assembly. As we learn more about growth of energetic systems generally, the tight relationship of energy and information can guide us toward goal-directed rules that optimize information acquisition and knowledge assembly in a growing IM3 Energy Use and Resource Model.

DISCUSSION

The growth of human technology has been so rapid on evolutionary time scales that it may create a runaway, positive, energy-technology feedback (ETF), similar to an audio "squeal" looping through microphone, amplifier, and speaker. The final signal becomes a function of the system configuration, independent of the initial input (Campbell, 1985). Ironically, many scientists and policy-makers have reassured themselves that a runaway greenhouse effect is not likely, owing to negative feedbacks in solar gain caused by cloud albedo; however, a runaway ETF may still occur and this underlying process can bring with it many undesirable consequences.

Energy and Entropy

A basic thermodynamic law states that energy is conserved. The total energy of a system, *E,* will be a combination of its kinetic and potential energy, and its internal energy, *U.* The change in a system's internal energy, ΔU, will be equal to the heat entering the system, ΔQ, and the work done on the system, ΔW:

$$\Delta U = \Delta Q + \Delta W \tag{12}$$

In thinking about how systems evolve, thermodynamicists have discriminated between the energy that is available to cause some process to happen, and the energy in the system that is too diffuse to be directed. The terms "useful energy", "free energy", and "exergy" have been offered to describe available energy, while "non-useful", "dissipated" or "waste" energy refer to the remainder.

To describe what happens as heat flows into a system, Clausius established a quantity called entropy (Greek: evolution), such that the change in entropy equals the change in heat content of the system per absolute temperature, *T,* for a reversible change.

$$dS = \frac{dQ}{T} \tag{13}$$

The thermodynamic entropy, *S*, describes the state of the system in Joules per degree Kelvin *(J/ K)*.

A statistical entropy was then identified with the thermodynamic entropy. The absorption of kinetic energy is associated with knowing less about the exact quantum configuration, as the system accesses a greater number of quantum states. A quantum state here, is a specific mix of electronic, vibrational, rotational and translational aspects of the kinetic energy. Where k is a positive constant and P_i is the probability of the system being in anyone quantum state i, we can write for the statistical entropy

$$S = -k \sum P_i \ln P_i \tag{14}$$

The statistical entropy increases as the system spreads its energy over more possible quantum states and, thus, the probability of the system being in any one state diminishes. Randomness increases. As energy finds more states in which to reside, there is greater heat content per unit temperature, meaning that the thermodynamic entropy increases, too. Conversely, the transformation of kinetic energy into quantum potential moves the system toward a more ordered configuration, i.e., a higher probability that the system will occupy fewer quantum states. The system will have a lesser heat content per unit temperature and, thus, a lower entropy. A fluctuation that alters energy storage or exchange can create a positive feedback that perpetuates the fluctuation. The system can transcend component independence to form a new organization, whose stability depends on this energy flow. Entropic dissipation has been posed and discussed as a driving force in the evolution of social systems (Wicken, 1986; Harvey and Reed, 1994).

Energy consumption drives social development; therefore, national energy consumption and gross national product are correlated (Cottrell, 1955). Food demand and fuel use are often translated into kilocalories to allow easy comparison with agricultural and fuel resources (Revelle, 1979). An "energy coefficient", defined as the ratio of energy consumption to the level of output, has been used to examine social energy demand (Watkins and Berndt, 1983), allowing economists to assess the growth of productivity as a function of energy and changing energy pathways (Jorgenson, 1984). This analysis, however, faces the difficulty of comparing thermal energy measurement with economic measurement (Bernard and Cauchon, 1987).

Money, Odum contended, flows inversely to the delivery of energy (Odum, 1971). Economics, however, does not precisely value the total physical energy present in a structure; rather, it values energy that is useful for human purposes. For instance, a carbon dioxide molecule contains more energy locked up in mass than does a methane molecule, but the methane can provide humans greater energy through its potential oxidation; thus, methane molecules have greater economic value. Useful energy density is closely related to the quantity called "exergy", which was the basis of "thermoeconomics" (Spiegler, 1983). Value becomes a mixed function of the fuel and human work expended to gather and distribute a resource (supply), together with considerations of usefulness (demand). Social structures that protect wealth, such as laws of ownership and police protection, essentially protect subsystem access to useful energy density.

