EMERGY SYNTHESIS 3:
Theory and Applications of the Emergy Methodology

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Protecting Environmental Welfare: Comparison of Emergetic and Economic Valuation

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ABSTRACT

To protect human and environmental welfare, the US Environmental Protection Agency (EPA) aims to base environmental regulations and policies on sound scientific and economic analyses. EPA has accordingly conducted analyses of both environmental and economic impacts of regulations for three decades but has yet to develop an effective methodology for the integrated assessment of impacts on the larger system as a whole, with social, economic, and environmental processes and interactions all considered within a consistent, unified, and realistic framework. Assessments that account for the integrated nature of these processes are crucial to avoid the oversights that can lead to a less-than-optimal management or protection of our environmental resources due to inadequate or erroneous information, poor decisions, or maladapted institutional resources. To address this need, we are investigating the linkages of socioeconomic processes, as driven by preference formation and satisfaction, with the environmental processes of available-energy exchange and transformation that provide our basic life support. We report here on an initial step in this effort, in which we compare emergetic and economic valuations in terms of their equilibrium orientations, underlying conceptions of value, and potential contributions to an integrated analytical framework for the evaluation of policy impacts on socioeconomic-environmental systems.

INTRODUCTION

Need for Improved Analytical Methods

Safeguarding a natural environment conducive to health and well-being within a highly consumptive society, which is the essential mission of the US Environmental Protection Agency (EPA), requires sound scientific and economic analysis of both environmental and economic systems. The impacts of human activities and proposed regulations on these systems must be understood in terms of their most critical underlying processes. A scientific understanding of these processes might be attained by determining the systems dynamics of the physical flows associated with them and of the energy distributions and transformations that drive them. Some forms of scientific analysis, such as emergy analysis, also recognize the critical (but seldom explicitly quantified) effects of information acquisition and diffusion on these dynamics. To the extent that human preference formation, satisfaction, and communication (through price and expenditure signals along with their associated purchasing-power and entitlement flows) are considered in these scientific analyses, they are typically treated as exogenous factors. Such an approach is unsatisfactory to the policy maker, however, who perceives these information dynamics as endogenous to the integrated environmental-socioeconomic system that environmental policy seeks in some manner to optimize.

In the case of emergy-based policy analyses, for instance, price is sometimes included as an exogenous (and implicit) determinant of transaction rates and thus of effective economic demand and its satisfaction. Beyond this recognition of price as a factor affecting economic exploitation and management of environmental resources, Odum (1994) provides a brief consideration of some hypothetical interactions between price and effective demand using highly stylized models and simple interaction diagrams. This approach of modeling one or two isolated interactions at a time could readily be extended beyond these two economic variables to include other important determinants of socioeconomic-environmental systems dynamics. An energy-systems perspective of such interactions that explicitly incorporates the dynamics of preference formation and satisfaction might then be developed based on observed relations between the relevant factors as these factors interact within an integrated socioeconomic-environmental system. Insofar as all these factors and their interactions within an integrated system together determine supply, demand, production, consumption, resource allocation and use, and human and environmental well-being, however, a strictly reductionist approach---in which these interactions are considered only in isolation---must remain inadequate.

Current Contribution of Environmental Economic Approaches

From this whole-systems perspective, then, protecting the environment requires tools both for measuring the status of environmental welfare and for analyzing the underlying web of environmental and socioeconomic interactions. With no consistent, unified scientific framework for analysis that explicitly incorporates human preference dynamics, a more disjointed approach has been required. Thus along with scientific analyses of environmental impacts, EPA has for three decades conducted economic analyses of the impact of regulations on economic output and flows (Portney, 1997), with the importance of this task to the agency indicated by EPA's employment of more than 100 economists with graduate degrees (Morgenstern, 1997). These economic analyses can incorporate environmental dynamics through the inclusion of a model of an environmental system or its effects within a standard economic model of production and utility or preference satisfaction. All the standard environmental economic approaches (such as hedonic-value and travel-cost models, simulated markets, contingent valuation, etc.) are variations of this attempt to extend the applicability of market-based systems of value or welfare generation and measurement to situations with missing or inefficient markets. The common objective of these approaches is to produce economic analyses and accounts that more accurately reflect the effects of environmental systems dynamics on preference satisfaction (Freeman, 1993; Hanley et al., 1997; Nordhaus and Kokkelenberg, 1999).

