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A General Engineering Framework for the Definition, Design, Testing and Actualization of Solutions within Complex Adaptive Systems of Systems (CASoS) with Application to the Global Energy System (GES)

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Abstract

Complex Adaptive System of Systems (CASoS) are ubiquitous: they include cities, infrastructures, governments, armed forces, nations – in short, systems that are *socioeconomic-technical* in nature. We developed a general *CASoS Engineering Framework* for the Definition, Design, Testing and Actualization of solutions within CASoS. This development was performed through focus on a high priority, specific CASoS, the *Global Energy System* (GES). The GES contains both complex earth and complex adaptive human systems of economic, socio-political, and technical nature. For the GES, we delineated a set of three nested Goals at increasing scale that achieve National to Global Energy Surety. We then formulated a conceptual model with entity based negotiated exchanges at a variety of scales (nations, industries, consumers), for resources (material, funds, energy), technologies (transform resources, emit CO_2) and with competing needs (energy surety, standard-of-living). A simplified version of the model was implemented and preliminary analyses of two test cases were conducted.

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EXECUTIVE SUMMARY

Complex Adaptive System of Systems (CASoS) are ubiquitous: they include cities, infrastructures, governments, armed forces, nations – in short, systems that are *socioeconomic-technical* in nature. As a national laboratory with an engineering mandate, nearly every important problem that Sandia confronts exists within a CASoS, as do, for example, nuclear stockpile management, nonproliferation, energy surety, and critical infrastructure protection. We must recognize this CASoS context in order to properly pose and solve problems while avoiding unintended consequences. Only through understanding the *socioeconomic-technical* context can we develop feasible solutions that are robust to uncertainties and enhance system resilience.

Here, we have developed a general *CASoS Engineering Framework* for the definition, design, testing and actualization of solutions within CASoS. This development has been performed through focus on a high priority, specific CASoS, the *Global Energy System* (GES), while keeping generic functions in mind. The GES contains both complex earth and complex adaptive human systems of economic, socio-political, and technical nature. The GES is currently one of the nation's and humankind's highest-priority, largest, most important CASoS.

Our general CASoS Engineering Framework includes three iterative and interacting phases:
1. **Defining** the CASoS, the *Aspirations*, the methods and theories, the conceptual models and the required data
2. **Designing and testing solutions** for robustness and critical enablers of resilience
3. **Actualizing** solutions within the CASoS (delivered, tested against real world requirements and adaptations, iteratively revised to match evolution of system environment)

Application of the CASoS Engineering Framework to the GES focused on the Defining phase in which we delineated a set of three nested Goals of increasing scale that achieve:
1. **National Transportation Energy Security**: specific energy need at the scale of the nation
2. **National Energy Surety**: all energy needs appropriately interconnected with other sectors (e.g., agriculture, economic output) at the scale of the nation
3. **Global Energy Surety**: all energy needs appropriately interconnected with other sectors at the scale of the globe

To tackle these Goals, we formulated a conceptual model to evaluate the effective means of achieving energy security or surety while meeting global carbon goals. The model represents interacting entities at a variety of scales (nations, industries, consumers) that have resources (material, funds, energy), technologies (transform resources, emit CO_2) and competing needs (energy surety, standard-of-living). A simplified version of the model was implemented as a proof-of-concept and preliminary analyses of two test cases were conducted.

Many of the problems we work to solve at Sandia are in the context of systems that are CASoS, yet we rarely treat them as such. The development of a CASoS Engineering Framework for application to the myriad socioeconomic-technical problems within SNL's national security mission is of critical importance. Successfully applying this framework to a significant and prominent challenge, such as controlling CO_2 emissions while maintaining/improving national energy surety, will demonstrate our ability to find practical solutions to difficult problems.

1. INTRODUCTION

Sandia has long nurtured diverse lines of research, development and application in systems engineering. As our capabilities in these areas increase, we encounter problems whose complexity, adaptability, interconnectedness, and heterogeneous structure challenge current methods. Understanding these *complex adaptive systems of systems*, or *CASoS*, becomes critically important as we look past the *physical systems* that have been our traditional focus to the vastly more complex *socioeconomic-technical systems* we must understand to design a secure future for the nation. Over the past few years an increasing number of new and ongoing projects, teams and business areas within SNL are moving to address problems in such systems. Examples include nuclear stockpile management, nonproliferation, future transportation energy, and critical infrastructure protection. CASoS are ubiquitous and often contain human, economic or social components. While the detailed contents of various CASoS differ widely, they are all deeply similar; the theories, technologies, tools, and approaches to enable the engineering focused solution of CASoS problems can be organized and integrated systematically[1]. Based on this recognition, it is possible to construct a *CASoS Engineering Framework* that will allow us to define and tackle critical, high impact problems within generic CASoS.

Here, we began the process of constructing a CASoS Engineering Framework. Such construction cannot take place in a vacuum; we needed to work with direct reference to a particular CASoS. The CASoS we chose was the *Global Energy System*, or *GES*. The GES is one of the largest, most complex, and most important CASoS. The GES is composed of the *complex physical systems* of the atmosphere, lithosphere, and hydrosphere, as well as the *complex adaptive systems* of the biosphere which prominently include human economic and socio-political systems, and energy generation, storage, control, and interdependent global distribution networks. Our nation and others require safe, secure, reliable, sustainable, and cost effective supplies of energy to support economic development and to maintain a high standard of living. Our nation's energy infrastructure evolved to meet these requirements with fossil fuels because of their inherent high energy density and flexibility. We are now left with several unintended consequences: high-CO_2 emissions, dependence on foreign petroleum for many critical activities (e.g., transportation fuels), and inadequate investment in energy source diversification. All of these consequences are now a threat to national as well as global security.

[1] Glass, RJ, AL Ames, WA Stubblefield, SH Conrad , SL Maffitt, LA Malczynski, DG Wilson, JJ Carlson, GA Backus, MA Ehlen, KB Vanderveen, D Engi, 2008, "Sandia National Laboratories A Roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative"

2. WORK ACCOMPLISHED

Over the course of the project we:

a. Defined the GES as a CASoS and an object of engineering design so that the attributes of the GES-CASoS were clear.

b. Developed a general CASoS Engineering Framework that could be applied to any problem.

c. Began evaluation of Transportation Energy as something concrete and of immediate importance (cost of gas was skyrocketing in summer 2008). In this process, we considered general influence matrices and the formulation of linear interdependencies and control logic. We also considered the issue of the true cost of transportation fuel through an evaluation of the current price bubble.

d. Defined a set of goals to refine the GES application space and allow the formulation of GES problems at multiple and nesting scales.

e. Developed a conceptual model for multi-scale analysis of the GES using entity based negotiated exchanges and then applied the model to two simple problems to evaluate its response and the feasibility for expansion.

These activities are presented in subsequent sections (**Sections 3-6**) of this report. **Section 7** enumerates Next Steps that should be accomplished to bring our effort to fruition.

Finally at the end of the year, we "thought" on three topics in support of several efforts being spearheaded by SNL management:

f. Composed "Thoughts on formulating the Transportation Energy Innovation Hub (TEIH)" in support of Ellen Stechel (6230) (**Appendix D**)

g. Composed "Thoughts on formulating Sandia's Energy Mission" in support of Terry Michalske (6100) (**Appendix E**)

h. Composed "Thoughts on Folding Climate into the Global Energy System CASoS" in support of Margie Tatro (6200) (**Appendix F**)

These final "thought" activities are documented in appendices and are not discussed further in the main body of this report.

3. DEFINING THE GES AS A CASOS AND AN OBJECT OF ENGINEERING DESIGN

CASoS is a concatenation of four sub disciplines or study areas: Systems, Complex Systems, Complex Adaptive Systems, and Systems of Systems. Definitions of CASoS are accomplished by addressing, at a minimum, the 7 points described below. A Complex Adaptive System of Systems requires:

1. **System:** A system is a set of entities, real or abstract, comprising a whole where each component interacts with or is related to at least one other component and they all serve a common objective. Any object which has no relation with any other element of the system is not part of that system.
    a. **Environment:** The system functions within an environment. Interactions with the environment should be less complex than internal interactions and make the drawing of the boundary between them derivable
2. **System of Systems:** The system is composed of other systems ("of systems"). The other systems are natural to think of as systems in their own right, can't be replaced by a single entity, and may be enormously complicated, or we would be dealing with a single system, rather than a system of systems.
3. **Complex:** The system has behavior involving interrelationships among its elements and these interrelationships can yield emergent behavior that is nonlinear, of greater complexity than the sum of behaviors of its parts, not due to system complication.
4. **Adaptive:** The system's behavior changes in time. These changes may be within entities or their interaction, within sub-systems or their interaction, and may result in a change in the overall system's behavior relative to its environment.

We are interested in problems regarding CASoS.

5. **Aspirations: What are the problems/opportunities/goals/questions?**

We are interested in doing something (designing, controlling, manipulating) with the system to solve a problem, exploit an opportunity, achieve a goal, or answer a question:

6. **Approaches:** What are the activities (e.g. observation, experiment, design, control, manipulation, modeling) that we might engage in to solve a problem, exploit an opportunity, achieve a goal, or answer a question.
7. **Attainability:** How are approaches/Aspirations rendered difficult/impossible by the fact that this is a complex adaptive system of systems?

Applying the above diagnostic to the GES results in the following definition of the GES as a CASoS.

1. **System:** The Global Energy System (GES) encompasses the physical components of the atmosphere, lithosphere, and hydrosphere, as well as the components of the biosphere

which prominently include human economic and socio-political activities, in addition to energy generation, storage, control, and interdependent global distribution networks. For humans, the most important function of the GES is its contribution to the sustenance of life on Earth.

   a. **Environment:** The boundary of the GES has often been drawn at the interface between human-created energy systems and natural systems; however, ignoring natural systems has proven short-sighted, e.g., greenhouse emissions. A more encompassing boundary considers all sources and sinks for energy, natural or man-made, and their effects in both physical and social realms (for example, the economy, air and water quality, war, etc); the environment includes the physical world beyond, as well as aspects of human life that are not work-energy related.

2. **System of Systems.** Each of the components is a system in its own right; many are poorly understood. For example, weather prediction (atmosphere) is extraordinarily difficult, and violent (extreme) weather events have powerful and poorly understood influences on the other components of the GES.
3. **Complex:** Each component system constituting the GES can exhibit complex or chaotic behavior. Interactions between these component systems are subtle and pervasive. Extreme variations in temporal scales (effects from nanoseconds to eons) and spatial scales (effects from microscopic to solar system) add to the intricacy of interactions. Large numbers of interactions at many different scales guarantee complex behavior for the GES.
4. **Adaptive:** The physical components of the GES are constantly changing: solar activity, volcanic activity, climate, sea level, constituency of water and air, weather phenomena. Species evolve within this changing environment and, at shorter time scales, so do human civilization and needs. All of these changes impact our ability to extract energy from the environment and put it to use. In response, we adapt/evolve our designed energy systems and our lifestyles.
5. **Aspirations:** Our nation and others aspire to secure, reliable, sustainable, and cost effective supplies of energy to support economic development and to maintain a high standard of living. At present we have high-CO_2 emissions, dependence on foreign petroleum for many critical activities (e.g., transportation fuels), and inadequate investment in energy source diversification. All of these conditions are now a threat to national as well as global security. Aspirations focus on rectifying this situation to build a robust and resilient energy policy with supporting infrastructure that is global in scope.
6. **Approaches:** Potential system-changing responses range from the socioeconomic (e.g., negotiation of global and national targets for CO2 emissions, incentives/restrictions, technology and fund transfer, war) to the technical (e.g., renewable energy sources, next generation distributed energy grids, energy storage systems, new transportation fuels, CO2 capture and storage).
7. **Attainability:** The GES is one of the largest, most complex, and most interdependent CASoS. Opinion differs widely on what the problems are, how big the problems are, and how to go **about** solving them. Defining problems that have feasible solutions, that can be shown to be robust, and that can be actualized to enable system resilience within the GES will be a huge challenge due to its combined technical, economic, social, and political facets.

4. A GENERAL CASOS ENGINEERING FRAMEWORK

Engineering within CASoS spans a wide functional space. CASoS are *complex*, often complicated, large and irreducible; their dynamics have a wide range of time scales, so that interpretation and quantifying the impacts of modification is difficult; they are *adaptive*, often hysteretic and/or recursive, so building understanding through testing is difficult because repeatable initial conditions are generally not possible and simultaneous tests are often not independent. Additionally, many critically important CASoS are *socioeconomic-technical* in nature, so a wide range of “physics” apply that must address technical concerns, economic concerns, political concerns, and the interfaces among them. Because socioeconomic-technical CASoS embed people, experimentation within them is risky and costly, often leaving modeling as the only practical option. All these factors encourage widely different opinions on what the problems are, how big the problems are, and how to go about solving them.

As engineers, our *Aspirations are to influence* (design, control, manipulate) CASoS to solve problems, exploit opportunities, and/or achieve goals. A focus on aspirations breaks us out of the endless cycle of learning more and more about the details of individual CASoS. *Aspirations* fall into a set of clearly identified categories: Predict; Prevent or Cause; Prepare; Monitor; Control; and Recover or Change. Within each category, three sets of similar questions naturally emerge that encompass: *Decision*, determining *Robustness of Decision*, and *Enabling Resilience*. In context of socioeconomic-technical CASoS, answering these questions *Informs Policy*. Through such systemization, we argue that the requisite theories, technologies, tools, and approaches for aspiration-focused CASoS Engineering are similar across many CASoS and can be organized within a *CASoS Engineering Framework.*

A general *CASoS Engineering Framework* must be wide and deep to cover the many potential opportunities for unexpected, nonlinear, interconnected behavior. We envision the framework to contain three phases applied primarily in succession but with some overlap and blending to deliver CASoS engineered solutions:

1. **Defining** (blackboard → details) 1) the CASoS of interest, 2) the Aspirations, 3) Choice of aspirations based on constraints and impact, 4) Choice of appropriate methods and theories from the full space of those possible based on aspirations chosen, 5) Appropriate conceptual models, and 6) Required data to support conceptual model development and validation. Possible methods, theories and fields of contribution include analogy, dimensional analysis and similitude, experimental design, system dynamics, non-equilibrium thermodynamics, complex adaptive systems, game theory, percolation phenomena, agent-based modeling, networks, system optimization and control, and many others.

2. **Designing and Testing Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. Designing and testing solutions will be problem-dependent; it will focus on answering the three general sets of questions relevant to any aspiration: 1) What are *feasible choices* within the multi-objective space, 2) how *robust* are these choices to uncertainties in assumptions, and 3) what are the critical enablers that increase system *resilience*. Included in this process is the delineation of unintended consequences and their amelioration/mitigation.

3. **Actualizing** the engineered solutions devised above within the real system. The engineered solution may be a concept, a computational tool, a sensor, a control policy, etc. This activity involves working with decision makers (change the world), other researchers (change the field) and people affected by the change (understand the impact). This involvement requires a long term commitment: these are high-consequence systems that adapt to change. Any change makes us part of the system with concurrent obligation through a solution's lifecycle.

As in classical engineering, iteration and blending among the phases is intrinsic. Actualization will require designing and testing to suggest future steps, and adaptations of the system might require us to return to fundamental thinking to understand the adaptations and possibly reformulate our aspirations as the system changes.

Possible methods, theories and fields of contribution are further enumerated in **Appendix A**. In **Appendix B** we have assembled a set of questions and answers for the uninitiated in CASoS and CASoS Engineering to help with articulating these concepts.

Development and refinement of the *CASoS Engineering Framework* must be accomplished through focus on high priority, specific applications while keeping an eye on the generic.

5. DEFINING A NESTED SET OF GOALS FOR CASOS-GES

One of the highest priority, largest, most important CASoS that we could apply the CASoS Engineering Framework to is the GES. As defined in **Section 3** above, the CASoS-GES is composed of the *complex physical systems* of the atmosphere, lithosphere, and hydrosphere, as well as the *complex adaptive systems* of the biosphere which prominently include human economic, socio-political, and energy generation, storage, control, and interdependent global distribution networks. Our nation and others require secure, reliable, sustainable, and cost effective supplies of energy to support economic development and to maintain a high standard of living. Our nation's energy infrastructure evolved to meet these requirements with fossil fuels because of their inherent high energy and power densities and flexibility. We are now left with several unintended consequences: high-CO_2 emissions, dependence on foreign petroleum for many critical activities (e.g., transportation fuels), and inadequate investment in energy source diversification. All of these conditions are now a threat to national as well as global security. Potential responses range from the *socioeconomic* (e.g., negotiation of global and national targets for CO_2 emissions, incentives/restrictions, technology and fund transfer, war) to the *technical* (e.g., renewable energy sources, next generation distributed energy grids, energy storage systems, new transportation fuels, development of CO_2 capture and storage).

The application space for the GES potentially encompasses the entire globe and all human activity upon it. To make progress, we can refine the Application Space in a number of ways. A natural refinement considers a given scale and focuses on achieving some form of stability or sustainability at that scale for a given set of energy needs.

Along these lines, we define the following set of three nested Goals.

1. **Achieving National Transportation Energy Security**: specific energy need at the scale of the nation
2. **Achieving National Energy Surety**: all energy needs appropriately interconnected with other sectors (e.g., agriculture, economic output) at the scale of the nation
3. **Achieving Global Energy Surety**: all energy needs appropriately interconnected with other sectors at the scale of the globe

The first of these three focuses narrowly on a critical measure, "security," defined at the scale of the nation, while the second two conceptualize the critical measure as "surety" given by a comprehensive combination of qualities (e.g., safety, security, reliability, cost effectiveness, and sustainability to include environmental qualities such as CO_2 emissions and economic qualities such as profit) that could be defined differently at each scale. Defined this way, our goals are "similar" at each scale and this similarity (or near similarity) can be used to conceptualize the system. Such similarity will also allow us to make use of similar methods and theories, tools and approaches at each scale.

We expect that in order to achieve any of these goals, aspirations that span the full range of categories (Predict, Prevent or Cause, Prepare, Monitor, Recover or Change, and Control) within the CASoS Engineering Framework will have to be addressed and interwoven. It is highly unlikely that a focus on a single category will achieve the stated goals; all may be intrinsic. However, we also expect that Control will rise above the others as an integrator for our stated goals. For each goal, we can consider the design of effective means (e.g., policies or control circuitry) to elicit the required behavior (e.g., CO_2 emissions) at scales that range from the individual (e.g., person or physical components of a power grid) to the system (e.g., corporation or regional power grid) to the system of systems at the national and global scales while minimizing the creation of undesirable, unintended consequences. Such design applies within the full range from the *socioeconomic* (e.g., negotiation of global and national targets for CO_2 emissions, incentives/restrictions, technology and fund transfer, war) to the *technical* (e.g., renewable energy sources, next generation distributed energy grids, energy storage systems, new transportation fuels, development of CO_2 capture and storage).

The methods, theories and fields of concentration that are required to achieve these goals constitute all those in the CASoS Engineering Framework (**see Appendix A**) and span the categories of system definition and broad conceptual modeling, aggregate methods and theories from which basic results may be taken and applied, detailed modeling and simulation approaches, system optimization and control, and evaluation and discovery.