Energy, particularly energy available for agriculture versus the energy needed by human metabolism, has been proposed by Hannon (1983) as a major factor affecting the social structure of Japan between 1600 and 1860 A.D. He constructed a model, in which peasants are "energy optimizers". The tax rate is made a function of land productivity, human metabolism, energy spent in hierarchical control, and the ratio of numbers of controlling hierarchy to peasants. He questioned whether stability in the peasant population was caused by the Tokugawa Shogun's control, or whether both were actually caused by prior limitations on energy resources. If the latter case is demonstrable, Hannon argued, then an analogous world government may be a predictable consequence of a worldwide limitation on energy resources (Hannon, 1985).

Odum (1971) demonstrated that analyzing evolving social systems in terms of power reveals basic patterns common to all biological systems. He looked at the controls that one subsystem exercises over energy forms or flows that are recognized and meaningful to a subordinate subsystem. He saw main power circuits controlled by smaller feedback circuits, which reinforce the main flow, resist it, or switch it to other destinations. These control circuits reduce extreme oscillations in energy supply and create more efficient distribution. Odum argued that, as more power is added to the system, stability is maintained by increasing diversity and specialization. Diversity spreads the power base and avoids destruction of the system in case of environmental cataclysm. Specificity "insulates" the flow of power, to allow finely tuned control.

Adams (1975), recognizing the importance of energy as a translation between thermodynamic theory and evolving social systems, claimed we still lack a model that can handle the broad diversity of energy flows and forms that constitute a human society. Thus, in his analysis of evolving social structure in late Victorian England, he reverted from energetics to economic statistics (Adams, 1982). Georgescu-Roegen (1973, 1976, 1982), although a proponent of entropy theory in economics, also expressed a reservation that Odum's energetic modeling had not yet made clear the net energy equivalents for materials consumed.

Useful Energy Density

“Useful energy density" may be preferable to "entropy" or "energy dissipation" as a yardstick for measuring system evolution. A kilogram rock lifted 10 meters off the ground will gain potential energy. If potential energy is akin to useful energy, then lifting the rock can make it more useful (i.e., it may have a storage purpose and value; and it can yield back most of the work of lifting). For similar reasons, tidal water held upriver behind a tide gate has gained usefulness over the same volume of water at the river’s mouth. For additional reasons, fossil fuel energy stored at the surface has gained in usefulness over energy not yet pumped from underground (oil or gas, for instance), from gains in accessibility more than simply from the gravitational potential energy gained.

A problem with the approach to analyzing system evolution in terms of entropy generation is that thermodynamic entropy and the statistical entropy of configuration both increase in isolated chemical systems, where energy is not forming into structure, or information, but in non-equilibrium systems heat dissipation can still increase while forming structure decreases statistical entropy within the system. The probability for a more ordered configuration to occur in the future will depend on the energy already stored in existing dynamic structure. Another criticism of the entropy approach can be given metaphorically: to analyze the evolution of art, we do better to focus on the paint stored on the canvas (useful energy density), rather than on paint spilled and splattered upon the floor (dissipated energy). Essentially this is focusing on technique, or know-how (Boulding, 1982).

The human species, representing only a tiny fraction of one percent of the total living biomass, may have incorporated more energy gravitationally in three-dimensional structure than has the rest of the biosphere. More significantly, the bulk of this storage has occurred only recently, as a function of our reaching fossil fuels and accelerating the feedback between energy and technology (Lancaster, 1989).

Social systems in the world are becoming more energetic and more complex (Abel, 1998; Arthur, 1999). A dilemma faces every energetic system: between investing in innovation (providing selective advantage in times of environmental stress) and spending energy toward current needs (more competitive in a stable environment). The apparent conflict between ecologists aligning complexity with stability and thermodynamicists arguing that complexity threatens stability needs to be resolved. How great an energy fluctuation is necessary, for what duration, and distributed through which control circuits, to produce a significant change in structure? Have fossil energies already provided such a fluctuation?

Energy Intensity

Energy intensity has been proposed by Hannon, Costanza and Herendeen (1986) as a suitable currency for understanding ecosystem structure and behavior. It is the total input energy needed to make a commodity, or the energy cost of a process, including the dissipated free energy. By weighting the commodity outputs by their energy intensities to form a process output value, they use embodied energy as the "fundamental" unit of transaction between components of ecosystems, in a manner analogous to the way dollar values are used to track exchanges in economic systems.