Despite the substantial resources that have been expended in developing and applying the analytical approaches used by environmental economists, a generally applicable and consistent methodology for integrated analysis has not been achieved. One persisting deficiency is the lack of a consistent framework for modeling or incorporating environmental dynamics within a market-based analysis. More fundamentally, however, environmental economics has not produced an adequate characterization of the divergence of the preference-determined measures provided by market mechanisms from actual effects on environmental policy goals. Market mechanisms weight preferences according to the purchasing power associated with them. Policy goal and implementation decisions are also informed by other measures of preference that are weighted according to voter participation or relevant expertise, for instance, and also by an enduring, viability-enhancing commitment to human health and to the survival, resilience, and vigor of our environmental systems. An adequate method of rectifying the divergence from policy goals introduced by market-based valuations has not been established.

Potential Contributions of Emergy Methodology

Emergy methodology offers a more uniform approach to integrated analysis that EPA has begun to assess as one possible option for addressing the above inadequacies, with three EPA scientists currently involved in this assessment. Because emergy, as a value metric, is not essentially linked with purchasing power or with economic entitlement distributions or flows, emergy-based valuations might help to rectify the aforementioned divergence, particularly with respect to the valuation of environmental dynamics and their associated services. Three aspects of emergy analysis suggest its potential relevance to policy goals and needs as outlined above. First, emergy-based valuation is derived from a theory of donor-based value applicable to any process in any system that can be effectively represented as a network of measurable distributions, flows, and transformations of available energy with established or derivable transformities (Odum, 1996). Thus some links between socioeconomic and environmental dynamics that are difficult to incorporate within a preference-determined model might be more effectively analyzed within an emergy systems model. Second, the donor-based emergy value associated with any well-adapted process (i.e., the emergy inflow to the process) is hypothesized to correspond with its potential contribution to the vigor, adaptivity, survival, and prevalence of systems that encompass and sustain it (Odum, 1994). Third, expertise with respect to any process that can be effectively represented in an emergy systems model can be incorporated without the distorting effects of the purchasing-power numeraire and the disconnect between this expertise and the perceptions of the economic agents that determine or set market-based values.

The difference in approach between emergy methodology and environmental economics has perhaps been most succinctly summarized by Odum and Odum (2000). Whereas environmental economics addresses market inadequacies with a host of methods intended to internalize market externalities, emergy analyses seek to externalize market internalities by valuating processes internal to the market on the same basis as the processes in the larger system upon which the market processes depend. To be successful, however, such analyses must be based on a sufficient understanding of these market processes, their energetics, and their interactions with other processes in this larger system. A more exact characterization of the commonalities and differences between market and nonmarket-environmental processes is needed, specifically in terms of the contributions of these processes to value generation and to valuation under the theories of value that underlie economic and emergy analyses. The understanding thus achieved should help to identify potential complementarities and conflicts among market and nonmarket processes, exigencies, and values that will be particularly important for reaching viable and constructive policy decisions.

We will proceed then to consider the underlying perspectives and theories of value that inform these alternative methods of analysis. Next, we will focus more specifically on the theoretical basis for the divergence of market-based valuation from policy goals, concentrating particularly on the overarching policy goal of safeguarding system viability. (The viability of an entity is its capacity for sustainable performance of all necessary functions effectively supporting its survival within a given environment and web of interdependent existence.) Finally, we will discuss some of the research needs that must be addressed to develop an emergy-based methodology for rectifying these divergences and for providing improved valuations from an environmental protection perspective.

VALUE THEORIES: AN ENERGY-SYSTEMS PERSPECTIVE

Roles of Human Society in Socioeconomic-Environmental Systems

In considering these theories of value as they relate to environmental policy concerns, our focus will be the interactions of human society (and thus of the economy and its dynamics) with the rest of the larger global system. Within an energy-systems context, then, we are specifically interested in both the requirements and the consequences of the energy-driven roles or contributions of human society within this global window of interest (Figure 1). Like other resource processors, human society is a source (and also an amplifier) of both ordering and disordering energy flows, both of which are required in proper balance for optimal functioning of a well-integrated/adapted, self-organizing system (Odum, 1977). Our society is typically viewed more specifically as a consumer, and more recently as a frenzor with respect to accumulated fossil storages (Odum, 1994). As a major consumer, human society is responsible for large disordering effects that must be compensated with large order-amplifying effects if this society is to contribute positively to the long-term viability of its encompassing and supporting systems—and thus also to increase the likelihood of its own survival and welfare. In this sense, the value of socioeconomic contributions is dependent on these order-amplifying effects. To provide net positive contributions to long-term viability as a frenzing component within the current global system, society must also introduce sustainable amplifying structures to this system that enhance long-term order production—or empower acquisition, via power acquisition and effective use, according to emergy theory.