Early in project development, system definition and abstract modeling will be most important. More detailed modeling and simulation will follow only as more detail is required. Such an approach encourages activities to be focused on the broad problem, without bogging down in details.

Below we focus on Goal 1 as an example for definition and the form that possible Aspirations might take. Goals 2 and 3 can be likewise evaluated.

5.1 Example for Goal 1: Achieving National Transportation Energy Security

Our first goal focuses on the limited area of achieving national transportation energy security.

5.1.1. Definition of Goal

We begin by defining:

- National: The scope of the effort is on the security of transportation for the nation. To the extent possible, we relegate all other nations to the environment.
- Transportation: Having to do with the movement of people and goods over land, on water, and through air. We exclude under water, through ground, and through outer space due to lack of large-scale implementations through these media.
- Energy: Energy used for transportation. Currently, this is largely through the use of fossil fuels, but we don't exclude other possibilities (e.g. wind, solar, nuclear, etc).

- Security: freedom from danger, fear, anxiety, or deprivation. Security can derive from being independent from foreign sources of energy and from being defensible against outside threats.

5.1.2 Aspirations

Next, we examine the form that various aspirations might take:

- Predict
  - Predict costs and availability of a portfolio of transportation energy sources (starting with petroleum, but expand to address others) due to a range of environmental influences, including ordinary behavior and a variety of environmental disruptions (hurricane, flood, war, terrorism, economic competition). Includes domestic and international sources.
  - Predict likelihood and likely locations for outside threats against foreign and domestic energy processes (extraction, transformation, delivery).
- Prevent or Cause
  - Determine effective means for preventing disruptions, either through acts of nature or intentional acts. Estimate their costs.
- Prepare
  - Determine effective means for preparing for disruptions to energy supply (e.g. petroleum reserves).
- Monitor
  - Devise effective means of measuring the security of domestic energy supply (security of facilities, security of sources (how empty is the well), security of supplier relationships).
- Recover or Change
  - Devise effective means of restoring the supply of an energy source after a disruption.
  - Devise a means of deciding how much to restore the supply of an energy source after a disruption (should one rebuild the oil wells?)
- Control
  - Devise a means of stabilizing the price and availability of a transportation energy source (controlling only one can cause extreme negative change in the other).
  - Devise a means of influencing the behavior of a population to change their behavior to alter the demand for an energy source (e.g. encourage use of alternate transportation sources, energy conservation).
  - Devise a means of encouraging diversification of energy sources, as a means of reducing dependence on a single source.
  - Devise a means of reducing demand for energy sources as a means of reducing dependence on a single source.

5.2 Choice of Aspirations

To achieve Goal 1, national transportation energy security, aspirations cannot be addressed independently. Each aspiration influences the others and all must be interwoven in a comprehensive engineered solution. As an example, consider Prediction. Prediction of time series' within *socioeconomic-technical CASoS* is in general limited to short horizons. However, in combination with another aspiration such as control we can often transcend this limitation as control places bounds on system behavior and thus constrains the realm of possibility. As another example, consider Prepare. Independently, preparations could be made for all contingencies. However, why prepare for an event if control is designed to significantly reduce the risk of the event occurring or if the system is modified so that it is resilient, significantly reducing the cost of recovery from the event? The same arguments apply to Goals 2 and 3. Therefore, we believe emphasis should be on *design of control* that increases system *robustness* (keeps it from breaking) and/or system *resilience* (makes it come back quickly).

5.3 An overarching conceptual model for the design and testing of solutions

As a first step towards conceptual model formulation, we focus on the socioeconomic end of the socioeconomic-technical spectrum. Here, we can consider a conceptualization that represents each of a number of entities (people, communities, nations, industries) that have resources (material, funds, energy), technologies (ability to transform resources and emit CO_2), and needs which are met by acquiring resources and emitting CO_2. These entities interact with each other in pursuit of private objectives and adopted constraints to form flows of resources, with attendant releases of CO_2. This general conceptualization of the socioeconomic CASoS implemented within a computational model could be used for analysis in context of all three of the goals stated above. Analysis can evaluate the components of surety and economic performance on scales ranging from the individual entity, to the nation, to the globe. The policies that constrain the behavior of the individual entities can be viewed as control signals. Decentralized control theory could be applied in order to identify controls that achieve the desired state for the system at either national or global scales. Such a model could then be used to evaluate the robustness of the policy and the critical enablers required to create system resilience.

6. CONCEPTUAL MODEL FOR ENTITY BASED NEGOTIATED EXCHANGES AND ITS IMPLEMENTATION WITHIN THE GES

The potential responses of the GES to alternative policies, stresses, and constraints can be studied using a generalized model of negotiated exchanges of resources among a set of entities. The number and nature of the resources, the number and types of the entities that exchange them, and the types of negotiations can be tailored to represent a wide range of specific problems.

In **Appendix C** we present the general model, specialize it for the GES and then consider a simple implementation. Below we summarize this effort.

6.1 General Model Conceptualization

We would like to understand the possible reactions of the global energy production system to a set of policies designed to reduce carbon emissions. The general resource exchange model framework described in **Appendix C** is naturally suited to this problem. The model must include Entities representing the organizations with significant influence on the production and use of energy. The processes we believe to be important include utilization, expansion, and deterioration of different classes of energy production capacity (coal, nuclear, oil, natural gas, renewables, etc.), production of goods and services using energy (and other) inputs, consumption of goods, services, and energy by households, provision of labor by households, extraction and transport of raw commodity inputs for producing energy and industrial goods, and development and adoption of alternative technologies for energy production, transportation, and manufacturing.

The model should be as parsimonious as possible while including these processes under the policies of interest. Policies to be evaluated include:

- Creation of carbon markets in individual nations or treaty blocs
- Creation of a global carbon market
- Imposition of a national/treaty bloc carbon tax
- Imposition of a global carbon tax
- Which, Carbon markets or Carbon Tax?

The rate and location of energy production, and the associated levels of macro-economic activity such as unemployment rate and GDP, result from the interacting decisions of the Entities. As discussed in **Appendix C**, these decisions are modeled as driven by some “utility” for the Entity (utility is explicit in the case of the utility maximizing formulation, and expressed in the classifier formulation by the resource changes used to reward rules). The utility formulation may include many kinds of resources, may differ among instances of the same kind of Entity, and may be neither perfectly informed nor risk-neutral.

6.2 Preliminary Implementation for a Single Core Economy

We implemented the general conceptual model for a single energy-based economy with a core set of elements. **Figure 1** diagrams the Entity types and Resource flows. The model includes five basic kinds of Entities: households, farms, commercial firms, fossil-fueled generators, and non-fossil-fueled generators. Four Resources are exchanged among the Entities: food, power, consumer goods, and labor. All exchanges for each kind of good are mediated by a single Broker type, which uses a continuous double auction to pair individual supplier Entities with consumer Entities. In addition to the exchanged Resources and the money resource, several additional resource types are defined to reflect the internal states of each Entity such as the number of people, land, capital and Carbon Emission credits and limits. Transformations within entities (a specific process or action affecting the entity) define the basic economic role performed by each Entity type, as well as internal processes such as population growth and depreciation of capital stock.

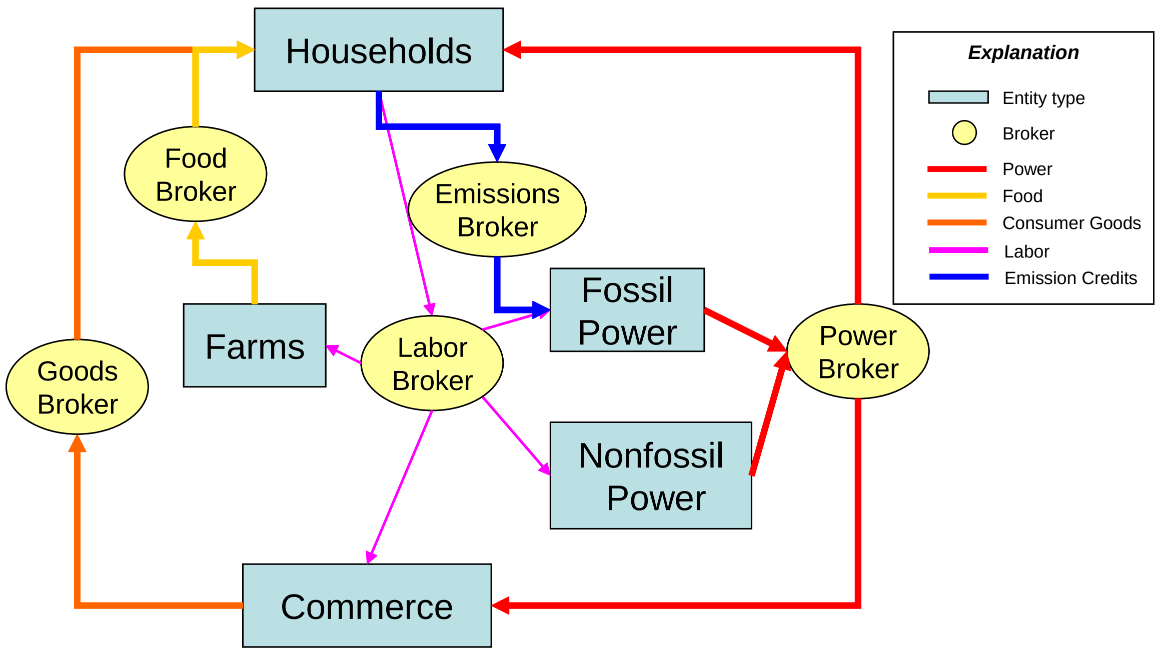

Figure 1: Classes of Entities in the initial model and associated Resource flows.

For this implementation of a single core economy, we simulated two situations whose outcomes can be qualitatively anticipated but which, if observed in the model, must emerge from its internal interactions rather than being forced by the model structure. In the first situation the fixed fossil fuel resource depletes over the course of the simulation, effectively removing power production capacity. We expect to see an increase in power price with time as this occurs, and a higher overall price compared to a reference simulation in which the initial fuel endowment is larger. This result is trivial given our understanding of how markets respond to scarcity, but the Entities in the model have no such understanding or (overt) constraint to respond in that way. In the second situation we impose a tax on fuel use by requiring fossil-fueled generators to consume a carbon credit in the process of generating power. They obtain this credit through a market, which is supplied at a fixed rate per unit time. The institutions that would create such a market in practice, and the flow of resulting revenues, may be quite complex: to avoid unwarranted complications we simply assume that carbon credits are created and sold by the household sector, as one possible design for such a scheme would return revenues generated by selling new credits to consumers in the form of rebates. The qualitative consequences are again easy to anticipate: an overall increase in power price, with a smaller share of production occurring through fossil fuels.

Expected behaviors for both situations were met by the simulation results. As an example for the carbon constrained situation, fuel consumption is radically curtailed. In conjunction with lower demand for consumer goods the carbon tax results in effective elimination of fossil-fueled generation by the end of the simulation (**Figure 2**).

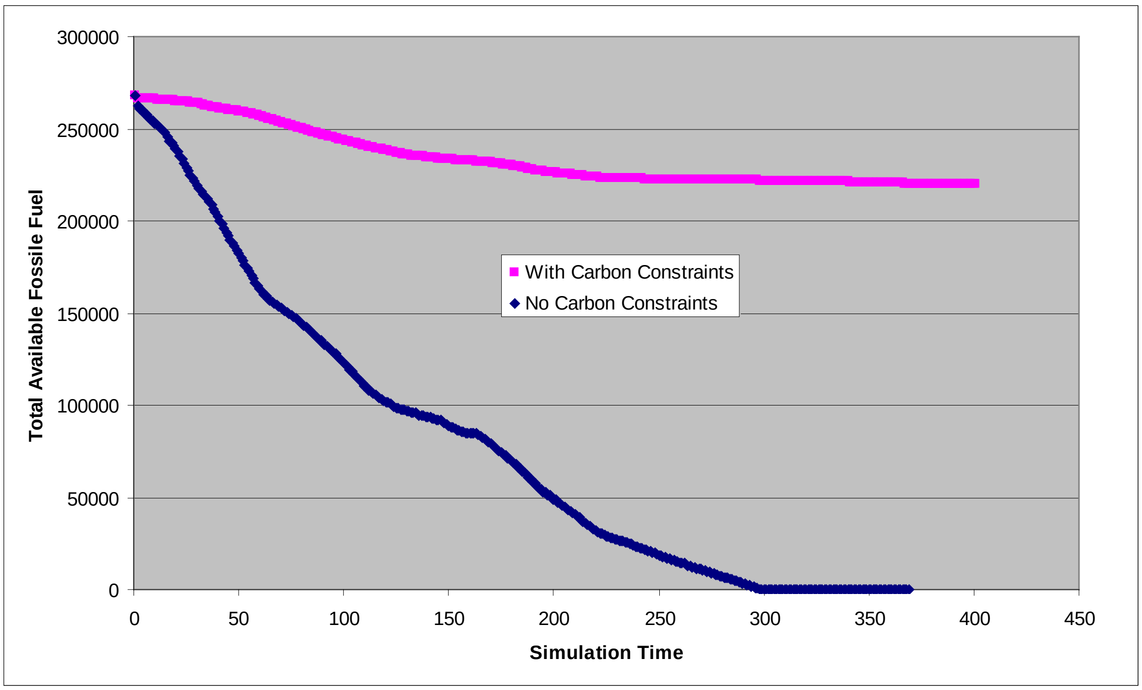

Figure 2: Total amount of fuel resource in the model with and without carbon emission constraints.

We emphasize that our preliminary implementation and results as yet have no bearing on the possible effects of a carbon market in the real GES. The purpose of the present implementation was to examine the interaction of a few core components that will be part of the larger model. No attempt has been made to parameterize these components in a meaningful way, and many essential components are yet to be included. The purpose of these simulations was to test the model's ability to produce selected qualitative responses that would be expected in a real system that matched the model constraints: an overall increase in power price as a finite fuel resource is depleted, and an increase in power price and decrease in usage if carbon emissions associated with fossil fuel use are taxed.

A full description of the preliminary implementation and results is presented in **Appendix C**.

7. NEXT STEPS

The Nested set of Goals presented in **Section 5** organizes a pathway for future work. Our conceptual model and its numerical implementation presented in **Section 6** and **Appendix C** shows promise and will be extended and applied within context of the design and testing of solutions phase of the CASoS Engineering Framework presented in **Section 4**.

We believe that the most significant impact of accomplishing our nested goals will be to contribute to the formation of local to national to international policy. We will focus on the socioeconomic side of the *socioeconomic-technical* realm as it is the driver for human interaction with the GES and therefore most critical over both the long and short range. Impact will be at a scale that is not normally considered by Engineers or by Sandia National Laboratories but is typical of what should be achievable through CASoS Engineering.

The initial sub-goal will be the design of effective means (policies/control) to meet carbon goals without creation of undesirable, unintended consequences. We wish to design policy that will elicit the required behavior of entities at scales that range from the individual to corporations to the nation to the global group of nations. Our Aspiration is thus within the category of *Control*. Control has two major components: incentives and restrictions. Effective control has to do with the formulation and application of appropriate policy with correct timing at all scales to meet both local and global constraints. We will conceptualize a critical measure of system "health" as "surety" given by a comprehensive combination of qualities (e.g., safety, security, reliability, cost effectiveness, and sustainability) that may be defined differently at each scale (entity).

Our objectives will be:

- Find the near-term *feasible choices* of policies applied at scales from global (International Carbon Treaty such as may follow Kyoto, to be negotiated in late 2009) to individual (may be different in different parts of the world) that enhances surety at all scales and meets a set of probable CO_2 targets; this includes consideration of multiple competing objectives and political achievability;
- Determine if choices are *robust* to uncertainties in the conceptual model, parameter choices, etc, and if not, define those uncertainties that must be reduced, or refine the Aspiration such that robust choices are possible;
- Determine the critical *enablers* of policy effectiveness to create system *resilience*.

Example alternative policies that act at large scales are cap and trade markets vs. carbon taxes as may be implemented within a Global Treaty to incentivize CO_2 emission reduction. Similarly alternative policies at the individual scale would expand action (choose to do) or restrict action (choose not to do).

To accomplish our objectives we will draw on and extend our new conceptual model constructed and implemented though this project. This model represents each of the number of large-scale entities (nations and industries) that have resources (material, funds, energy), technologies (ability to transform resources and emit CO_2) and needs which are met by acquiring resources and emitting CO_2. These entities interact with each other in pursuit of private objectives and adopted constraints to form flows of resources with attendant releases of CO_2. Three model extensions are required and presented in **Appendix C**.

First, we will extend the model to a more complex basic economy in a single region (see **Figure 3)** that includes additional components of the basic economy (industrial production and mining), distinguishes oil production and processing from other industrial processes, and includes fuel use for transportation of diverse goods. Capital maintenance and expansion will be enabled through issuance and sale of securities, mediated by a financial entity. Impacts of global carbon emissions on regional climate and the impacts of climate change on other regional systems within the CASoS need to be accommodated here as well, although those connections are not yet shown in **Figure 3**. A government entity will be introduced as the source of carbon credits. We will test this more complex configuration against expectations about the impact of carbon credit issuance, relative attractiveness of immediate vs. deferred consumption by households, and other changes in key controls.

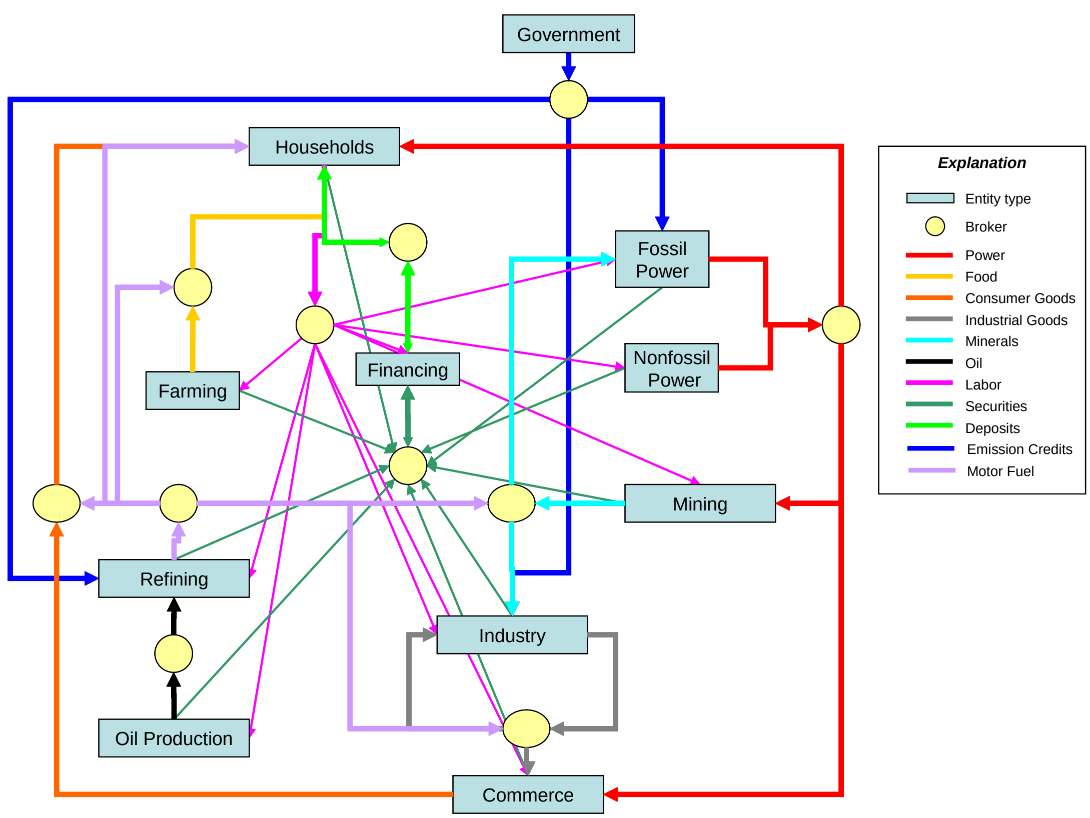

Figure 3: Entities and Resource flows in each region of the extended model.