Ulanowicz (1986), following Odum's energy-flow analyses for the Crystal River ecosystem in Florida, developed "ascendancy" as an increasing function underlying growth and development. Ascendancy is the product of the size and articulation of the system, being similar to Denbigh's integrality (Schneider, 1988). Size is characterized by the total system throughput, with the summation of all the system flows being related to the number of compartments and linkages. Articulation is an organizational measure, related to "average mutual information", and units of information (bits) are scaled to the predictability of the flow paths. This derives from using statistical entropy as a measure of the probable residence of quantum energies among multiple possibilities. Ulanowicz stated that system ascendancy is expressed in the "form of an entropy", yet it "takes on the same units as those of work when the medium in question is energy". His units were kcal bits $m^{-2}y^{-1}$. Wicken and Ulanowicz (1988) have proposed tying ascendancy together with growth equations, in order to begin to assess ecological development quantitatively.

More recent work on energy efficiency (Farla et al., 1997) and energy intensity has focused on developing physical indicators for monitoring (Worrell et al., 1997; Farla, 2000; Farla and Blok, 2000; 2001; Ramirez et al., 2005) as well as examining material production (Groenenberg et al., 2005).

Stability and Sustainability, control and freedom

An important challenge for governance in the coming century is to determine at what point economic growth will overburden the Earth's carrying capacity (Arrow et al., 1995), and at what point human energy consumption is no longer sustainable, a line of inquiry that requires integrated Earth system analyses (Schellnhuber, 1998; 1999; Kates et al., 2001; Schellnhuber et al., 2004), as well as requiring analyses on much smaller scales (Moll et al., 2005).

The 1973 energy crisis was a reminder that social stability can be affected by shifts in energy flow. Carneiro (1982) has suggested that a social system will always return to equilibrium so long as an "elastic limit" is not exceeded by a fluctuation, and that perhaps the New Deal legislation, following the major economic depression in the U.S., is an example of this re-equilibration. This idea is supported by Odum's description of assaults on stability in energetic circuitry. Energy circuits, built by innovation, can confer advantage only so long as innovation in competing systems lags behind. But as a system ages, its capacity for innovation is reduced, "elasticity" diminishes, and a younger, competing system deprives the older one of critical energy. This process can describe the aging of an urban system and infrastructure, as well as the aging of a national governmental branch or entire governmental system.

A social system with little available power cannot support many feedback controls; thus, it is more susceptible to random oscillations. Simple lowering of energy flux and flow in a system could be a natural regulator (Eigen and Schuster, 1979). Odum noted that creating regular oscillations in a simple system may be an energetically cheaper way to gain stability than a strictly maintained flow, where social control circuitry commits energy to the controlling subsystem (Pattee, 1973). Financial credit, for instance, allows governmental structures (potential energy) to create oscillations in flow dynamics (kinetic energy) or to damp such oscillations. Direct taxation provides a similar control circuit.

As nations and their social subsystems become components of a higher level system, then a loss of component freedom will occur at the national organizational level. Nations will steadily yield control to an international dynamic that possesses a greater momentum. For instance, the sharp shock to financial markets in October, 1987, and the longer downturn in years 2000-2002 evidence a tightly-coupled world economy. Within the framework of nuclear deterrence, too, a continual maintenance of weapons and aggressive posturing has built an accepted deterrent structure, held as an everpresent tension, which operates to prevent substantial change in governmental organization in any single party. Each nation becomes less able to risk serious reforms in governance, for fear of jarring international relationship. This could mean that changes in national government for the benefit of human quality of life will grow even less likely in the future. This is a grim projection, but if it stems from fundamental principles of energetic systems, it should be demonstrable and predictable. Governmental structures attempting to counter the pressures of overarching and underlying evolutionary dynamics will do well to understand these dynamics better. Improving the modeling of energy flow, storage, structuring, dynamic coordination and the usefulness of energy in the energy-technology feedback will assist this realization.

Adams (1982) has suggested that social systems have already formed a supersocial system. He proposed that the decline of late Victorian Great Britain was essentially Britain's contribution to a higher level of social structure, a "survival vehicle" that will follow its own evolutionary expansion-perhaps to the detriment of some of its national components. The United Nations, a centralized world government structure, might be considered the beginning of a higher level system which, as yet, commands too small an energy flow to allow for much control over component nations. Its stability depends on moving very slowly in its programs, in order to avoid a political misstep. It could be argued that both these examples are merely part of the "horizontal" aspect of social evolution, or that a supersocial structure is on our horizon.