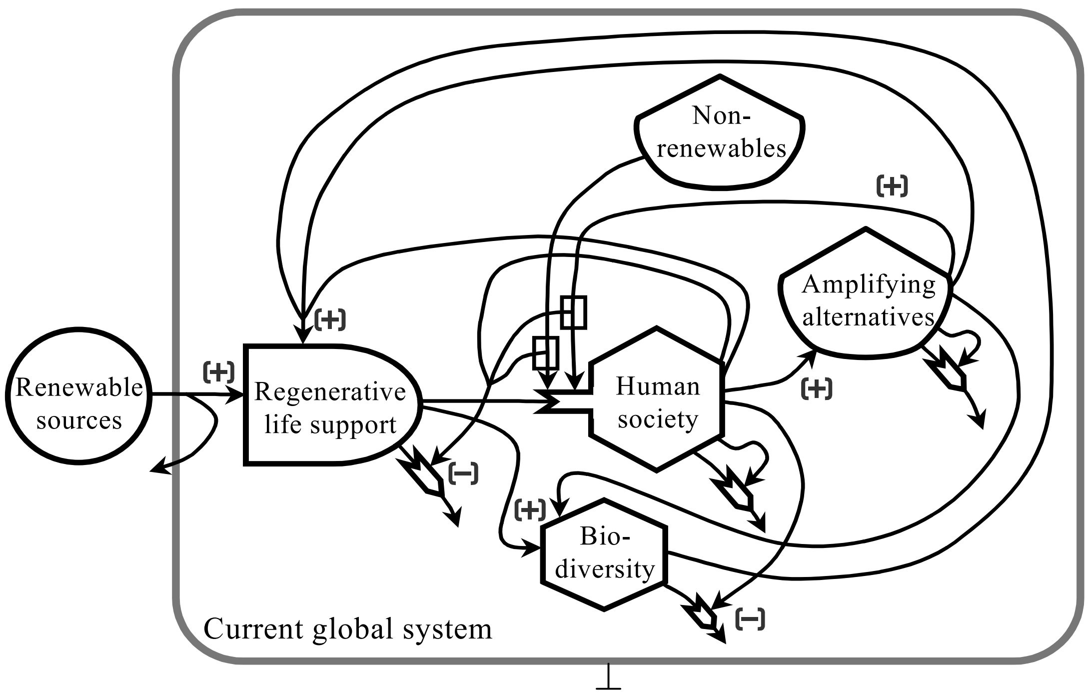

Figure 1. *Major ordering and disordering flows within the current global system that are important to monitor and regulate/control in the interest of protecting environmental welfare. Long-term welfare enhancement corresponding with empower maximization might be promoted under current conditions by increasing sustainable productive flows (+) and decreasing unsustainable disorder-enhancing flows (–), which do not contribute adequate production-amplifying reinforcement. The flow from current-system nonrenewables must also decrease eventually, and sooner could be better than later if the transition can be achieved without undue or increased disruption (of system viability or human and environmental well-being). The amplifying alternatives include all high-exergy storages introduced or supported by society that amplify system empower acquisition or allocation to regenerative life support, biodiversity, or human society and that might substitute for nonrenewables in providing such support. All elements in the above system are subject to entropy-related available-energy losses, as indicated by the heat-sink symbol attached to the system window.*

Odum (1977, 1994) and others have suggested that a particularly important role for humans might be processing information using systems models (permitting more rapid, multilevel optimization of the dynamics and viability-enhancing functions of systems). This information-processing capacity provides a greatly increased potential for introducing innovative designs and processes for maintaining balance among flows (ordering and disordering, accumulating and frenzing, previously adapted and novel) and among selection pressures (generated through cooperative and competitive interactions among components—and also environments—at various system levels). Ultimately, such capacity could permit use of this period of frenzing for the introduction and testing of novel amplifying structure/cycles that increase long-term system empower (that persists beyond the frenzing period) in a manner that enhances the viability of the integrated environmental-socioeconomic system. In this capacity, society would also be an accumulator and preserver of information-rich production-amplifying storages and processes.