Second, we will also extend the model by defining multiple regions (**Figure 4)**, but with varying endowments, such as the number of entities of each kind, the initial allocation of basic resources such as productive land, oil, and other mineral resources, and the efficiency of productive technologies reflected in the coefficients of their process reactions. These regions will interact through markets for most of the modeled resources, including oil, finances, motor fuels, and food. Labor and power markets are typically limited by national boundaries so interregional markets for these resources are not proposed. A given entity in a region, e.g. a Farm, may participate in a local market only, or in both a local and an interregional market. In addition to having different endowments of basic resources and technologies, regions may differ in the extent of their connection to interregional markets. Our initial studies will focus on the interactions among such a small number of regions whose parameters have been defined to reflect mature, emerging, and developing economies.

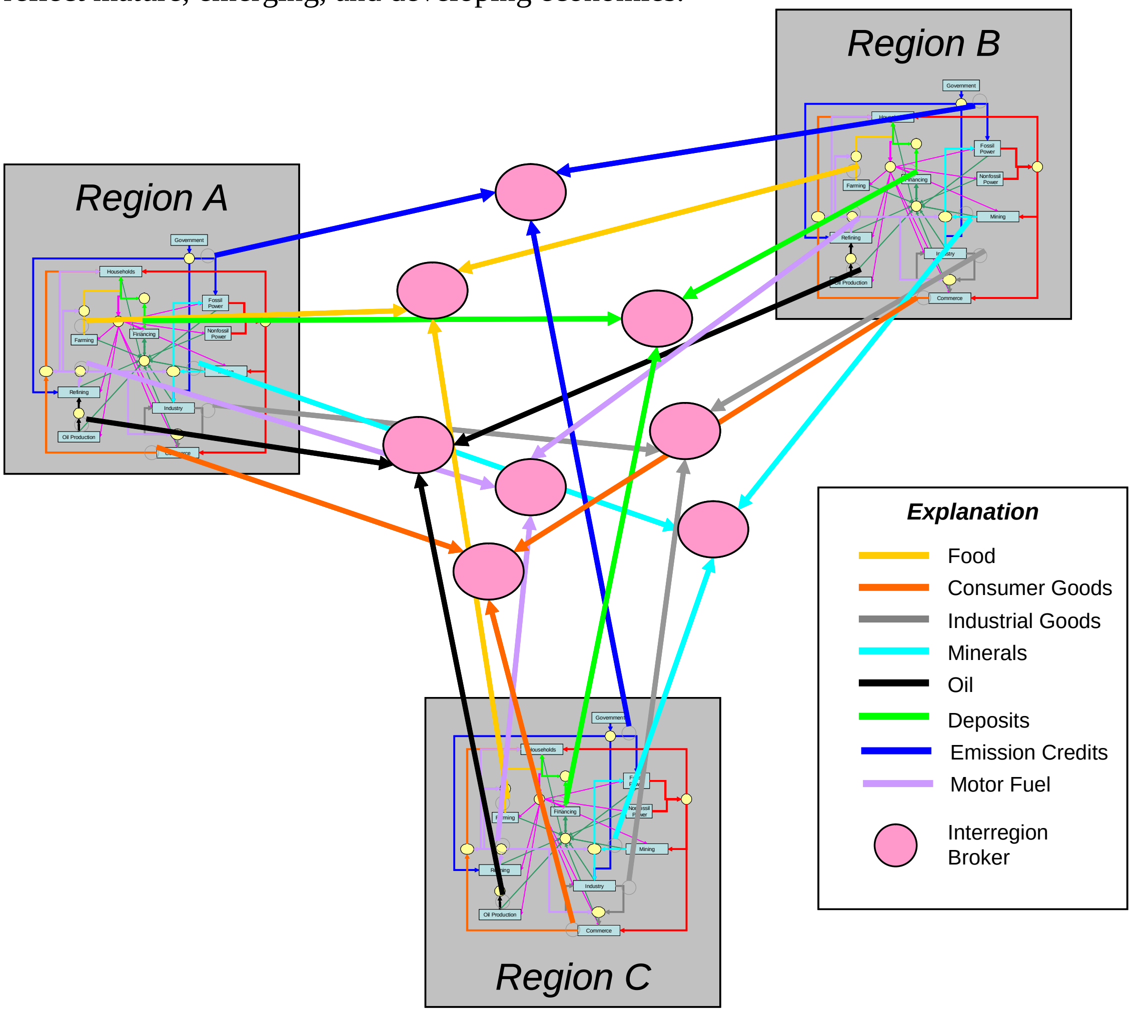

Figure 4: Interaction among regions through interregional brokers.

Third, we will extend the model to a larger set of regions, and a hierarchical structure of market interactions among them to reflect nations interconnected by trade agreements and common or readily convertible currencies (**Figure 5**). The function of government will be elaborated to include financial and fiscal influences, infrastructure investment (reflected for example in labor productivity and transaction costs), defense and other protective measures, and possibly other controls (e.g., taxation of certain transactions). Additional interregional influences, such as multinational entities, may be included as well. Many of the basic entity types considered (such as Industry and Financing) may be defined in much greater detail. Our intuition is that such refinement is unlikely to change the basic results regarding the differential effects of the policies to be considered, however some level of refinement may be needed to test this intuition, and to demonstrate the robustness of results to additional refinement. Our approach will be to resist arbitrary demands to increase resolution, because such demands will rapidly produce a model that cannot be tested and understood.

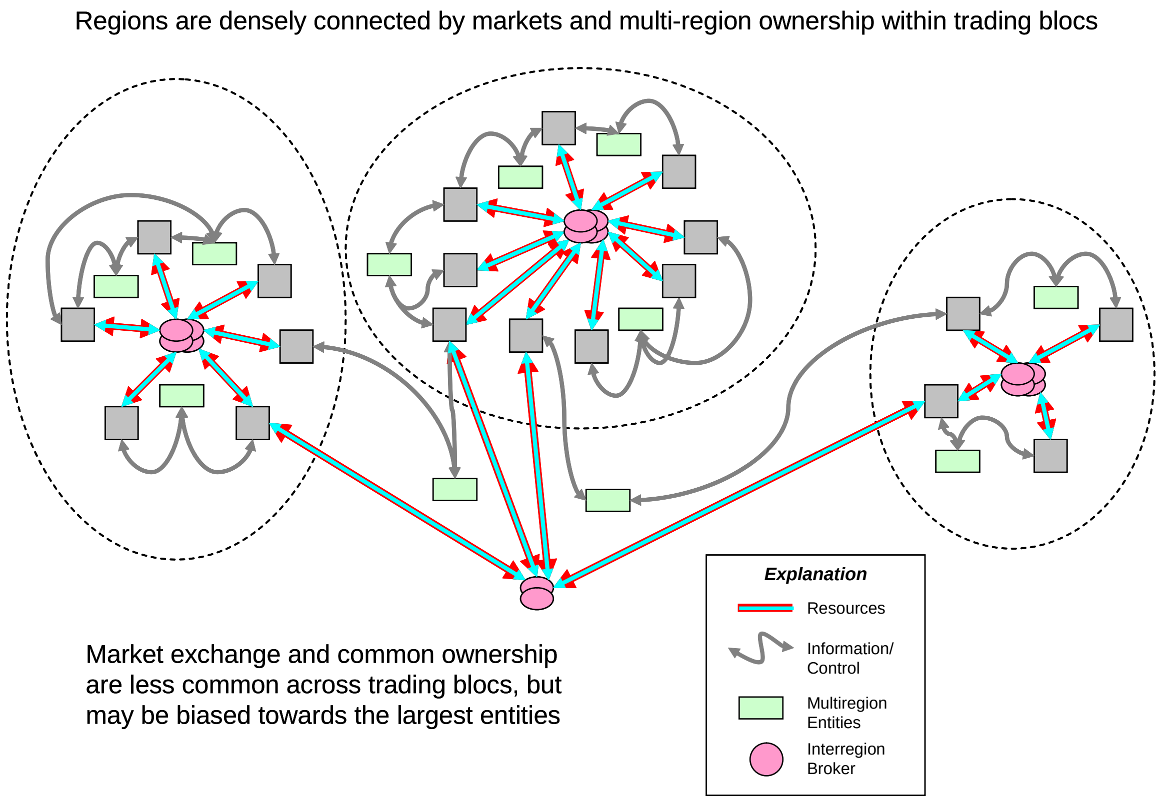

Figure 5: Hierarchical pattern of region interconnection represents currency zones and trading blocs.

Analysis using the extended model will evaluate the components of surety and economic performance on a global and entity level. The policies that influence the behavior of the individual entities can be viewed as control signals. Decentralized control theory may be applied in order to identify controls that achieve the desired state for the global system. The model will then be used to evaluate the robustness of the policy and the critical enablers required to create system resilience.

8. SUMMARY

The purpose of this project was to begin to develop a Complex Adaptive Systems of Systems (CASoS) Engineering Framework for application within general CASoS and begin its exercise within context of the Global Energy System (GES). The GES is a CASoS that includes the complex physical sub systems of the atmosphere, biosphere, lithosphere, hydrosphere, and solar system as well as the complex adaptive systems that are human such as economic systems, socio-political systems, and energy generation, storage, control, and distribution systems.

In this project, we first sketched a preliminary CASoS Engineering Framework. As engineers, our Aspirations are to influence (design, control, manipulate) CASoS to solve problems, exploit opportunities, and/or achieve goals. Aspirations fall into a set of clearly identified categories: Predict; Prevent or Cause; Prepare; Monitor; Recover or Change; and Control. Within each category, three sets of similar questions naturally emerge that encompass: Decision, determining Robustness of Decision, and Enabling Resilience. Feasible, robust, resilient solutions for CASoS problems can be achieved through implementation of three overlapping phases: 1) defining, 2) designing and testing solutions, and 3) actualizing solutions. Exercise of the CASoS Engineering Framework integrates methods from diverse subject areas such as system dynamics, non-equilibrium thermodynamics, system optimization and control, complex adaptive systems, percolation phenomena, and networks.

We next began application of the CASoS Engineering Framework to the GES with focus on the defining phase. We delineated a set of three nested Goals of increasing scale that achieve:

1. **National Transportation Energy Security**: specific energy need at the scale of the nation
2. **National Energy Surety**: all energy needs appropriately interconnected with other sectors (e.g., agriculture, economic output) at the scale of the nation
3. **Global Energy Surety**: all energy needs appropriately interconnected with other sectors at the scale of the globe

To achieve these Goals, we formulated a conceptual model that could be used to evaluate the effective means (policies/control) of achieving energy security or surety while meeting global carbon goals. Our Aspiration was within the category of Control. The model represents interacting entities at a variety of scales (nations, industries, consumers) that have resources (material, funds, energy), technologies (transform resources, emit CO_2) and competing needs (energy surety, standard-of-living). A simplified version of the model was implemented as a proof-of-concept within the National Infrastructure Simulation and Analysis Center's (NISAC) Loki toolbox and preliminary analyses of two test cases were conducted. The limited purpose of these simulations was to test the model's ability to produce selected qualitative responses that would be expected in a real system that matched the model constraints: an overall increase in power price as a finite fuel resource is depleted, and an increase in power price and decrease in usage if carbon emissions associated with fossil fuel use are taxed. The behavior of the initial model conformed to important qualitative expectations about the real system.

As Next Steps to accomplish our objectives we will draw on and extend our new model constructed though this project. Three model extensions are required: 1) to a more complex and complete basic economy in a single region: 2) to multiple regions with varying endowments reflective of mature, emerging, and developing economies, and 3) to a larger set of regions and a hierarchical structure of market interactions among them to reflect nations interconnected by trade agreements and common or readily convertible currencies. Analysis using the extended model will evaluate the components of surety and economic performance on a global and entity level and can be used to evaluate the robustness of the policy and the critical enablers required to create system resilience.

Many of the problems we work to solve at Sandia are in the context of systems that are CASoS, yet we rarely treat them as such. The development of a CASoS Engineering Framework for application to the myriad of socioeconomic-technical problems within DOE/NNSA/DHS national security missions is of critical importance. Successfully applying this framework to a significant and prominent challenge, such as controlling CO_2 emissions while maintaining and improving national energy surety, will demonstrate our ability to find practical solutions to difficult problems.

APPENDIX A: METHODS, THEORIES, AND FIELDS OF CONTRIBUTION FOR APPLICATION WITHIN THE CASOS ENGINEERING FRAMEWORK

Methods, theories, and fields of contribution can be organized into a series of sub categories. The following, while far from complete, exemplifies such categorization:

System Definition and broad conceptual modeling:
Components and influence charting
Analogy
Dimensional analysis and similitude (similarity theory)
Measurement definition
Definition of Environment boundaries

Aggregate methods and theories from which basic results may be taken and applied:
Thermodynamics and Statistical Mechanics
Non-equilibrium thermodynamics
Percolation
Networks
Game theory
Complex adaptive systems
Trading and markets

Detailed modeling and simulation approaches:
system dynamics
agent-based modeling
discrete-event system modeling

System optimization and control
Discrete and continuum linear and nonlinear optimization
Hybrid, adaptive and optimal control
Engineered Collectives (e.g. decentralized control)
Agent-based optimization
Extended and ensemble Kalman filters

Evaluation and Discovery:
Uncertainty analysis (sensitivity analysis)
Experimental design
Data mining

APPENDIX B: QUESTIONS AND SHORT ANSWERS FOR CASOS QUIZZES

We have compiled a list of questions people tend to ask or should be asking about CASoS along with some answers.

What is a CASoS?

A complex, adaptive system of systems. They exhibit unexpected behaviors due to the complexity of their interconnections, they adapt, and they're constructed of components sufficiently complex and difficult that each component can be considered a system in its own right. Systems involving multiple humans are generally CASoS.

Why are you working on CASoS rather than something else?

Management asked for it.

All the world's biggest issues (e.g. wars, energy, poverty, hunger, nukes, …) are CASoS problems. We as a lab owe it to the world to take a shot at this.

The most challenging problems of the coming decades will involve CASoS. In many ways this shift from more traditional engineering problems is due to increasingly pervasive and global scale of production and distribution networks in the areas of food, energy, water, labor, finance, etc. Expansion of these networks to the global scale along with increasing resource consumption has removed excess capacity from many interconnected distribution networks.

Why do you believe that CASoS systems are hard?

They are big, complicated, counterintuitive, hard to measure, hard to modify because they adapt. They are generally very important, so they're hard to experiment with (expense, difficulty in making changes to them, difficulty in measuring results, ethics). System and environment definition are often not clear-cut. The Adaptive nature of CASoS includes emergent and transient definition of systems and relationships between them and their environment.

Why do you believe that CASoS systems are sufficiently easy that you can do something with them? Why do you believe your process for dealing with CASoS systems is sufficient?

We've been working with some (e.g. Pandemic Influenza). We've seen some interesting successes, frequently requiring a fresh look at the problem. It seems to take more than a first-order naive model of them. A systems view is generally necessary, and it requires thinking about multiple potential questions, multiple potential answers, and examining the interrelationships between them. Curiously, when we've constructed the "right" model, it often requires simpler models with easier-to-verify parameters than the typical models being constructed for them.

What is your CASoS process?

We're still working on it, but so far we've done well with broad, high-level thinking, combined with simulation that emphasizes the network nature of the system. We're leveraging traditional systems engineering processes (requirements, conceptual design, detailed design, test, manufacture). We're leveraging complexity theory, so we're looking at ways of separating forests from trees, and ways of measuring when the complexity can be large. We understand that systems adapt, so we're looking at solutions that change the system in ways that ensure that the solutions grow with the adaptations.

How is CASoS Engineering different than SoSE (system of systems engineering)?

SoSE focuses on the structure of the system, and so SoSE doesn't have to be complex or adaptive. Generally the concerns in SoSE are that the systems are evolving concurrently, are hard to manage, cannot be changed (unlike components which can be altered to make the system work). CASoS adds to this the notions that the system is complex (counterintuitive behavior a function of the interactions), and adaptive (the systems and the connections between systems change to adapt to changes in the environment, so solutions don't keep working by themselves).

How do you deal with the fact that CASoS systems adapt? Doesn't this mean that no solution will ever be adequate?

It means that solutions have to also be adaptive, to change with the system as the system changes. It means that point solutions are probably not adequate, and that it's a good idea to have multiple solutions in your pocket before you go trying to change a CASoS. Same thing as walking into a class of 3-year-old children. They adapt too. Don't turn your back on them, have a wide ranging game plan, be prepared to adapt your solutions to the way the system works, and it can be a lot of fun.

Are you just making all this up?

Well, yes and no. There isn't a lot of theory out there, so we're collecting what we can, trying it, adapting it to fit, and continuing forward. Such has been done before in any number of fields - when you're trying something new, you sometimes need new tools.

But, we have been working on some of these kinds of problems for some time. We know the feel of effective solutions, and know something about how to obtain them. We're not going in empty handed.

What are your tools for working on this?

Tools and approaches include complexity theory, systems engineering, system-of-system engineering; modeling and simulation; conceptual design; systems thinking; combinatorial consideration of interactions among system elements (random juxtaposition?); structured ways of thinking about the problem; broad unstructured ways of thinking about the problem; questioning the wisdom of previous attempts; paying attention to the underlying assumptions of previous solutions that might have at least partially worked.

Why do you believe various CASoS systems are comparable and deeply similar to each other?

1. We've seen the same thing in classical systems engineering (compare electrical, hydraulic, spring-mass-dashpot, etc systems and you find identical underlying mathematics).
2. Fractal behaviors are an important part of complex systems. Fractals are self-similar. We expect to see similarities across domains, as well as similarities between various levels of the same problem.
3. In writing the CASoS roadmap, we discovered significant similarities across domains, both in their structure, in the kinds of models one might build, in the kinds of issues one might address in trying to solve something. Glass saw similarity between pandemic, wildfire, and the need to spread ideas. Both the technical solution and the political solution to the problem had structural similarities to putting out a fire (or starting one).

Isn't it all just one big CASoS?

Sure, constructed of systems which themselves are CASoS, and so forth. Great fleas have lesser fleas, upon their backs to bite 'em, and the little fleas have lesser fleas, and so ad infinitum.