Many founding structures of current governments were written before the concepts of energy and evolution emerged in science, and before the powers of hydrocarbon-driven technology were felt. Amendments notwithstanding, these documents may provide insufficient mechanisms for governmental design to evolve unbeleaguered by aging subsystems, i.e., our society may not have an adequate reproductive system. The provision for total rewrites (such as a potential Constitutional Convention in the U.S.) might have attempted to offer this function, but the process fails to provide a strong gestational code (i.e., a set of parameters for creation of new governmental structures); thus, the process may be too fearsome to be embraced. At the United Nations level, a more modern understanding of systems dynamics, life and energy resources may be able to guide a growth of newer structures and, more importantly, may be able to focus more on evolving value in human society than on preserving status quo. Seeing the usefulness of energy (utilergy) more clearly within natural systems and unconscious human systems could lead human society toward controlling utilergy in a more conscious system.

Parallel between the IM3 Learning/Research Model and Fundamental Principle of Growth in Energetic Systems

An interesting parallel can be seen between the energy-acquisition process of an energetic system and the information-acquisition process of an IM3 learning method itself. In modeling a living system, an energy-gathering step can be made adjustable in response to a demand function and a dynamic organization function (which may respond to the demand function) can recognize its systems energy needs and adjustably instruct the energy-gathering step. Here the demand function is parallel to a management function in the IM3 structure, while the dynamic organization function is parallel to the modeling function. Generalizing then, as shown in Table 1, below: a step C is adjustable in response to a function A, while a function B, in response to the function A, can recognize its resource needs and adjustably instruct the step C:

General	A	B	C
IM3 method	Management	Modeling	Monitoring
Energy Resource Network	Demand	Dynamic organization	Acquire energy

Table 1. Three component model generalized, aligning information acquisition in IM3 model and energy acquisition in energy-resource network modeling.

CONCLUSION

Governments are struggling to control social energy consumption and its consequences. To understand the adaptive compromises that lie ahead, we must learn more about the natural parameters that drive and bound society's growth. Sustaining and/or converting a fossil-fuel-driven economy through an impending decline of oil reserves may be possible only if we are able to perceive the strength of these dynamic forces.

Those crafting human laws must develop greater awareness of energetic laws. This paper has presented “usefulness of energy,” or “utilergy,” as a quantity defined in terms of positive effect upon an energy-technology feedback (ETF) in an energetic system. Global governance of energy resources will be helped by understanding the ETF, which is the underlying cause of global warming and other aspects of global environmental change.

The ETF must be studied and understood at multiple organizational levels, both as a physical force and/or as a dynamic process that could be susceptible to engineering. To do so, however, we must build modeling tools and perspectives that help us see the problem more clearly. A research framework has been presented here for modeling energetic subsystems in ways that will allow visualization of this feedback.

An Integrated Management, Modeling and Measurement (IM3) energy-resource learning framework has been illustrated for application to the problem of governing energy resources, energy use and the energy industry. Network components for this modeling approach have been proposed.

“Utilergy” is offered as a modeling parameter that can improve our understanding of growth and stability functions fundamental to human energy use. The IM3 framework will translate measurement of the real-world system into helpful modeling parameters that managers can manipulate in order to focus their view of the dynamic system.

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Dr. Justin Lancaster is a research scientist with substantial experience in business and law. During the 1980s, he worked with Roger Revelle and Charles David Keeling in the CO2 Research Group at the Scripps Institution of Oceanography, followed by postdoctoral research at the California Space Institute and Harvard University in the early 1990s. He has been a principal investigator and coordinator for collaborative projects involving MIT, Harvard, CMU and eight other universities. He founded the Environmental Science and Policy Institute in 1988 and worked on integrated assessment and global warming policy into the mid-1990s, participating in the 2d World Climate Conference in Geneva and the Earth Summit in Rio. Since 1996 he has held executive team roles in six start-up companies, most recently in the area of systems biology and bioinformatics. Dr. Lancaster received his M.S. and Ph.D. from the University of California, San Diego, and his J.D. from the Vermont Law School. He is admitted to practice law in MA, CA, CO and VT and before the U.S. Patent and Trademark Office. He is a member of the American Geophysical Union, the Society of Risk Analysis, the Oceanography Society, the Prometheus Society and the Sigma Xi scientific honor society.