Although some such uses of frenzing periods by well-adapted components are suggested by the pulsing paradigm (Odum, 1994; Odum and Odum, 2001), the extent to which human society is accomplishing this objective is not yet clear. Human preferences tend to be oriented toward shorter-range goals, and these preferences substantially shape actual societal contributions. Human contributions that might further this objective involve harnessing more of the renewable energy flow that is currently lost as residual flow (from a flow-limited source, for instance), accessing nonrenewable energy sources that otherwise would never become available to this global system, or using existing flows more effectively to reinforce viability and well-being at all levels. Although the third of these options has been the most often emphasized by environmental policy makers, some emergy theorists might object that the global system is already fully adapted (after more than 4 billion years) to effectively harness all the energy it receives at steady state (i.e., from its long-term-average renewable sources). An emergy theory well grounded in the selective reinforcement theory from which it was derived (Odum, 1994) would probably find such a position dubious, however. Such well-grounded emergy theory further reinforces the preference for policies that seek improved viability/welfare through a more effective and better-coordinated use of existing system influxes while also clarifying the potential long-term contributions of emergy analysis and other possible system-optimizing mechanisms.

Convergent and Divergent Perspectives on System Equilibration and Adaptation

Achieving our fundamental environmental policy goals (safeguarding and enhancing health and well-being) implicitly depends on modeling the global system with sufficient accuracy to permit a reliable redirection of energy flows for optimal system balance, coordination, and viability. Attaining this accuracy is then a common objective of scientific and economic analyses of environmental policy, whether emergy- or market-based. As noted above, however, emergy- and market-based analyses have each tended to emphasize processes and flows that the other treats as detail that can safely be omitted. This divergence results from their differing perspectives on system equilibration, equilibrium orientation (or extremum propensity), and value determination. In brief, the proximate goal of an emergy-oriented policy would be to optimize systems for maximum empower; the proximate goal of a market-oriented policy would be to optimize systems for maximum market efficiency. (We use the term "equilibrium" to refer to the result of the adaptation of a system to its environment through a process of variant generation and selection. Such an equilibrium does not imply succession to a sustained steady-state climax; some of a system's state variables might be non-stationary at equilibrium, were its hypothetical equilibrium dynamics ever attained.)

The theory upon which emergy-oriented approaches are based hypothesizes maximum system empower as the orientation associated with system equilibration, which occurs through differential prevalence of alternative system designs in response to competition for and selective reinforcement of empower acquisition. The theory upon which market-oriented approaches are typically based hypothesizes maximum preference satisfaction (in terms of the monetary numeraire, which is necessary to obtain the aggregated-utility, or "social-welfare", functions most frequently used by environmental economists) as the defining orientation of the equilibration of free and efficient markets. This equilibration is hypothesized to occur through differential prevalence of alternative production and consumption processes in response to competition for and selective reinforcement of preference-satisfying resources (i.e., of purchasing power and associated entitlements).

The potential connection of emergy- and market-based values with environmental policy goals derives from the association of differential prevalence and selective reinforcement with the viability of a system and its elements. In the case of emergy-based values, the absolute requirement for available energy and the long-term viability associated with relative system-level vigor and adaptability are emphasized. In the case of market-based values, a theoretical dependence of subjective well-being on preference satisfaction and of preference satisfaction on free and efficient markets is emphasized, along with the association of short-term viability with relative advantages with respect to preference satisfaction. In both cases, the relevance of values to policy goals depends on the strengths of the hypothesized equilibrium orientations and associations and on an adequate characterization of the actual dynamics of equilibration and of the critical factors affecting it. Although an ideal of equilibration based on decisively effective competition and adaptation is foundational to both theories of value, the associated applied methodologies were developed as policy-analysis aids largely for evaluating situations in which the requirements of their respectively ideal competitive equilibriums have not yet been met.