If it is just all one big CASoS, where do you start?

Almost anywhere that's convenient. Initial thinking about any problem is cheap; it's the details where things get expensive. So think hard about the issues, think hard about the potential solutions, think hard about how to change the world and achieve big wins -- it's a means of seeing many avenues to work on, and is relatively cheap compared to going down wrong, narrowly considered paths.

What are the ethics of changing the question you're asking to match the answers you think you can find, rather than just solving the problems?

The issue is in seeing the problems for what they really are. You might find that some of the biggest problems aren't what you thought they were, but you have to see the big picture. Take any big problem, and you might conclude that it's bigger than it really is (mountains out of mole hills), or that it's only a problem because people insist that the solution benefit them in selfish ways, ...

How is this different from CAS work going on at places like Santa Fe Institute?

Places like SFI are studying complex adaptive systems. We're interested in engineering solutions for such systems. We are *very* interested in SFI's results, but we're also interested in solving problems. Recall that a stronglink/weaklink concept permits nuclear weapons to address a wide variety of potential threats in a very simple, robust way. Maybe we can find similar levers to address CASoS issues -- it's possible that the solutions can be very simple, but we have to think well about the problem to make sure we're really solving real issues.

So why can't we apply typical engineering approaches to these problems? What makes them so special/hard? Why do we need a big project in this area?

Problems that arise from CASoS are, by definition, complex and are not well predicted or controlled by traditional engineering techniques. Here is a simple example problem to help make the case. Water security work at Sandia has resulted in algorithms and software to predict the next measurement of water quality based on several hundred recent measurements of that water quality. Water quality is a function of the characteristics of the water source and the treatment, amount of mixing with other waters and the flowpath it takes to reach the sensor. None of these things change drastically over time, treatment, mixing and aging are diffusive processes and the algorithms work quite well. Given that the stock market is also a time series, why do we still work at Sandia? Changes in the value of the stock market are one output of a globally connected CASoS and are considerably different than those that change water quality. Today, social-political-technical information that impacts the stock market and other complex systems moves at the speed of light (literally, across fiber optic cables) and combines with other information at multiple time scales in a non-diffusive manner and impacts the stock market (system of interest) in drastically different ways than we could possibly predict with traditional engineering tools. Etc.

APPENDIX C: CONCEPTUAL MODEL FRAMEWORK FOR ENTITY BASED NEGOTIATED EXCHANGES AND ITS APPLICATION TO THE GES

The potential responses of the GES to alternative policies, stresses, and constraints can be studied using a generalized model of negotiated exchanges of resources among a set of entities. The number and nature of the resources, and the number and types of the entities that exchange them, and the types of negotiations can be tailored to represent a wide range of specific problems. We briefly summarize the general model, and then specialize it for the GES.

General Model Components

Entities: Objects representing individuals or organized groups of individuals (such as companies, governments, trade blocs) pursuing an objective by controlling a set of *Resources*. The objective depends on the levels of those Resources, for example maximizing the amount of some Resource, or of a weighted combination of Resources, or of the rate of production/use of a particular Resource. An Entity's Resource levels are influenced by the set of *Transformations* that take place within it, and by bilateral *Interactions* that Entities can have with one another. Interactions are of two types, *Exchanges* of Resources and *Messages.* Messages direct the formation, dissolution, and operation of exchange *Relationships*, and can control an Entity's transformation processes. Specific models may use messages for other purposes as well. The Entity's decision problem is to select among the possible messages available in its current state. Formulating this decision problem defines the model dynamics; a subsequent section below describes current formulations.

Resources: Specific materials, capabilities, or information that Entities act to manage. Resources can usually be exchanged, produced, and destroyed over time. They may correspond to tangible items such as fuel or money, but might represent more abstract characteristics such as skills or dispositions. Entities usually place some direct or derived value on each type of resource, which in general may be either positive or negative. Resources can be treated as discrete or continuous. An Entity's state is in part defined by the amount of each resource it possesses.

Transformations: Processes that convert one set of resources into another, in fixed proportions. Transformations are associated with specific Entities, and they operate on the resources controlled by the Entity. Transformations can be thought of as chemical reactions: they may require one or more catalysts in order to take place, and the maximum rate of transformation may be constrained by the amount of catalyst present. The general structure of a transformation is shown in the following diagram:

$$a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \xrightarrow[c_1 z_1, c_2 z_2, \ldots c_l z_l]{r} b_1 y_1 + b_2 y_2 + \ldots + b_m y_m$$

Where x_i are the input Resources, y_j are the product resources, and z_k, if included, are catalysts. The coefficients a, b and c represent weights applied to the resources and catalysts. Resources can be used but not consumed in the transformation. For example if the Entity represents a firm, then catalysts correspond to factors of production. The catalyzed transformation rate will depends on catalyst availability:

$$rate = r * \min_k \left(\frac{[z_k]}{c_k} \right)$$

where $[z_k]$ is the Entity's amount of resource z_k. If no catalysts are involved the reaction rate depends on the Entity's size:

$$rate = r * size$$

The stoichiometric coefficients and rate constants that define transformations may change over time, representing technological improvements or other kinds of learning. New kinds of transformations, representing new kinds of technologies, may be introduced over time as well. While a transformation is always associated with a specific Entity, and operates on its Resources, the same kind of transformation may take place in many Entities. For example many manufacturers may use the same production process.

Relationships: Pathways for Interactions between pairs of Entities. Interaction types include resource Exchanges and Messages. Relationships may be permanent, transient, or single use. A particular Relationship might allow either Exchanges or Messages or both. A Relationship need not be visible to both Entities. All interactions between Entities occur through relations of one kind or another.

N-ary relations such as participation in markets and trading blocs, as well as ownership and political subordination may be represented as binary relations between participating Entities and specialized Entities representing these collectivities. Entities of this kind may or may not control their own resources in pursuit of an objective: their objective may depend on the resource levels of their constituent Entities. Two such specializations are central to building a generalized resource exchange model:

Brokers: Services that connect Entities willing to trade one Resource for another with Entities who want to make the complementary trade. In general any pair of Resources might be traded, but it's convenient to define a "money" Resource to denominate trades. Rules controlling how buyers and sellers are matched and how trades are settled are defined by further specialization. Brokers may be used to create single-use relationships between buyer and seller, or may be used to establish longer-term Relationships through which the buyer and seller subsequently exchange messages and resources. Specialized brokers might also act as dealers, holding Resources on their own behalf and acting as market-makers for the Resource.

Groups: Collections of Entities that have particular kinds of Interactions, or constraints on their Interactions, because of their membership in the Group. Groups represent any kind of collection, such as ownership of several Entities by another, countries or other political subdivisions that constrain and enable Relationships, trade organizations, etc. Membership in a Group is modeled as a membership Relationship. In general an Entity can belong to any number of Groups, although certain kinds of Groups (such as countries) may allow membership in only one Group of that kind. Groups may be nested: the membership relationship may be transitive; however the model requires Entities to navigate membership hierarchies if the specific application uses this property.

General Entity Decision Logic

Model dynamics are determined by the Entities' decision logic for actions that influence Transformations, Interactions (exchanges, messages), and Relationships. There are many ways of formulating this decision problem, and our model framework allows for new formulations to be added over time. Model dynamics are driven endogenously by the sequence of decision events. A typical event entails a specific Entity consulting its state, which includes the levels of its resources but may include other variables, and then sending a message to another Entity (or to itself). The decision process is therefore a mapping between states and messages. We have chosen two initial implementations: an explicit optimization of expected utility, and a classifier system.

In the first, the objective is formulated as utility maximization, where utility is some arbitrary function of the level of Resources owned or controlled by the Entity. For each action under consideration, the Entity enumerates a set of possible outcomes. These outcomes are exclusive and exhaustive – they model the Entity's beliefs about the possible consequences of the action. Each outcome is defined by a set of changes in the levels of some or all state variables. Each also has an associated probability. (**Figure C-1A**) For each outcome, the associated state variable changes combined with the current states yield a utility value. The set of (utility, probability) pairs defines a discrete utility distribution for each action.

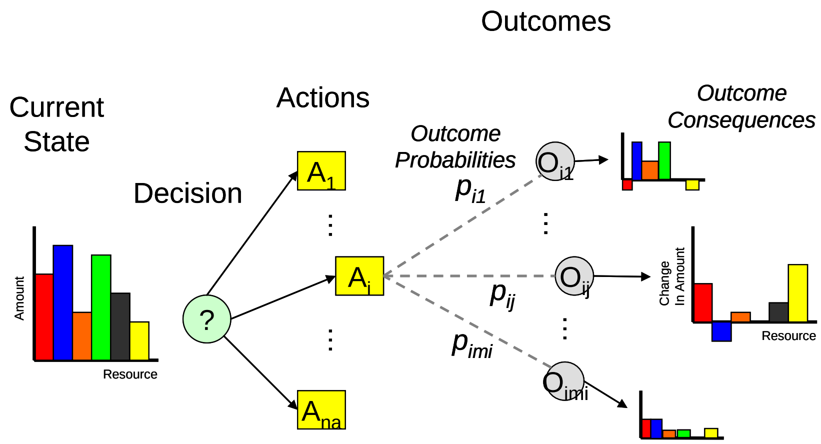

Figure C-1A: Decision Formulation - Representation of outcome uncertainty

These utility distributions are then used to calculate a scalar indicator for the attractiveness of each action (**Figure C-1B**). The utility distribution is first modulated by a function describing the Entity's disposition towards risk. Risk-neutral Entities weigh any utility, regardless of size, by its probability. Risk-averse Entities give more weight to negative outcomes and discount large positive outcomes. The attractiveness of each action is simply the normalized integral of the outcome distribution weighted by the Entity's risk preference function. Finally the Entity selects among actions based on their attractiveness. The selection rule can be simple maximization, or can be formulated to model considerations such as persistence bias or the inability to discriminate among small differences in attractiveness.

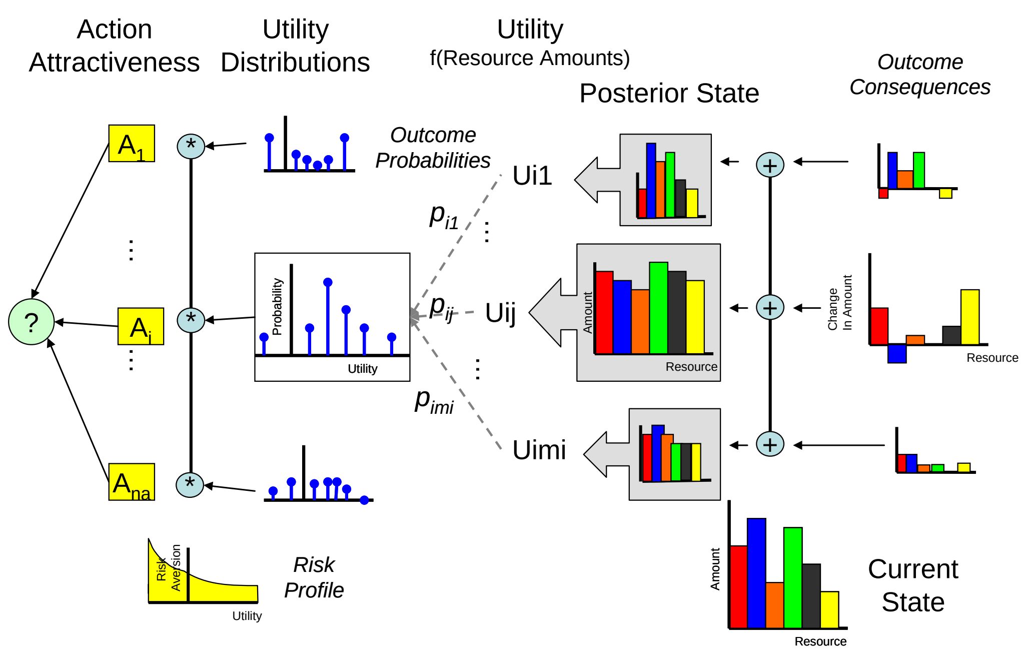

Figure C-1B: Decision Evaluation - Evaluation of action attractiveness

In the classifier system formulation, each Entity maintains a set of weighted rules. Rules consist of a set of qualifier clauses expressed as thresholds on some subset of the state variables and their rates of change, and an action clause consisting of a message. Each rule is initially assigned a random numerical weight. Rule weights are adjusted over time using a "bucket brigade" reinforcement process driven by episodic reinforcements from the environment. At each decision point, the Entity consults its library of rules to find the subset whose qualifying conditions are satisfied by its current state. It then selects the qualifying rule with the largest weight. A fraction of this weight is removed as a tax, and is added to the weight of the immediately preceding rule. After the selected rule is executed, resulting in a message being sent, any subsequent reinforcement received from the environment adds to the rule's weight. In this way rules that produce immediate reinforcement reinforce the rules that foster their execution, which in turn reward their enabling predecessors, and so on. The rule library is periodically updated by removing low-weighted rules and replacing them with variants produced from a genetic algorithm operating on the retained rules.

GES Application

We would like to understand the possible reactions of the global energy production system to a set of policies designed to reduce carbon emissions in order to achieve the nested goals mentioned in **Section 5** of this report,. The general resource exchange model framework described above is naturally suited to this problem. Below we outline such a model, and provide some illustrative results from an initial implementation of a simple core economy.

The model must include Entities representing the organizations with significant influence on the production and use of energy. The processes we believe to be important include utilization, expansion, and deterioration of different classes of energy production capacity (coal, nuclear, oil, natural gas, renewables, …), production of goods and services using energy (and other) inputs, consumption of goods, services, and energy by households, provision of labor by households, extraction and transport of raw commodity inputs for producing energy and industrial goods, and development and adoption of alternative technologies for energy production, transportation, and manufacturing.

The model should be as parsimonious as possible while including these processes under the policies of interest. Policies to be evaluated include:

- Creation of carbon markets in individual nations or treaty blocs
- Creation of a global carbon market
- Imposition of a national/treaty bloc carbon tax
- Imposition of a global carbon tax
- Which, Carbon markets or Carbon Tax?
- ….

The rate and location of energy production, and the associated levels of macro-economic activity such as unemployment rate and GDP, result from the interacting decisions of the Entities. As discussed above, these decisions are modeled as driven by some "utility" for the Entity (utility is explicit in the case of the utility maximizing formulation, and expressed in the classifier formulation by the resource changes used to reward rules). The utility formulation may include many kinds of resources, may differ among instances of the same kind of Entity, and may be neither perfectly informed nor risk-neutral. The classes of Entities that seem to be required in order to capture both the relevant processes and the controlling (or reacting) entities are described below in **Table C-1**. Note that some proposed Entities (e.g. household sector) represent large numbers of individuals: formulating the decision process, internal dynamics, and interaction rules for these composites will require careful consideration of their scale. It may ultimately be more efficient to disaggregate these composites into a large number of individuals whose decision rules and interactions can be more clearly conceptualized.

Table C-1: Proposed components of a GES model

Entity Type	Actions	Instances	Resources
Country	Treat with other countries; Set/collect taxes; Build and maintain infrastructure, including energy transportation; Regulate transportation and industry (emissions, energy intensity standards,…); Maintain military; Provide public services; Invest in research and exploration; Threaten, attack, or protect shipping routes; Threaten, attack, or defend other countries; Lease/extract resource reserves;	Perhaps several of each of various subtypes, e.g. industrialized, industrializing, undeveloped; perhaps one per real country	Population, Government debts and assets, Government employment, Participation in nationally-owned raw material resources or production
Household sector	Provide labor; Consume goods and services; Save/invest; Consume energy and transportation; Seek education; Emigrate; Reproduce;	At least one per country; perhaps distinguished by skill level or education within a country	Population, housing, savings, debt, direct and indirect ownership of stocks and bonds, transportation stock
Energy producers	Operate plant; Expand, shrink, maintain plant; Contract for inputs (including permits); Contract to provide energy outputs; Fund research; Modify production technology; Follow regulatory constraints; Obtain financing through loans, equity	At least one for each kind of generation technology within a country; many instances should probably be included to allow	Generation assets, Employment, ownership of fuel resources, intellectual capital in generating technologies, debt

Entity Type	Actions	Instances	Resources
	markets, private sources;	for competitive dynamics.	
Other producers	Operate plant; Expand, shrink, maintain plant; Contract for inputs (including labor and energy); Contract to provide outputs; Fund research; Modify production technology; Obtain financing through loans, equity markets, private sources;	Subdivided by coarse economic categories (e.g. agriculture, mining, industry, commerce, retail) and by several generic product categories, with many instances in each category.	Equipment, Employment, intellectual capital in production technologies, debt
Multi-nationals	Buy/sell production resources in various countries; Supervise or preempt actions of owned resources; Obtain financing through loans, equity markets, private sources; Influence regulation and taxes in countries	Several for each area of concentration (e.g. commodities, finance, consumer goods, technology)	Ownership of other Entities (energy producers, other producers, banks), Debt and equity held on its own account
Banks	Take deposits and make loans; Create investment capital for producers of energy, goods, and services.	Distinguishing tiers will be important for capturing both regional variations in access to capital and international capital flows. Minimum resolution would include a bank in each nation, one or more multinationals per currency zone, and several international banks bridging currency zones	Deposits and loans, Debt and equity held on its own account

Application to a single region core economy

A model of this complexity is best assembled incrementally so that the behavior produced by the various structural features and kinds of interactions can be tested and understood in simpler contexts. We have begun by modeling the core elements of an energy-based economy operating in a single region. **Figure C-2** diagrams the Entity types and Resource flows. The model includes five basic kinds of Entity: households, farms, commercial firms, fossil-fueled generators, and non-fossil-fueled generators. Four Resources are exchanged among the Entities: food, power, consumer goods, and labor. All exchanges for each kind of good are mediated by a single Broker, which uses a continuous double auction to pair individual supplier Entities with consumer Entities. In addition to the exchanged Resources and the money resource, several additional resource types are defined to reflect the internal states of each Entity.