Market Equilibration, Valuation, and Divergence from Policy Goals

When markets are operating efficiently (so that all transactions that entitled individuals would prefer to make, given a perfect understanding of their nonmarket consequences, are indeed made), price is the standard economic measure of marginal value. Upon equilibration of such a market, the price and quantity of goods produced are such that marginal cost equals marginal benefit (in terms of the standard preference-satisfaction, i.e., monetary, numeraire). Producing either more or less of the item decreases the corresponding net benefits at this point, so resources are allocated to production in a preference-maximizing manner (Figure 2). These marginal benefits and costs are also equal, respectively, to people's willingness to pay or to accept compensation for an item, and thus also to its equilibrium price. Price thus accurately signals marginal purchasing-power-weighted preference value under these conditions. (Price is not necessarily acceptable as a signal for health- or well-being-related costs or benefits under these conditions, however, given that market mechanisms can assign very little weight to even the most basic health preferences or needs of those with very little purchasing power or entitlement.) Given perfect market mechanisms as premised above and a preponderant human preference for the survival of the larger systems on which human society depends, the equilibrium market values for environmental processes, storages, and flows would correlate closely with their importance to the viability of these larger systems.

Divergence between market values and generic preferences for environmental system viability can also arise due to missing or poorly adapted markets, information flows, or energy circuits. Such conditions result from both short-term perturbations (such as innovation or introduction of new processes, system designs, policies, or forcing functions) and long-term structural factors (such as social organizations, institutions, and entitlement systems that exacerbate externalities, adverse selection conflicts, monopolistic resource and capital allocations, or irresponsible management of public goods). The effects of such divergence can include reduced purchasing-power-weighted productivity or preference satisfaction as well as reduced empower acquisition and short- or long-term system viability. Environmental economic theory addresses these further limitations of market values for effective policy analysis (Freeman, 1993; Friedman, 2002), without, however, providing a consistent framework for a scientifically informed analysis of the environmental effects of economic activities.

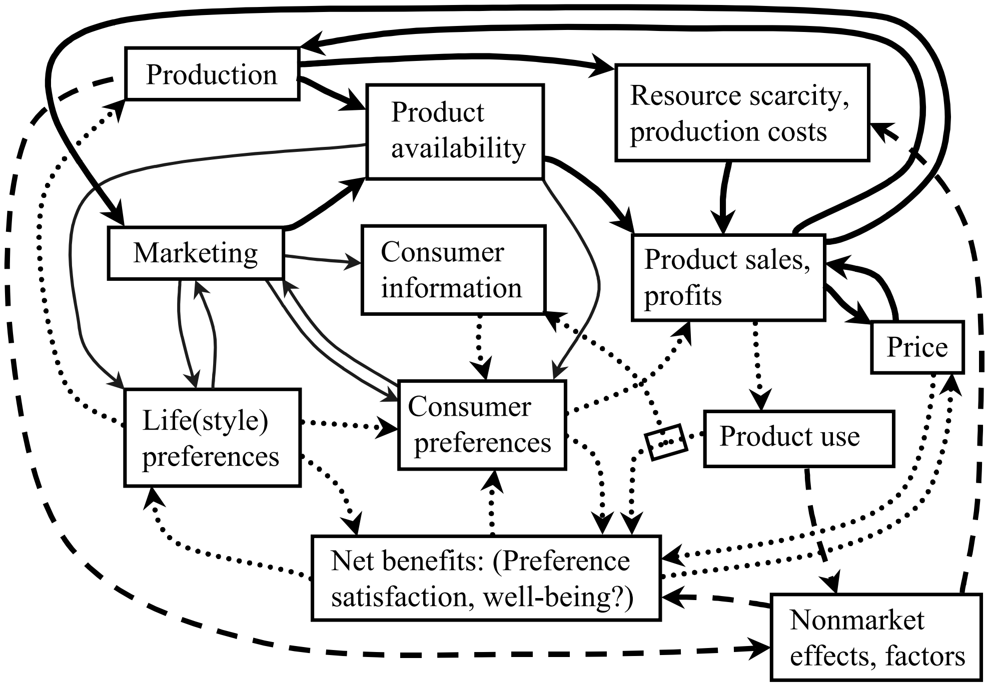

Figure 2. *Web of important influences on market equilibration and on resulting market-based production and valuation. Equilibrium prices and quantities of products subject to a decentralized market mechanism are determined by preferences and by resource accessibility and initial distribution. Individual human preferences determine production and consumption choices that set equilibrium prices equal to marginal preference-satisfaction values. Given an identification of individual, purchasing-power-weighted preference satisfaction with social welfare, such prices accurately reflect contributions thereto. The critical relations linking preference fulfillment and price are indicated with dotted lines. Resource-, production-, and purchase-driven relations are indicated with thick solid lines, which also coincide with the relations that typically serve as the focus of mainstream economic analyses. Other relations considered critical by some economists but often neglected in economic analyses are indicated with thin solid lines. Influences that result in deviations from the market-equilibrium ideal (based on effects of production and use on costs and benefits that are not mediated by the market mechanism) are indicated with dashed lines, which coincide with relations of specific concern to environmental economic analysis.*

ACHIEVING EMERGY VALUATIONS THAT COINCIDE WITH POLICY GOALS

Empirical and Theoretical Research Needs

Emergy methodology might be augmented to meet this need through the integration of the environmental economic methods within a consistent emergy-theoretic framework. However, the susceptibility of emergy values to divergence from values commensurate with effects on viability (Odum, 1994; Brown and Herendeen, 1996; Collins and Odum, 2000), particularly with respect to the evaluation of recent innovations, novel development or policy proposals, and coproduct contributions, must also be investigated more thoroughly. More generally, emergy valuation of energy circuits, information flows, and emergy acquisitions and expenditures in environments lacking adequate mechanisms for selective reinforcement of system-viability-enhancing processes requires appropriate reference values for alternative processes within comparable environments. Such requirements might be met by calibrating appropriate indices, such as the emergy investment ratio, for instance. Empirical testing of the usefulness of these indices is critical to our assessment of the relation between emergy values and the viability of environmental systems. This testing must build on the simple relations between emergy- and market-based values or indices that are currently derivable from previous valuations of similar systems or goods and services (Levine and Butler, 1982; Odum et al., 1987). Identifying specific factors that account for the observed convergences and divergences and quantifying the relations among them might begin to address this policy need.

While the above empirical approach depends on a substantially increased resource allocation to emergy valuations, the potential usefulness of the resulting comparative studies can be better established and more effectively communicated through a more precise and realistic modeling of integrated socioeconomic-environmental systems. Given the importance of price and preference in organizing economic activities and the potential complementarities and conflicts between selection that maximizes preference satisfaction and selection that maximizes empower acquisition, factors affecting these two determinants of system organization and viability (see Figure 2) must be explicitly incorporated within an energy-theoretic perspective. A more precise understanding of the role of human preferences in the self-organizing and equilibrating dynamics of socioeconomic-environmental systems at all scales is essential to the development of an analytical framework that is both consistent and realistic. Given our focus on protecting human and environmental well-being, we want to consider specifically how the current mechanisms designed to maximize some form of human preference fulfillment relate to human well-being, the likelihood of system survival, and to other human goals (related, for instance, to equity and environmental well-being).

Energy-Socioeconomic Systems Models

To this end, we hope to develop energy-socioeconomic systems models that capture in a highly generic manner the respective effects and relative importance of preference- and empower-maximizing resource expenditures or allocations within a representative range of system designs. When selection among alternative allocations of environmental production to two goods (at whatever scale, public or private, market or nonmarket) is driven predominantly by preference-based competition for purchased inputs (Figure 3), for instance, the respective emergy contributions to the viability of the larger environmental systems might not be effective in maximizing either system empower or viability. Tradeoffs between preference- and emergy-determined values will be particularly important in such cases if there is a conflict between preference- and emergy-based selection. The emergy contributions of Good *a* might exceed those of Good *b*, for instance, while the preference intensity for Good *b* exceeds that for Good *a*. The empower-maximizing alternative in this design (Good *a*) does not receive any selective advantage, with respect to its alternative within this system (Good *b*), for the amplification of system empower that it provides. Following selection within this system, then, the allocation of environmental resources will reflect the resulting prevalence of the preference-maximizing alternative (Good *b*), which is selectively reinforced with respect to Good *a*.

In a different system design, in which the empower-maximizing alternative did receive a selective advantage in terms of empower acquisition from the environmental system, it might prevail. In some circumstances, the increased system empower could then provide resources for the persistence of both alternatives along with a higher long-term preference fulfillment. Thus the short-term and long-term preference-maximizing alternatives might differ. Such an empower-maximizing design, or an alternative in which the same alternative maximized both short-term preference satisfaction and empower, could prevail over the one depicted here. If the empower-maximizing alternative cannot survive in the short term, however, such a design will have little likelihood of developing (within the current accumulating-frenzing cycle). If the empower- and viability-maximizing alternatives did coincide, we would then want to consider policies that supported an alternative expenditure mechanism without introducing undue inefficiencies and unsustainable conflicts with the system's