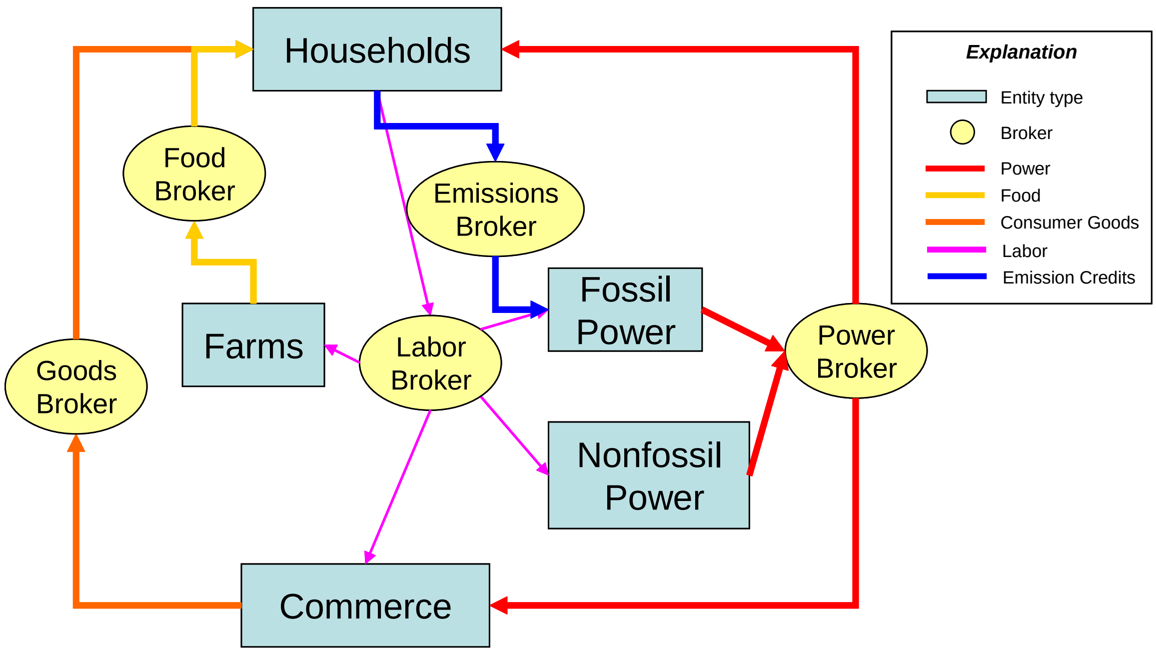

Figure C-2: Classes of Entities in the initial model and associated Resource flows.

Table C-2 details the model structure, listing the specific Resources maintained by each Entity type and the kinds of Transformations that take place within them. These Transformations use fixed rates and coefficients. Each Transformation models a specific process or action affecting the entity. They define the basic economic role performed by each Entity type, as well as internal processes such as population growth and depreciation of capital stock. The model is intended to include no more than the core elements of an economy in the most general terms. Each type of Entity and Resource can be analyzed in arbitrary detail in subsequent iterations, for example by refining generation technologies, manufactured goods, and labor.

Table C-2 – Specification of Entities in the initial model

Entity Type	**Instances**	**Resources**			**Transformations**					**Reinforcement**	Size Range
		Inputs	***Outputs***	***Other***	***Description***	***Inputs***	***Catalysts***	***Outputs***	***Rate***		
Households	100	Food Power Goods	Labor Emission Credits	People Goodness Carbon Limit	Working		People	Labor	1	Goodness	1-10
					Breeding	Food	People	People	0.05		
					Dying	People	People		0.02		
					Labor transience	Labor	Labor		1		
					Consuming goods	Goods	People	Goodness	1		
					Consuming power	Power	People	0.05*Goodness	1		
					Power transience	Power	Power		1		
					Creating credits		Carbon Limit	Emission Credits	1		
					Credit expiration	Emission Credits	Emission Credits		1		
Farms	10	Labor	Food	Land	Growing food	Labor	Land	Food	1	Money	10-100
					Labor transience	Labor	Labor		1		
Commerce	10	Labor Power	Goods	Commercial Capital	Producing goods	Labor 0.3*Power	Commercial Capital	5*Goods	1	Money	10-100
					Labor transience	Labor	Labor		1		
					Power transience	Power	Power		1		
					Capital depreciation	Commercial Capital	Commercial Capital		10^{-4}		

Table C-2 – Specification of Entities in the initial model (continued)

Entity Type	Instances	Resources			Transformations					Reinforcement	Size Range
		Inputs	*Outputs*	*Other*	*Description*	*Inputs*	*Catalysts*	*Outputs*	*Rate*		
Fossil Generation	10	Labor Emission Credits	Power	Fuel[2] Generating Capital	Generating power	Labor Fuel Emission Credits	Generating Capital	Power	1	Money	10-100
					Labor transience	Labor	Labor		1		
					Power transience	Power	Power		1		
					Capital depreciation	Commercial Capital	Commercial Capital		10^{-4}		
					Credit expiration	Emission Credits	Emission Credits		1		
Nonfossil Generation	10	Labor	Power	Generating Capital	Generating power	Labor	Generating Capital	Power	1	Money	10-100
					Labor transience	[illegible]r	Labor		1		
					Power transience	Power	Power		1		
					Capital depreciation	Commercial Capital	Commercial Capital		10^{-4}		

[2] Fuel is an input in the *Generating power* transformation, but is initially owned by the generator and is therefore not acquired by the generator Entity through a transaction

A few basic household processes are discussed below as examples of how the transformation formalism can be applied to specific cases. People are the key resource within household entities. Their essential economic product is the Labor resource. Each person is assumed to produce one unit of Labor per unit time, expressed in the transformation

$$\varnothing \xrightarrow[1 \cdot People]{1} 1 \cdot Labor$$

Labor is sold to Commercial and Industrial entities as an input to their economic transformations via Labor brokers. Unsold Labor cannot be stockpiled by Households for future use. To capture this constraint, we stipulate that Labor decays in Households according to the transformation:

$$1 \cdot Labor \xrightarrow[1 \cdot Labor]{1} \varnothing$$

This kind of transformation is used in other situations to model the transient quality of services and goods that cannot be stored, for example the Power resource produced by generators. A similar transformation, but with a much slower rate, is used to model death:

$$1 \cdot People \xrightarrow[1 \cdot People]{0.02} \varnothing$$

This transformation would cause the population to collapse over time if it was the only transformation affecting people. Reproduction replenishes the population, but only if sufficient food is available. This simple model is captured in the transformation

$$1 \cdot Food \xrightarrow[1 \cdot People]{0.05} 1 \cdot People$$

In the cases of abundant Food, this transformation will cause the population to increase exponentially at a net rate of 0.05-0.02 = 0.03 People/People/time. Food constraints will curtail net reproduction, and the absence of Food will lead to collapse.

People are gratified by the consumption of consumer Goods. This assumption is reflected in the transformation:

$$1 \cdot Goods \xrightarrow[1 \cdot People]{1} 1 \cdot Goodness$$

For households Goodness is the reinforcing resource: any rule that leads to an increase in Goodness (e.g. by acquiring Goods) is rewarded by the amount of Goodness created. Rules that are successful in bringing in Food become reinforced through their indirect tendency to increase Goodness by creating more People. There are also indirect ways of motivating Power consumption; however here we simply treat it as another kind of consumer good:

$$1 \cdot Power \xrightarrow[1 \cdot People]{1} 0.05 \cdot Goodness$$

Transformations in the remaining model Entities have the same simple structures as the household transformations described above, and use the same basic underlying concepts (production of some resources by consuming others at a rate limited by the current stock of some capital resource, decay and growth of that capital resource, decay of transient resources, etc.). In the case of commercial firms and power production facilities the Transformation coefficients cause capital stock Resource levels to change very slowly so that they are effectively constant during the simulation. One of the next elaborations to this model is including a capital market which will allow firms to maintain and expand production capacity. Fossil fuels are the only Resource in the present model that is depleted during the simulation: each fossil-fueled generator is allocated a fixed stock of this Resource, which depletes over the course of the simulation. While households are reinforced by the abstract Goodness resource, all other Entity types are reinforced by Money.

Unit values for rates and coefficients have been adopted by default. A few were modified in the course of model testing (e.g. the coefficients for producing consumer goods) in order to roughly balance the allocation of exchanged resources among the sectors. The transformation rates and coefficients are fixed, the messages sent by each Entity control the transactions they use to obtain input resources and sell output resources. These transactions result from the bids and offers they make to the appropriate brokers. Bids and offers consist of a maximum amount and a price. Bid amounts and prices are discretized to create a finite number of decisions. Bid amounts are specified in relation to the Entity's size parameter, so that rules can be shared among Entities of different sizes. A notional price of 1 Money unit was supposed for all Resources, with initial bid and offer prices ranging from 1/3 to 3.

We use the classifier system for the Entity's decision process. For each kind of broker interaction in the system (for example, a bidding relationship between a farm and a labor broker) we generate 1000 random rules governing bids and offers. Each rule has two parts: a condition that definines when the rule can be applied (in terms of resource levels and rates); and a message to place a bid or make an offer. The initial rules are generated by randomly sampling the number of conditions, limiting resource value for each condition, and the amount and price of the bid or offer. All parameter values were sampled from finite distributions. The transactions that follow the selection of a rule have the occasional result of increasing the amount of an Entity's reinforcing resource. These reinforcements are used to reward the classifier rule that produced the corresponding message. Over time the Entities develop a set of rules that tend to maximize their reinforcement. The weights that each Entity develops for its set of rules are periodically used to update the weights of the global rule set maintained for the relationship type (farmers' bidding relationship with the labor broker, for example). This updating makes the experience of all Entities available for newly-created Entities, which initialize their rule assignments from this global rule set. The global rule set itself is also occasionally updated using a genetic algorithm which preserves highly-weighted rules and replaces discarded rules through mutation and recombination operations on the retained rules. Mutations can occasionally produce rule parameters that are outside of the original sampling limits.

Initial results for example cases:

We use this simple economy to simulate two situations whose outcomes can be qualitatively anticipated but which, if observed in the model, must emerge from its internal interactions rather than being forced by the model structure. In the first situation the fixed fossil fuel resource depletes over the course of the simulation, effectively removing power production capacity. We expect to see an increase in power price with time as this occurs, and a higher overall price compared to a reference simulation in which the initial fuel endowment is larger. This result is trivial given our understanding of how markets respond to scarcity, but the Entities in the model have no such understanding or (overt) constraint to respond in that way. In the second situation we impose a tax on fuel use by requiring fossil-fueled generators to consume a carbon credit in the process of generating power. They obtain this credit through a market, which is supplied at a fixed rate per unit time. The institutions that would create such a market in practice, and the flow of resulting revenues, may be quite complex: to avoid unwarranted complications we simply assume that carbon credits are created and sold by the household sector, as one possible design for such a scheme would return revenues generated by selling new credits to consumers in the form of rebates. The qualitative consequences are again easy to anticipate: an overall increase in power price, with a smaller share of production occurring through fossil fuels.

These qualitative expectations were met by the simulation results. **Figure C-3** compares the volume and price of power traded in the power market in the case of depleting fuel supply (**Figure C-3A**) and with a larger fuel supply (3 times the reference supply) which is not totally depleted by the end of the simulation (**Figure C-3B**). There is a clear increase in price, and a decrease in consumption following total depletion, which occurs at a simulation time of approximately 300. Before this time the price is generally lower, and consumption generally higher, in the case with larger fuel supply. The configuration with more limited fuel appears to anticipate depletion by increasing price and retarding consumption before the total fuel supply is depleted. Because each fuel-consuming generator only observes one history of depleting its fuel resource, there can be no selective pressure favoring rules that monitor resource depletion. The increase in price can be explained by the variability across the population of fuel-consuming generators. Some have small initial allocations or high sales and so exhaust supplies early in the simulation, forcing them to withdraw from the market. This allows the remaining suppliers to successfully offer at higher prices, which they learn to do. The market signals scarcity through increasing price even though individual suppliers do not predicate their bids on fuel resource levels. In contrast, the scenario with larger fuel supply shows neither late increase in price nor decline in production.

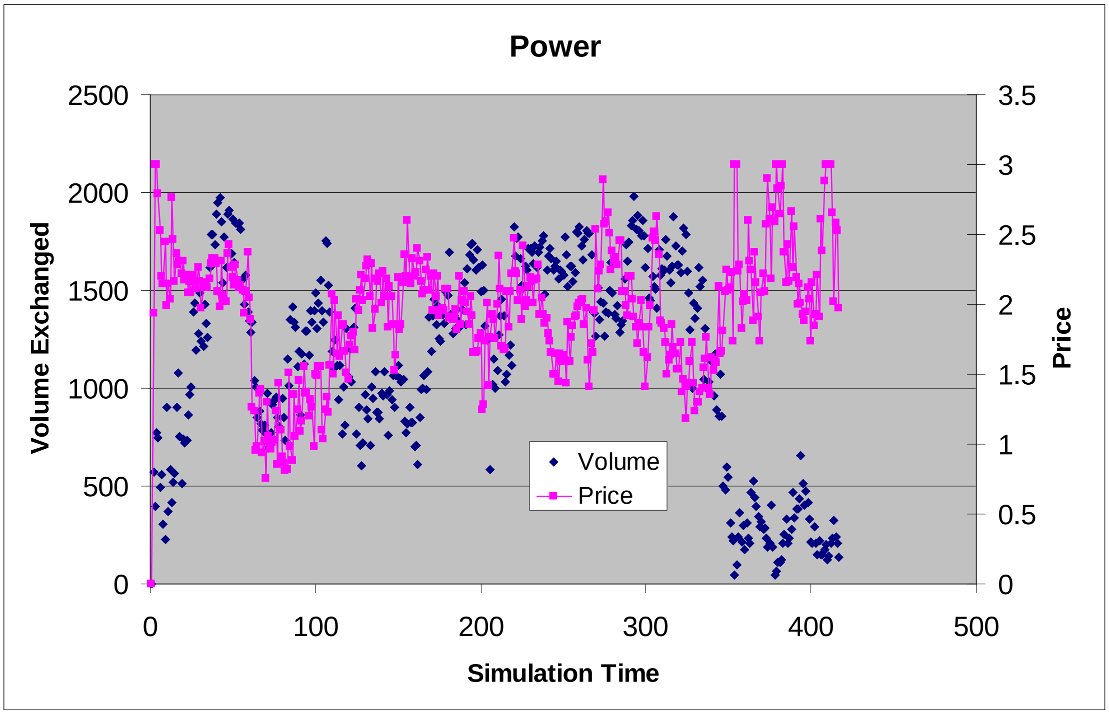

Figure C-1A: Volume and price of power in the reference case with limited fuel resources and no carbon constraint. Fuel is depleted at a time of approximately 300.

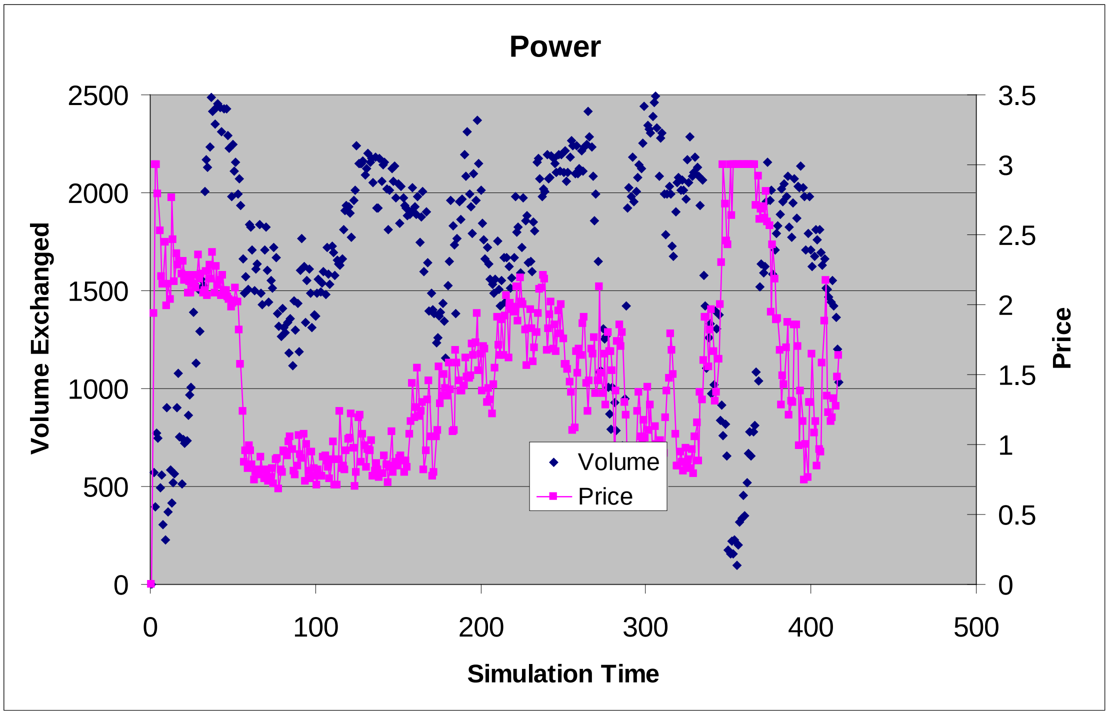

Figure C-3B - Volume and price of power in the case of 3x the initial fuel allocation as the reference case.

Imposing a carbon constraint has a dramatic influence, beginning with the power market. **Figure C-4** compares the original results (from **Figure C-3A**) with the case of an imposed carbon constraint. The power price is much noisier in the latter case, and is higher on average, but the effect on the volume of power traded is more pronounced and systematic: there is far less power consumed in the case of limited emissions. Less power is consumed because consumption by the household and commercial sectors (the only consumers in the model) is suppressed. **Figure C-5** compares the volume and price of exchanged consumer goods in the unconstrained (**Figure C-5A**) and carbon-limited (**Figure C-5B**) cases. The volume is lower in the carbon-constrained case, and the price level somewhat more volatile.

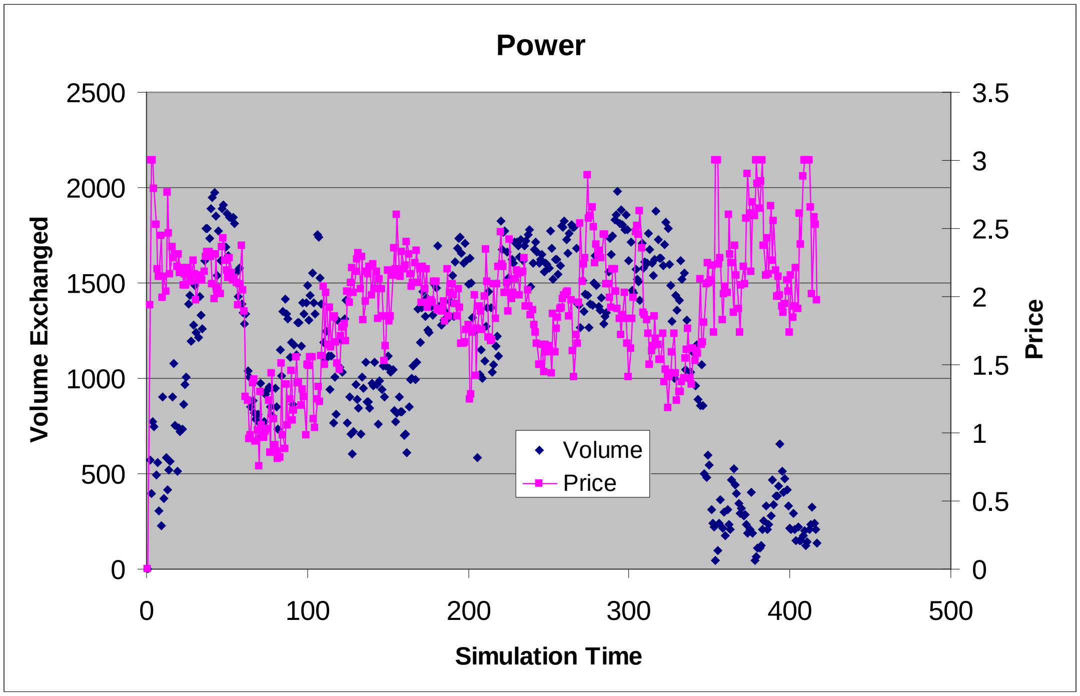

Figure C-4A: Volume and price of power in the reference case with limited fuel resources and no carbon constraint. Fuel is depleted at a time of approximately 300 (same as Figure 2A).