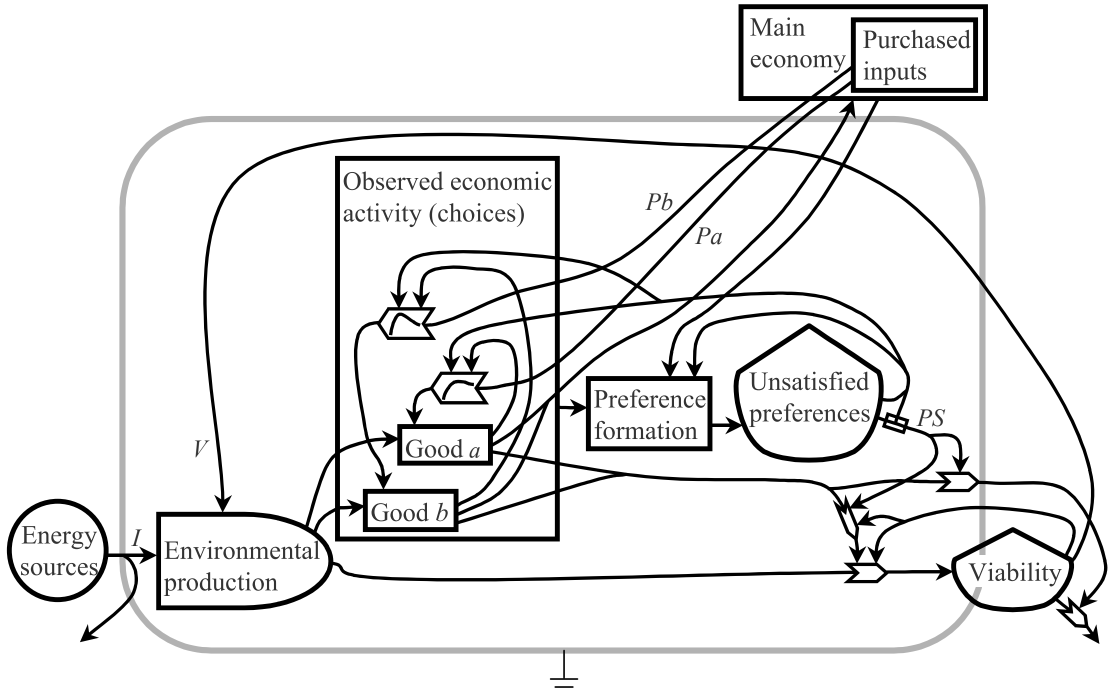

Figure 3. *Effects of preference-dominated selection among alternative public or private goods on viability. Use of environmental production within this system is primarily determined by preference-driven application of purchased inputs. Allocation of these inputs (Pa and Pb, respectively) to Goods a and b contributes to short-term maximization of preference satisfaction (PS), with both constructive and destructive effects on viability, which provides a reinforcement (V) to environmental production that amplifies its unpurchased empower (I) without selectively reinforcing production or use of Good a or b. (Viability is a storage, similar in nature to diversity, of the energy or emergy specifically associated with this system property, although it is not a storage physically separable from or within the system as diagrammed.)*

intrinsic selection dynamic. In the case of alternative uses of a public resource, for instance, a pooled preference-derived resource expenditure might be allocated according to some function of emergy flows (the relation between amplifying emergy and purchased emergy, perhaps). Ex ante analysis of the effects of this alternative expenditure allocation would focus on its effects on both cumulative preference satisfaction and system empower acquisition to more fully assess both short-term and long-term viability or welfare.

CONCLUSIONS

Use of integrated analyses of socioeconomic-environmental systems to improve our protection of environmental welfare will depend on the adequacy of our understanding of energy- and preference-driven selection dynamics. Incorporation of these potentially disparate determinants of system welfare and viability (along with their relations with other critical factors and policy goals) in integrated analytical models that are useful as well as realistic remains a long-term objective for effective management of socioeconomic-environmental systems. The contribution of economic analyses to this effort will depend on the modification of environmental economic methodology to address conflicts between purchasing-power-determined selection and other social goals such as optimal human health, environmental welfare, and long-term system viability. The contribution of emergy methodology will depend on its further development to more explicitly account for the effects of information flows, multilevel selection, and novel processes and designs on both short- and long-term system viability and prevalence.

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