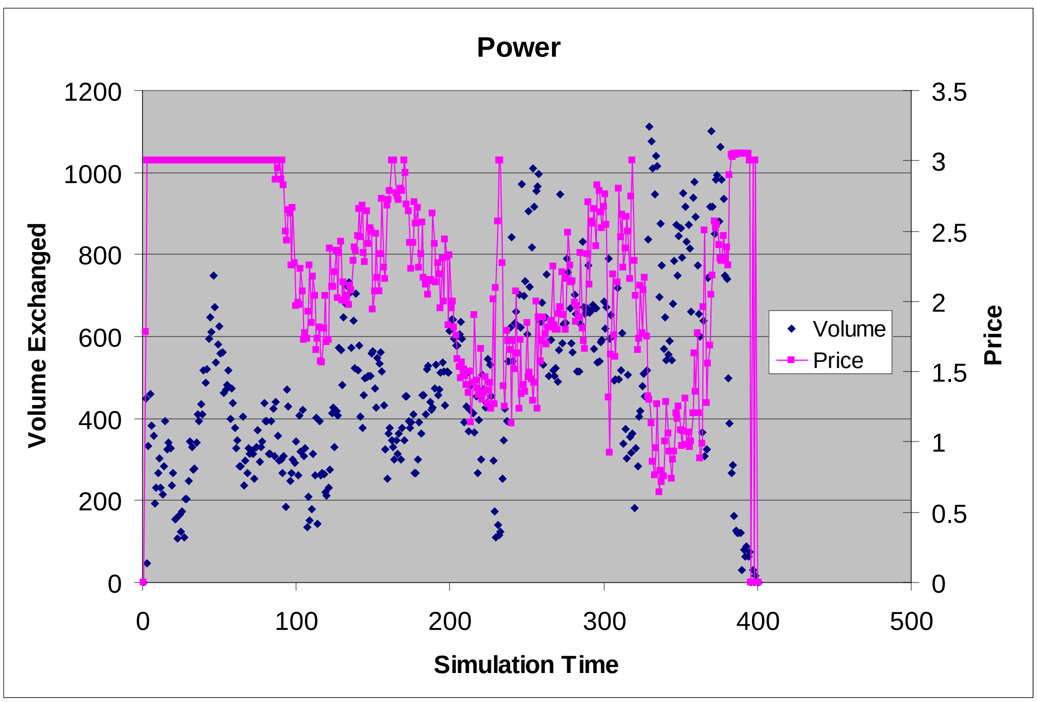

Figure C-4B: Volume and price of power in the case of carbon limits implemented by an emissions market. Prices are more volatile, and the amount of generation is substantially lower than in the reference case.

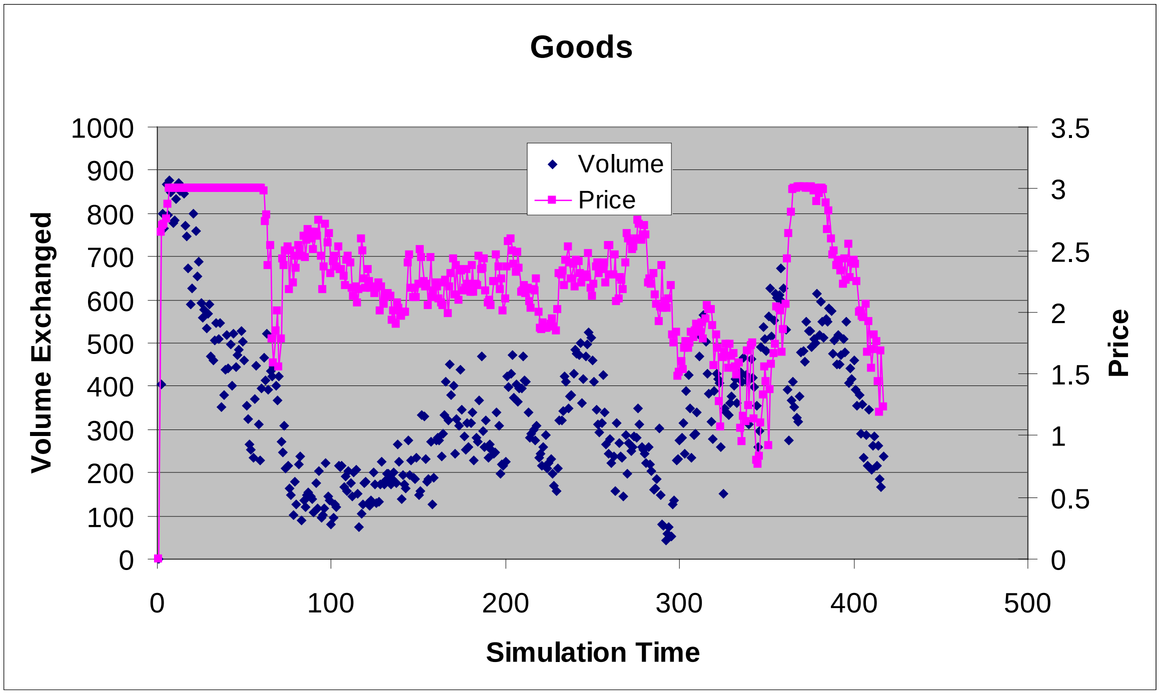

Figure C-5A - Volume and price of exchanged consumer goods in the reference case with limited fuel resources and no carbon constraint.

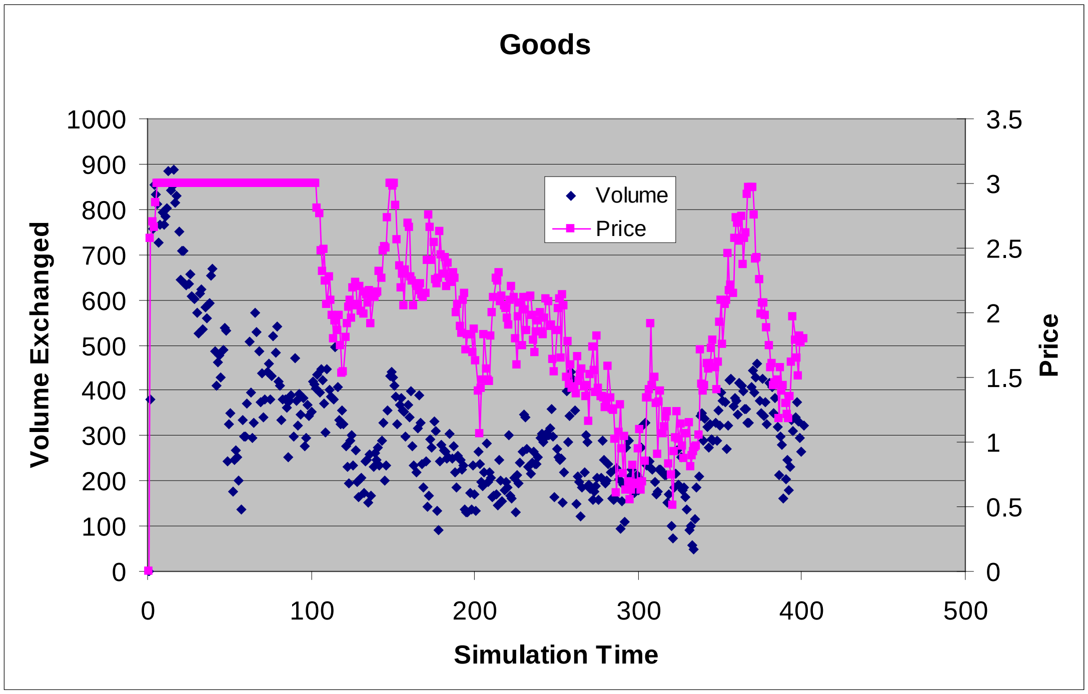

Figure C-5B - Volume and price of exchanged consumer goods in the case of carbon limits implemented by an emissions market. The volume of goods produced is ultimately lower than in the case of no carbon constraints. This is consistent with the suppression in power consumption.

The overall effect of the carbon constraint can also be seen by looking at the distribution of money across the Entity classes in the model. The total money in the model (in its current configuration) is fixed, however the allocation among entity classes shifts with time, and responds to structural changes in input requirements and technologies. **Figure C-6** compares the time history of the total amount of money in each Entity class in the unconstrained (**Figure C-6A**) and carbon-limited (**Figure C-6B**) cases. Money controlled by fossil-fueled generators depletes over time in both cases (because depleting reserves necessarily removes production capacity), and is lower in the case of carbon constraints (because carbon constraints impose an additional input cost on this sector). Although the volume of power and commercial goods is reduced in the carbon-limited case, the money held by these sectors is not substantially lower. This is due to the fixed money supply in the model: money lost from the fossil-fueled generators is necessarily spread among the other sectors.

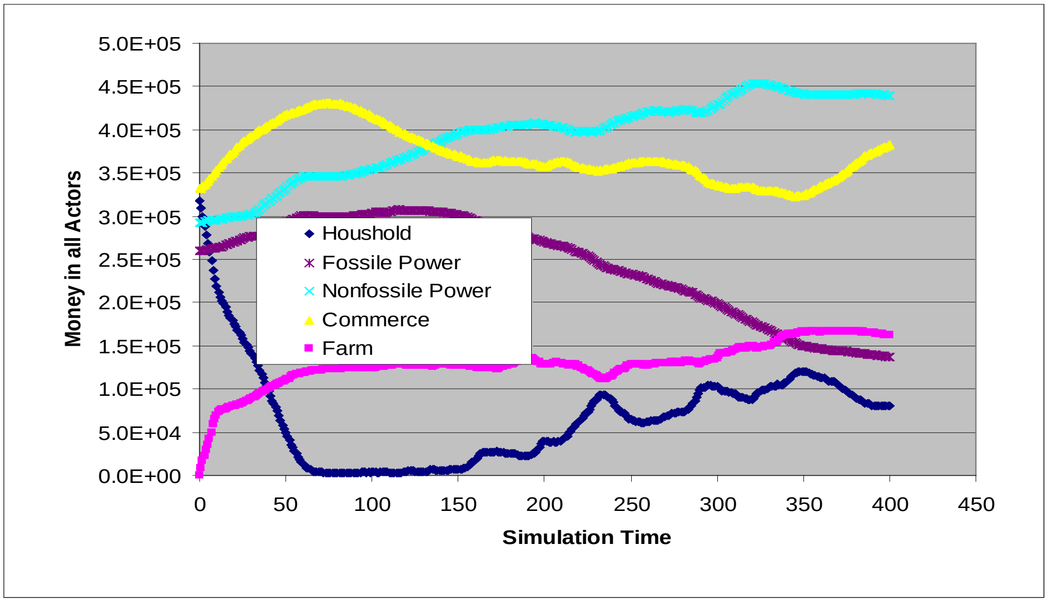

Figure C-6A: Total money in all Entities in each class in the reference case with limited fuel resources and no carbon constraint.

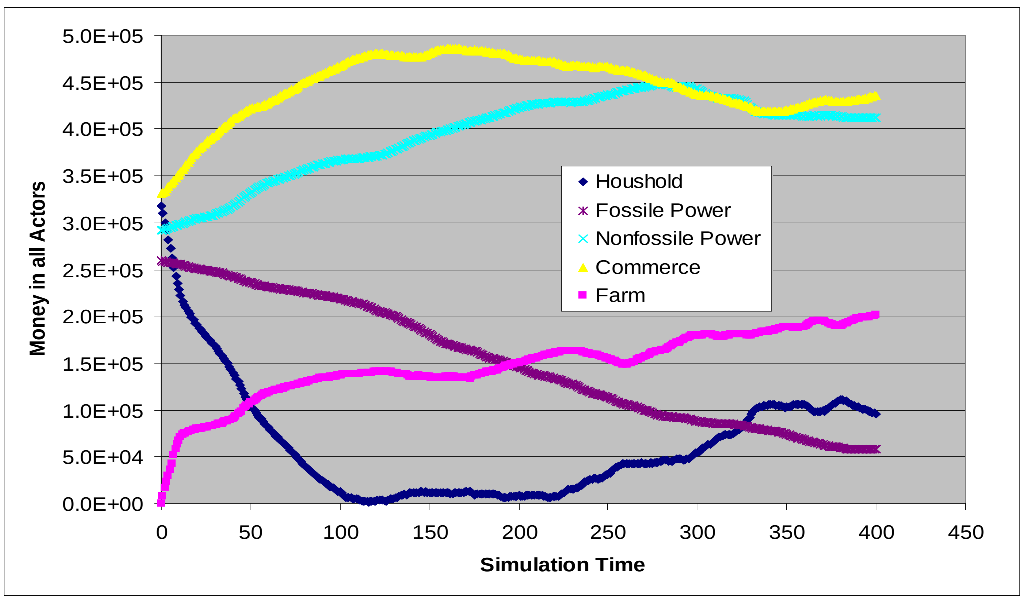

Figure C-6B - Total money in all Entities in each class in the case of limited fuel resources and carbon limits implemented by an emissions market. Fossil-fueled generators have less money, as expected by the imposition of a new input cost. Non-fossil generators and commerce retain a large share of total money.

Fuel consumption is radically curtailed by imposing carbon constraints. In conjunction with lower demand for consumer goods the carbon tax results in effective elimination of fossil-fueled generation by the end of the simulation (**Figure C-7**).

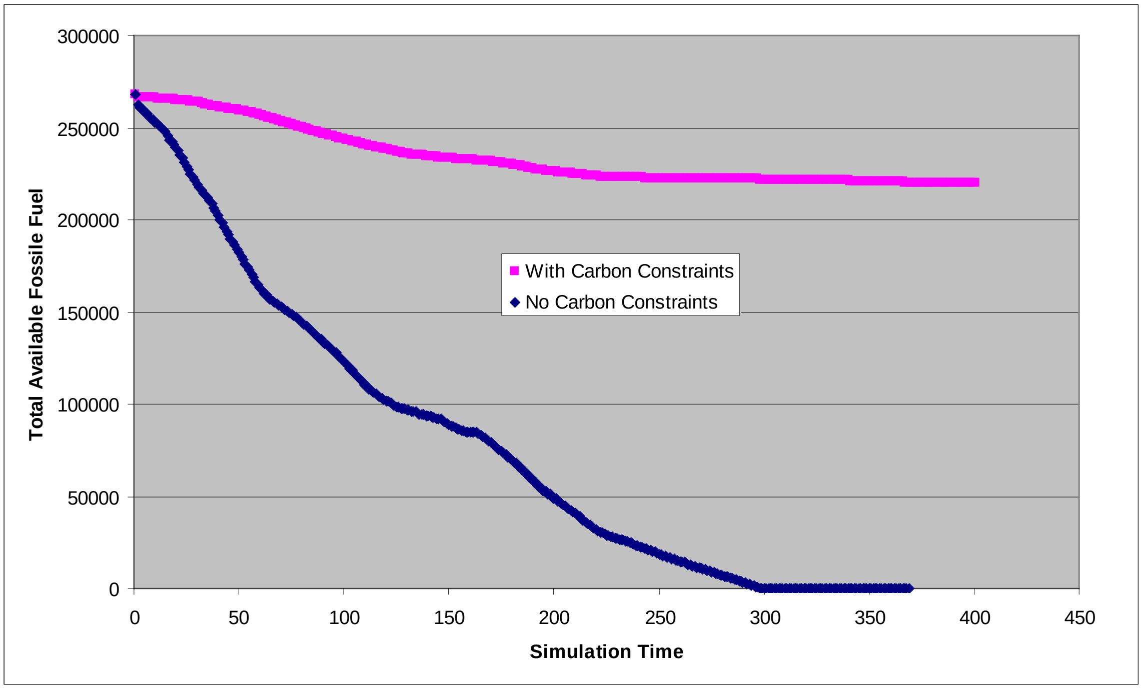

Figure C-7: Total amount of fuel resource in the model with and without carbon emission constraints.

We emphasize that these calculations as yet have no bearing on the possible effects of a carbon market in the real GES. The purpose of the present model is to examine the interaction of a few core components of the larger model. No attempt has been made to parameterize these components in a meaningful way, and many essential components are yet to be included. The limited purpose of these simulations was to test the model's ability to produce selected qualitative responses that would be expected in a real system that matched the model constraints: an overall increase in power price as a finite fuel resource is depleted, and an increase in power price and decrease in usage if carbon emissions associated with fossil fuel use are taxed.

Next Steps

The behavior of the initial model conforms to important qualitative expectations about the real system. This is encouraging, however the initial model's response has not been systematically explored. Our next step is to complete the analysis of the simple model through variation of parameters characterizing the modeled system and the adaptation process. We will also compare the results of the two decision logic formulations: the classifier system used for the present calculations and the reaction modeling approach.

We will next define a more complex basic economy in a single region, containing instances of the entities defined in **Table C-1**, above. **Figure C-8** diagrams the entity types and resource flows in this model (for readability, the names of the various resource brokers have been suppressed, and the pervasive flows of labor and financial securities have been subordinated). This elaboration includes additional components of the basic economy (industrial production and mining), distinguishes oil production and processing from other industrial processes, and includes fuel use for transportation of diverse goods. Capital maintenance and expansion is enabled through issuance and sale of securities, mediated by a financial entity. Impacts of global carbon emissions on regional climate and the impacts of climate change on other regional systems within the CASoS need to be accommodated here as well, although those connections are not yet shown. A government entity is introduced as the source of carbon credits. We will test this more complex configuration against expectations about the impact of carbon credit issuance, relative attractiveness of immediate vs. deferred consumption by households, and other changes in key controls.

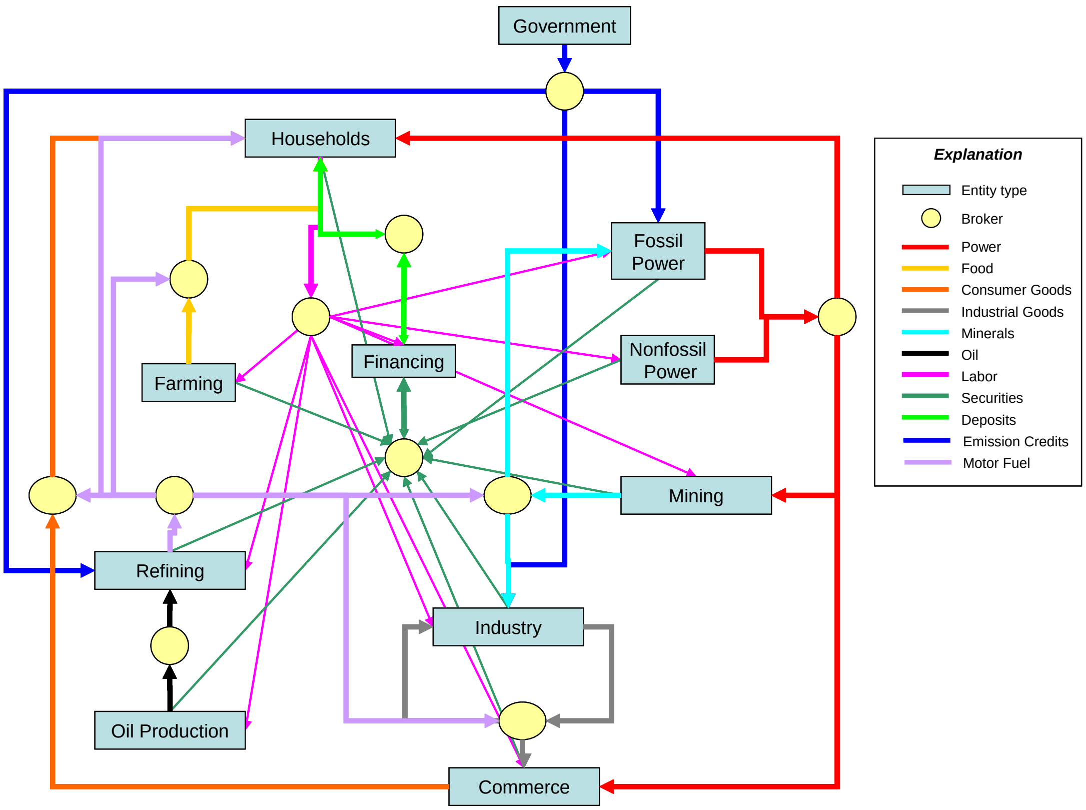

Figure C-8: Entities and Resource flows in each region of the extended model.

Once the behavior of this model is understood and accepted, we will make a second kind of elaboration by defining multiple regions with the structure of **Figure C-8**, but with varying endowments, such as the number of entities of each kind, the initial allocation of basic resources such as productive land, oil, and other mineral resources, and the efficiency of productive technologies reflected in the coefficients of their process reactions. These regions will interact through markets for most of the modeled resources, including oil, finances, motor fuels, and food. Labor and power markets are typically limited by national boundaries so interregional markets for these resources are not proposed. A given entity in a region, e.g. a Farm, may participate in a local market only, or in both a local and an interregional market. In addition to having different endowments of basic resources and technologies, regions may differ in the extent of their connection to interregional markets. **Figure C-9** illustrates the proposed interregional flows among three regions. Our initial studies will focus on the interactions among such a small number of regions whose parameters have been defined to reflect mature, emerging, and developing economies.

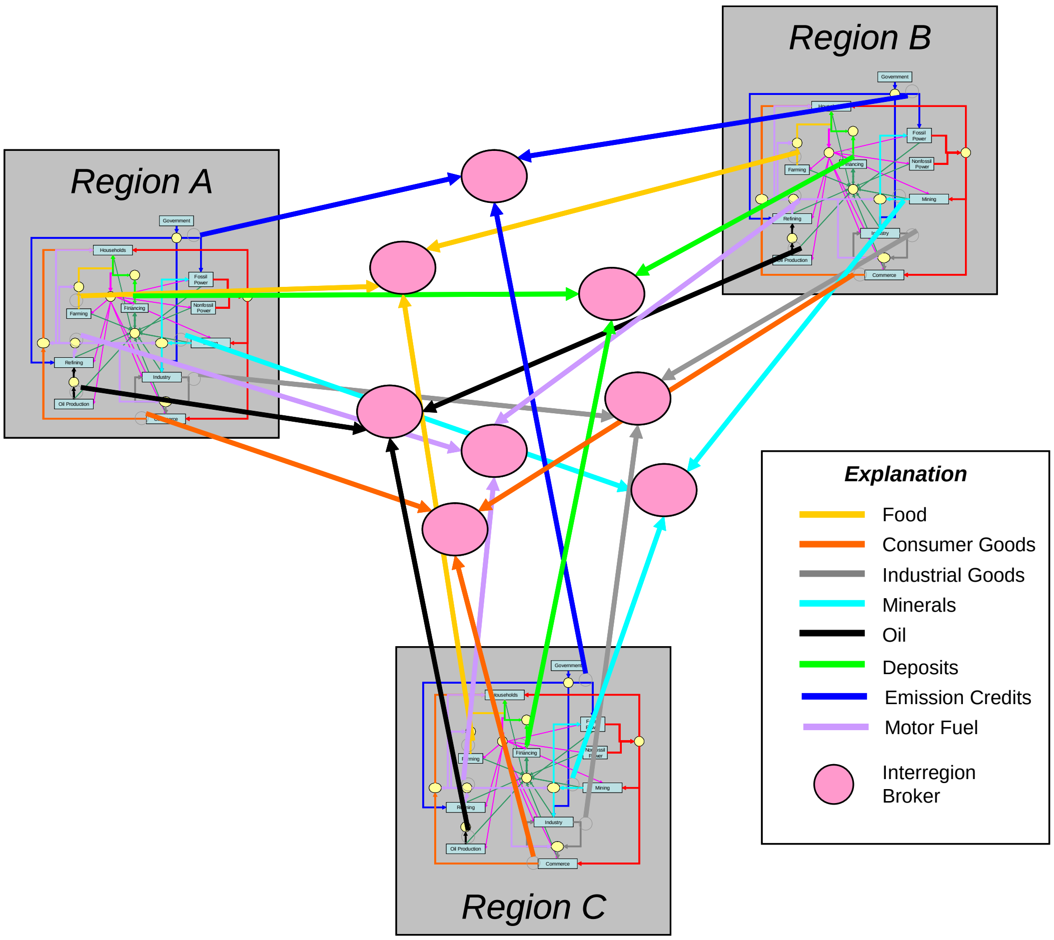

Figure C-9: Interaction among regions through interregional brokers.

A final model will be defined by elaborating on the basic elements that we have introduced and studied sequentially using the preceding models. First we will define a larger set of regions, and a hierarchical structure of market interactions among them to reflect nations interconnected by trade agreements and common or readily convertible currencies. The function of government will be elaborated to include financial and fiscal influences, infrastructure investment (reflected for example in labor productivity and transaction costs), defense and other protective measures, and possibly other controls. Additional interregional influences, such as multinational entities, may be included as well. **Figure C-10** presents a schematic of the interregional interactions in this model. Many of the basic entity types considered (such as Industry and Financing) may be defined in much greater detail. Our intuition is that such refinement is unlikely to change the basic results regarding the differential effects of the policies to be considered, however some level of refinement may be needed to test this intuition, and to demonstrate the robustness of results to additional refinement. Our approach will be to resist arbitrary demands to increase resolution, because reflexive refinement will rapidly produce a model that cannot be tested and understood.

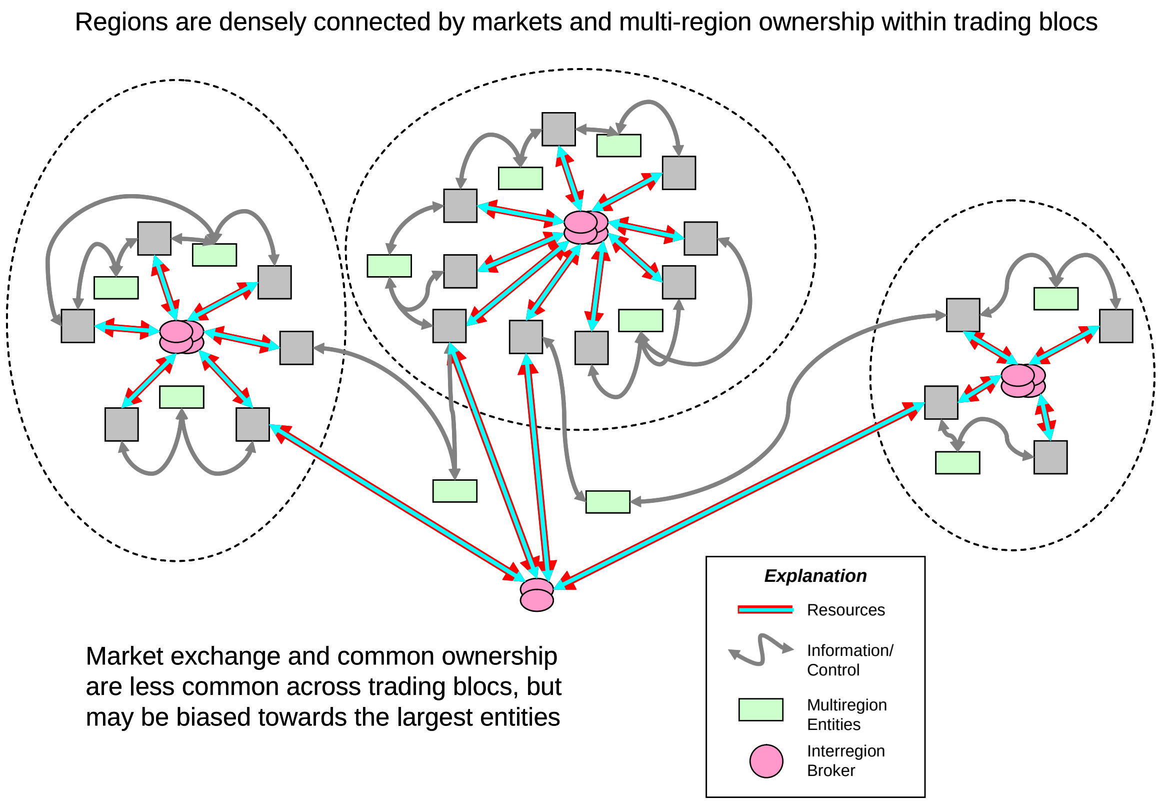

Figure C-10: Hierarchical pattern of region interconnection represents currency zones and trading blocs

APPENDIX D: THOUGHTS ON THE TRANSPORTATION ENERGY INNOVATION HUB (TEIH) SYSTEMS ANALYSIS COMPONENT

Contents

Givens: Background on the TEIH provided by Ellen Stechel

Hub Concept: Changing the Game, Securing the Future

> The Transportation Energy Innovation Hub will accelerate the development of viable and robust solutions to the Nation's transportation energy challenges through discovery, innovation, and collaboration. The Hub will enable the effective and coordinated use of national assets – individuals, universities, national laboratories, non-profits, and industry – to address energy security and climate change. It will employ an open access, networked knowledge community that includes academic and international science, and will focus this web of knowledge on achieving a safe and secure transportation energy future. It will develop an evolving "roadmap to rapid solutions" for transportation energy based on continuing open access systems analysis of technical, political, societal, and economic drivers and characteristics.

What are the critical capabilities, connections, or qualities needed for such an enterprise to succeed? What would attract a wide-range of stakeholders to participate in Hub research and activities? Please give us your ideas.

Topic: Vehicle Electrification

> A promising path to energy security and lower carbon emissions is electrification of our transportation fleet. The technical challenges range from energy storage to power train management to creation of a new infrastructure to accommodate plug-in vehicles. Specific areas of research might include advanced materials to improve the economics and performance of batteries or fuel cells; safety and reliability of high energy density batteries; and the investigation of new hydrogen storage materials.

What do you think are the key issues and most promising technologies Sandia can address to enable vehicle electrification?

Renewable Fuel Production

In the US, petroleum provides more than 96% of the resource to produce fuel for our transportation fleet. The lack of substitutes for petroleum is a key issue for both energy security and climate change. Development of alternative, economical renewable fuels will have tremendous leverage, especially if they are fuels that can be used with existing distribution infrastructure and vehicles. Specific areas of initial interest include the biology of algal fuel production; thermochemical and electrochemical CO_2 and H_2O splitting; CO_2 capture and release chemistry, materials, and nanoscience.

Fuel Utilization

Personal transportation options will evolve with increased efficiencies in combustion engines, introduction of alternative low-net-carbon fuels, and increasing vehicle electrification, but internal combustion engines will remain in the transportation picture for decades, particularly in applications that require significant range and load. Thus, the path to low-carbon transport starts by increasing the efficiency of combustion engines.

What advances can Sandia enable that will have the most immediate and/or significant impact on ICE fuel efficiency?

Systems Analysis

Underpinning the technical thrusts would be a fourth critical component: comprehensive systems analysis, supported by realistic and credible modeling and simulation. A secure and environmentally responsible transportation future will require not just a combination of new and advanced technologies and fuels, but also policy transformation and critical investment decisions in R&D and deployment paths. Informing the creation of sound policies and making the right investments requires a systematic, in-depth understanding of the complex interrelationships within the energy system—and between the energy system and other infrastructure elements. For example, we need to understand the land, water, infrastructure, and energy requirements associated with producing and distributing alternative fuels and the impact of policies on the maturation and adoption of solutions.

How can Sandia's systems modeling expertise be brought to bear on this problem?

Seven Principles for the Pilot Hub

Outcome Oriented	Not technology oriented	Define an outcome-oriented scope for ensuring a sustainable and secure energy future, focusing worldwide science and technology capabilities on achieving outcomes, as opposed to on specific solutions or technologies.
Systems Context	Drives R&D investment	Make R&D investment decisions guided by a systems context with community input. A systems context considers potential impact, scalability, and timescale, within the broader global energy sustainability and

		security perspectives.
State-of-the-Art Facilities	Open Campus Design	Anchor the Hub with a core physical location containing state-of-the-art facilities and high quality staff, providing infrastructure and capabilities that are critical to success of all hub participants, including the international community.
Build inclusive communities	Open Innovation, Flexible Public/Private Partnering	Build an inclusive community, fostering a model of true open innovation. Bring together activities and promote information sharing that help bridge the gaps between basic research, applied research, private sector commercialization, and public sector policy construction.
Active management of the portfolio	From Science to Innovation and Application	Actively manage a portfolio of work from science to innovation and application with the involvement of the full range of key stakeholders (including Office of Science, Applied Energy Programs, and private sector).
Open access	Modeling and information framework	Accelerate learning and understanding related to, as well as community confidence in, the information and modeling underpinnings for the outcome oriented focus and systems context of the hub.
Relationship between Hubs		Create networked relationships with other Hubs to attain a full system outlook; the collection of Hubs should form a continuously connected network blanketing the landscape for energy sustainability and security.

Fundamentals for Definition

What is TE?

Transportation Energy (TE) is one of energy's many uses within the Global Energy System (GES). TE can have a variety of forms (liquid fossil/renewable fuels, gaseous fossil/renewable fuels, hydrogen, electricity, etc.) each enabled/created by a number of technologies (list some of them) which all have specific requirements for materials, energy, funds, infrastructure and labor to produce and use, each creates a specific waste stream (carbon emissions, water & air pollutants, etc.), and each has specific health and safety costs and constraints. TE molds many aspects of a civilization's infrastructure (far beyond the physical infrastructure created to support TE) which in turn structures/constrains many aspects of civilization. Structure and function go hand in hand, in many ways, a civilization is it's infrastructure. Thus, whether we are conscious of it or not, the use of specific forms of TE enables and influences the evolution of civilization, but also imparts huge inertia and hysteresis (irreversibility) that constrains current and future options. For example, the layout of railroads in the nineteenth century did much to shape the distribution of the population along railway lines, just as the automobile has caused those cities to grow in the familiar pattern of urban centers and suburban sprawl. This sprawl, in turn, increases dependence on the automobile.

How must we view TE?

TE must be viewed within context of the Complex Adaptive System of Systems (CASoS) that is the GES. People, cities, states, nations, etc, use TE as one of many forms of energy to meet their needs, to improve their standard of living, to develop/grow. TE fundamentally influences (enables? constrains?) human interaction (everything from how to live, to where to live, what to do (jobs available), what to buy, who to interact with and why) at organizational scales ranging across the spectrum (individual, household, business, city, county, state, nation, continent, globe). For instance, who to interact with and why at the global scale defines the flow of oil from nation to nation. TE enables commerce, and (along with global rapid information flow) enables the global economy (why worry about the economy in any other country or even in a different city if no goods migrate between us and them?) Human interaction at all scales is constrained (facilitated?) through formal to informal agreements (instruments such as contracts, laws, treaties, stock, loans, derivatives of loans) either directly, or indirectly on influencers such as TE.

Decisions regarding TE influence the other flows within the GES (materials, energy, information, funds, people, influence, etc) and vice versa.

Examples: City planning influences TE and vice versa; Business operations influence TE and vice versa; Witness the current illustration of the interdependency of ethanol production, agricultural products, food costs, world hunger, civil unrest, and emerging security problems throughout the world. (possibly expand)

The effects of TE are not only limited to infrastructure and economic concerns, but also are deeply intertwined with culture. NASCAR and our enduring obsession with large automobiles is a defining feature of Americanism, and this aspect of our culture has been remarkably resistant to economic and environmental pressures to reduce gasoline consumption. Similarly, China and other emerging economies are struggling with the opportunity to build more enduring transportation infrastructures and the desire to embrace the automobile as a symbol of prosperity and individual power. Can we anticipate how these cultural factors will constrain our choices in TE?

There are many feedbacks, these feedback adapt, the vehicles for agreements adapt (and create new ones, consider the oil futures market).

Where must we draw the bounds for TE Systems Analysis?

Can we define and engineer solutions for TE independently? Yes, but doing so in the past has led to many unintended consequences in the present. The feedbacks to other components of the GES make this impossibly difficult. For example, will changing patterns of transportation and shipping replace mass markets with a resurgence of local industries? How will media change in response to changes in transportation? Would a shift to smaller vehicles reduce stress on roads and bridges, saving money in infrastructure maintenance? (Construction standards for Interstate roads are determined by large truck use, not cars and for transportation costs larger is actually better.) How will economic and policy analysis change if we choose to replace the view of fuel prices as suddenly rising with a recognition that historical prices have been unrealistically low? All these feedbacks are adaptive, and new organizations, needs, structure will emerge that makes independent analysis fundamentally flawed. Can we set goals within TE that are in context of the GES and then proceed to engineer solutions for TE? Yes, but the goals will change in time as the

GES continues to evolve. Goals change in response to evolving needs and constraints of the larger, more comprehensive CASoS. Thus, systems analysis for TE must be appropriately embedded within systems analysis of the GES.

Conclusions:

The *Systems Analysis Component* of the Transportation Energy Innovation Hub (TEIH) must be broader than TE alone. It must form a foundation for analysis that includes all forms of energy and at scales up to the global, the Global Energy System (GES). It must place TE within this context and then consider the three technical components specific to the TEIH (Vehicle Electrification, Renewable Fuel Production, Fuel Utilization). In this way, *the Systems Analysis component provides integration of all energy R&D with policy and implementation that is comprehensive and beyond borders*. (this concept should be strengthened… it sets the level and scale for the system's component… while the Hub concept is to be *replicated*, this component of the Hub will *expand* to incorporate additional Hubs while the other components won't, it is fundamentally different from the other components). In this way, the systems analysis component lays the foundation for the entire National Energy Innovation Initiative (NEII), but is not dependent on the NEII multi-hub concept coming to fruition.

Systems Analysis Component

The Systems Analysis Component must embrace a general *Systems Engineering Framework for CASoS* that is both wide and deep so as to cover the many potential opportunities for unexpected, nonlinear, and interconnected behavior. Such a framework must encompass analysis of TE within the broader GES and treat the TEIH itself (it's structure and function). The TEIH will be an organism defined by it's entities (people to groups of people to facilities) their internal and external interactions (at all scales), and goals that drive these interactions (funds, problems, mission, also scale dependent). It grows, adapts, and evolves in response to stimuli and constraints. A comprehensive view that places analysis of TE within the GES and recognizes itself as an agent of change that is also a CASoS that can be designed and controlled has never been taken before. This is a tremendous challenge, but it is the key to a success that will last the test of time.

General Systems Engineering Framework:

Three activities generally comprise an engineering activity: Define, Design and Test Solutions, and Actualize Solutions within the system of interest. In context of our current application, we can elaborate each:

1. **Define** (blackboard to details) 1) the CASoS of interest, 2) the Aspirations which typically fall into a set of clearly identified categories: Predict; Prevent or Cause; Prepare; Monitor; Control; and Recover or Change, and these will engage diverse consumers of knowledge, ranging from operational organizations to policy discussions; 3) Choice of Aspirations based on constraints and impact, ; 4) Choice of appropriate methods and theories from the full space of those possible based on Aspirations chosen, ; 5) Appropriate conceptual models, and 6) Required data to support conceptual model development and validation. Possible methods,

theories and fields of contribution must be fully inclusive and include analogy, dimensional analysis and similitude, experimental design, system dynamics, non-equilibrium thermodynamics, complex adaptive systems, game theory, percolation phenomena, agent-based modeling, networks, system optimization and control, and many others.

2. **Design and Test Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. Designing and testing solutions is problem-dependent, it focuses on answering three general sets of questions relevant to any Aspiration: 1) What are *feasible choices* within the multi-objective space, 2) how *robust* are these choices to uncertainties in assumptions, and 3) what are the critical enablers that increase system *resilience*. Included in this process is the delineation of as many unintended consequences as possible and their amelioration/mitigation. Specific concern should be applied to seeking solutions that address multiple aspects of the problem, approach solution via multiple avenues (synergistic leverage), and that adapt as the system adapts.

3. **Actualize** the engineered solutions devised within the real system. The engineered solution may be a concept, a computational tool, a sensor, a technology, a process, a control policy, etc. This activity involves working with decision makers (change the world), other researchers (change the field) and people affected by the change (understand the impact). This involvement requires a long term commitment: these are high-consequence systems that adapt to change. Any change makes us part of the system with concurrent obligation through a solution's lifecycle. This emphasis on broad engagement in both producing and actualizing ideas will require that TEIH embrace emerging media. The classical cycle of paper writing, refereeing, publication is too slow and narrow to support this vision. How can we, for example, use computer-media to add intelligence to scientific communication, to enhance collaboration (or redefine the nature of collaboration), to shorten peer review times (or redefine our community of peers), to replace the idea of published papers as snapshots of the scientific process with a continuous model that makes public the full range of debate and improvisation that underlies the neat expression of scientific conclusions?

As in classical engineering, iteration and blending among the phases is intrinsic. Actualization requires designing and testing to suggest future steps, and adaptations of the system often requires a return to fundamental thinking to understand the adaptations and possibly reformulate Aspirations as the system changes. In context of a comprehensive effort such as the TEIH, there will be many concurrent threads of activity and these threads will interact with each other. As a simple example, a particular thread may become delayed in testing thus causing an actualization problem due to public perception, which in turn causes a different thread to have greater potential (higher ranking) and so this other thread is pushed forward.

The general systems engineering framework will be applied quite broadly first to the GES, then to TE within it and then to sub-systems within the TE.

It will also be applied to the TEIH itself.

The application to the GES and TE leads to a set of Substantive Goals, the application to the TEIH to a set of Functional Goals for the TEIH.

Substantive Goals for the Systems Analysis Component:

Substantive goals are those that create understanding and support the definition, design, testing and actualization of solutions:

1. Apply General Systems Engineering Framework to the GES

   The GES is composed of the *complex physical systems* of the atmosphere, lithosphere, and hydrosphere, as well as the *complex adaptive systems* of the biosphere which prominently include human economic, socio-political, and energy generation, storage, control, and interdependent global distribution networks. Our nation and others require secure, reliable, sustainable, and cost effective supplies of energy to support economic development and to maintain a high standard of living. Our nation's energy infrastructure evolved to meet these requirements with fossil fuels because of their inherent high energy and power densities and flexibility. We are now left with several unintended consequences: high-CO_2 emissions, dependence on foreign petroleum for many critical activities (e.g., transportation fuels), and inadequate investment in energy source diversification. All of these consequences are now a threat to national as well as global security. . Potential responses range within the *socioeconomic-technical* realm from the *socioeconomic* (e.g., negotiation of global and national targets for CO_2 emissions, incentives/restrictions, technology and fund transfer, war) to the *technical* (e.g., renewable energy sources, next generation distributed energy grids, energy storage systems, new transportation fuels, development of CO_2 capture and storage).

2. Place and analyze TE in context of the GES

   This was begun above in "Fundamentals for Definition" section above and pieces from there can be brought in here.

   Places TE in context of large scale conceptualization with recognition of dependencies that are not normally considered in many traditional TE analyses

3. Integrate traditional analysis approaches of TE and it's sub-components into the larger GES analysis

   - There are MANY energy models that have been developed over the years for use in evaluating policy in this arena, TE is a component of many of these models
   - SD models mostly at national scale (query George Backus, Len Malczynski, Arnie Baker, others)
   - SD models at global scales (Daisy world, Limits of Growth, etc)
   - Life cycle models (Ellen mentioned the "wheels to something-or-other" model)
   - Place these traditional models/analyses in context of the GES, integrate them, combine them, connect them, compare them, question them… this will require the development of a supportive mod-sim-analysis environment (**see Functional Goals**). Current technologies have produced a wealth of promising collaboration technologies, such as web journals, blogs, wiki, etc. These challenge traditional notions of collaboration (how many contributors to Wikipedia know who their collaborators are?), quality control (replacing reviews by small committees of specialists with vast communities of diverse

talent), and the lifecycle of knowledge itself (publishing is less a vehicle for claiming ownership of an idea than a stream of partial ideas supporting its creation). The TEIH has a unique opportunity to push this along by adapting these media to the particular needs of systems analysis and model building. How can the semantic structure and behavior of computer simulations drive collaboration beyond the flat semantics of texts to something richer? What would it mean for diverse, independent collaborators to work together on simulation models? How would making the social component of model-building explicit change the way we think of models? What would the inevitable debates and disagreements mean for model development and confidence building? How would we manage the torrent of intellectual property this could produce?

4. Extend traditional analysis through recognition of behaviors inherent in Complex Adaptive Systems of Systems such as increasing gains, emergence, self-organization, competition, cooperation, adaptation, surprise, crisis and discovery

   - Traditional analyses analysis often do not allow for surprise, emergence, etc. While they often contain many feedbacks and detailed processes, they have difficulty incorporating mechanisms that operate at the local scale that can take the system in very different directions.
   - These are the mechanisms that give rise to complexity rather than complication, two very different animals.
   - Complexity arises through the interaction of entities at scales ranging from the local to the global with feedbacks between.
   - Through focus on complication, we often miss the forest for the trees.
   - Conceptual approaches not normally used in the analysis of energy must be brought into the fold: non-equilibrium thermodynamics and the definition of sustainability, game theory (classical) and behavioral game theory (based on what actually happens), network theory…
   - Combining these approaches with traditional analysis will require the development of a supportive mod-sim-analysis environment (**see Functional Goals**). Current modeling environments are little more than applications of standard Software Engineering methods such as version management systems, automated test management, etc. What would happen if we thought of models as something other than computer programs with a certain class of input/output behaviors? For example, what would happen if, instead of thinking of a model as a predictive representation of its world, we thought of it as a shared focus of attention in a large, self-configuring community of researchers? What internal structures of the model would we need to make visible to make this work? How would this emphasis on models as focus of collaboration change our notion of validity? Currently, we think of the model as end product and largely ignore the path of its development; could we shift this value proposition to recognize that the history of the model's development is as valuable as the end result? How would this shape the design of development environments.

5. Create a foundation for analysis and integration of all energy R&D&A (beyond the TE component) and the policy to implement, guide and adjust the GES on into the future (adaptive dynamic control/modification).

   - Because TE is a component of the GES and must be placed (and modeled) within it, what is done in the TEIH Systems Component creates a foundation for expansive analysis of the GES as well.
   - Extended energy components include: electric grid, fixed power generation from fossil (coal, gas), nuclear (fission, fusion) and renewable (wind, water, geothermal…) sources
   - Extended interdependencies include: population, standard of living (drive), food, water, environment, security, trade, supply chains, economics…

6. Use advanced media to engage the full range of customers as well as collaborators (or better yet, to obliterate the distinction).

   As experience at Sandia Labs has shown, doing science in the service of a political entity is problematic. Is this inevitable, or is there a better way to place science in service of the public good? For example, the use of models in public policy debates has a checkered history, with people shopping for models that support their position. Could the TEIH use interactive media to engage decision makers both early enough in the process and with a sufficient depth of understanding to change this? How can we use visualization techniques better to present the non-linear insights of computer models to people whose intuitions are solidly linear? Or, for another example, currently science more or less informs policy, but there is less effort to understand and improve the way policy makers use science. Suppose we could track the TEIH's influence on policy, including the inevitable distortions of science at the hands of politicians, and use this history better to guide our engagement with the political sphere?

Functional Goals for the TEIH:

The SEVEN PRINCIPLES in the Givens section above spell out the functional goals for the TEIH. Relative to the Systems Analysis Component:

1. Run the TEIH as a CASoS: Design it, control it, and evolve it using CASoS Engineering concepts (adaptive dynamic control/modification).
2. Evolve Holistic Creative Innovation and Interaction Environment for expansive thinking and collaboration across diverse subjects areas (physical science to behavioral/social science to engineering) and action areas (research to policy to actualization) that is both virtual (spokes) and set in space (the hub facility)
   a. Hub facility: building, space, tools, support staff, views, integration of subject matter with participant's lives and the world around them. The hub facility cannot feel isolated (e.g., outside the Eubank gate at Sandia might be isolated), a full analysis of "isolation" must be done. The Hub facility must have a "draw" that is holistically compelling.

    b. Extended Hub: virtual spokes to industry, government, universities, other labs, extending within and external to the United States.
    c. Get input from CS folks who design cutting edge "collaboration" environments that would facilitate virtual spokes, integrate their ideas here
3. Create Modeling, Simulation, and Analysis Environment (such as we conceived in the CASoS roadmap) that seamlessly integrates everything from conceptual design to data storage and mining to experimental design to parallel processing on huge clusters to parameter sweeping and phase space behavioral delineation to visualization
    a. federation of existing models (a critical component to get folks in the door)
    b. rapid flexible model generation "sandbox" to ask what if's and increase understanding
    c. building of new communal models (such as was done in climate area), grow directly from the rapid generation "sandbox" taking the best of from existing federated models
    d. intrinsic, transparent V&V applied to all models/experiments/analyses added to or developed within the TEIH
    e. Get input from CS folks who design cutting edge "modeling-simulation-analysis" environments that would facilitate all the above, integrate their ideas here
4. Use advanced media to engage the world of policy analysis, government, and public debate in ways that better honor the needs of science.

Additional Thoughts

Uniformity, competition and cooperation:

Solutions will always be in competition with one another.

If one attempts to uniformize within the hub, then it will push completion outward to be between the hub and non-hub. We don't want this.

The hub should embrace completion, should be a center for bringing people and solutions together where the benefits of particular solutions can be evaluated and weighed against each other. It is unlikely that a single solution will be found that fits all situations (industries, nations, level of economic/infrastructure development).

The hub must be unbiased and inclusive.

The system's component must not be used to eliminate ideas. It should be used to embrace and think through ideas, identify the situations where these ideas would be a best fit. The future may hold such situations.

Think of ideas as species that must compete with each other to survive. Some ideas will find niches where they do best. Some ideas require other ideas to survive or flourish. Some ideas will die … When perturbed, is the "ecosystem" of ideas robust?

The hub must also embrace cooperation.

The ecosystem not only encourages ideas to compete, it should also encourage them to look at other ideas and consider blending them. Genetic mutation of ideas might be the strongest result we can get -- ideas that have advantages of both their parents, but stronger than either.
Game theory suggests that competition-based equilibria are easier to understand than cooperation/merging, but don't we *know* that cooperation-based equilibria are more stable? Certainly equilibria are more stable than optima.

Surprise and discovery:

We must allow for surprise and discovery. These are generally not included in models.

Many economic models are flawed in their inception in thinking that an accountant's approach to the universe yields opportunity. They discount the value of innovation, determining that it merely puts off the inevitable, making it more brittle, while ignoring the potential for completely new opportunities.

Such models yield surprise only when parameters are put in ranges not previously considered, questions are asked about things excluded (or not included) by the model.

But this surprise was always there and not seen because the phase space wasn't shown, and also missing for small parameter changes because a proper bifurcation analysis is lacking. One only sees changes for large parameter change because they don't see the entire map.

This is not true surprise, or emergent surprise, or discovery; what is in the model was always there and could be found through straight forward analyses.

True surprise is not necessarily *in* the model; it can result from subtle interactions that are not in the model, from completely rethinking the model in new terms, making or breaking connections that hadn't been previously considered, or from new understandings of what the problem really is. Models tend to capture the way we currently think about the problem, so they are highly unlikely to capture surprise and discovery opportunities.

Emergence and crisis:

We must allow for emergence.

We must not only allow for it, but encourage it. If we can encourage emergence -- provide the right environment, the right ground rules, encourage interconnections and interrelationships to be explored, then we can blend the top down SoS approach with the bottom up CAS approach. This is intrinsic to the CASoS approach that utilizes and guides emergent system behavior.

We must allow for human behavior at many scales that may change some options from possible to impossible (and vice versa) through a "pandemic" of perception instigated within a susceptible population.

Crisis can clarify/reduce options, possibly define a single path… (Hari Seldon)

Self sustaining (adapting) Solutions:

Can we create self-sustaining solutions (think "phase-locking") that use the adaptive process itself to drive them?

Dynamic Adaptive Control:

All CASoS containing humans have “influence” processes where individuals to groups to institutions are influenced by what other individuals to groups to institutions do.
Influence processes often lead to the fundamental inability to predict certain types of outcomes.
Prediction can be enabled in such systems by monitoring early time system response.
Dynamic adaptive control would combine monitoring of appropriate system response with imposition of appropriate controls to guide the CASoS in desired directions or to stay within set bounds.

APPENDIX E: THOUGHTS ON FORMULATING SANDIA'S ENERGY MISSION

Contents

Task Definition from Terry Michalske September 12, 2008

- Formulate a High Road that frames Sandia's Energy Mission (above the fray of all the individual interest groups, so that we don't have to spend all our time defensively reacting to them)
- What are the Goals and Outcomes of this High Road?
- What are the overarching Questions that we could use to formulate the Goals and Outcomes of the High Road?
- Timeline: something to Terry by September 19, 2008, Terry must have nearly baked articulation by Oct 1, 2008; this will then be reworked to be presented by Hunter Nov 10, 2008.

Background: The Global Energy System (GES) is a CASoS

We classify the Global Energy System (GES) as a Complex Adaptive System of Systems (or CASoS).

Complex: The energy system's behavior is a function of the many interactions between its elements and emerges as different from a simple sum of the behavior of its elements and thus can be counterintuitive and more complicated than simple linear models would suggest.

Adaptive: Elements of the system, such as the people served by the system, adapt their behavior to influences within the system (e.g. they buy less gasoline when the price goes up), and in turn modify the systems inner workings (e.g., they impose policy to increase the gas efficiency of cars).

System of Systems: The elements of the energy system are complicated and sometimes complex systems in their own right (e.g. countries, companies, the environment).

The science of engineering change in such systems is currently emerging.[3] At this point, it is clear that it is not possible to construct complete models of CASoS systems. Strong interrelationships within the system mean that unexpected consequences must be carefully considered; CASoS systems can produce very counter-intuitive nonlinear behaviors.

It is also clear that changing such systems can be very difficult both because entrenched behavior can be difficult to overcome and because the systems adapt in strange ways to the changes. People tend to deal with problems in a localized cause-effect manner, while CASoS systems tend to exhibit globally interconnected behavior. Attempts to apply local solutions to global problems can produce very negative unanticipated effects, far out of scale relative to scale of the local solution.

A general framework for the CASoS Engineering is currently being developed within context of the GES. A summery of this framework as a work in progress is given in the final section.

Players in the GES

There are various players in the Energy problem, including, most prominently, Industry, Domestic Government, International Government, Academia, Consumers, Advocacy groups, and Researchers.

Each of these groups encompass many factions, each of which can be considered a special interest. They play specific roles, and those roles tend (because we are human) to be somewhat locally focused.

Any time a “solution” is proposed for energy systems, there will be people who are ready to exploit it, people who want to prevent it, people who want to misuse it for other ends, people who will adapt their behaviors in unexpected ways to the new solution. The complexity of the energy system guarantees these response behaviors; any attempt to push forward *new solutions* can create tremendously difficult obstacles, all of them stemming from what appear to be special interests.

Dimensions of Potential roles for Sandia

Aspects of solutions pursued. Sandia could pursue purely technological solutions (i.e. invent another widget), purely social solutions (i.e. convince people to change their behavior), or a combination of these. Sandia has a long history of excellent technical activity. Although not an historical strength, quantitative analysis of the social aspects of CASoS has been emerging over the past few years at Sandia in recognition of the importance of these forces in understanding the complexities of CASoS-induced vulnerabilities. In fact, this emergence, while not an historical strength, has become a strength none the less.

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[3] Glass, et al, Sandia National Laboratories A roadmap for the Complex Adaptive Systems of Systems (CASoS) Engineering Initiative, SAND 2008-4651.

Degree of involvement. Sandia can pursue a spectrum of involvement, including observe (watch technology develop), evaluate (compare possible solutions), engage (invent possible solutions), drive (define the agenda). Lower degrees of involvement entail far less risk relative to the many players in the arena, but have correspondingly lower impact and rewards.

Possible "High Roads" for Sandia in Energy

Technical observer/evaluator

Sandia could limit its activities to watching technical developments and evaluating potential technologies in purely technical terms. Such an approach avoids political entanglements, but limits opportunity and can say little about the overall market potential for any given technology (due to ignored social issues).

Socio-technical observer/evaluator

Sandia could limit its activities to watching and evaluating, but increase focus to include social concerns (e.g. what is the climate effect of a new technology). Such an approach potentially engages a larger spectrum of special interests (as a means of including more of their concerns in various evaluations), while avoiding potential political entanglements (we favor no specific groups, but include all). Our perspective grows to include many more interactions, so we are much more capable of producing good predictions of what new technologies will do.

Technical engagement

Sandia can involve its people in attempting to invent new technological devices, without considering social consequences. Such devices are likely to work well in the lab but might have difficulty making it to the real world. We rely on our technical reputation to bring customers, and hope they can work out the social ramifications of the work.

Socio-technical engagement

Sandia can consider social ramifications in creating new designs, both in devising technical requirements (to produce more socially relevant designs) and in defining new approaches (considering different political approaches to delivering solutions). The potential solutions arrived at by such an approach are much wider than typically considered, as there are many more degrees of freedom. They are also potentially much more relevant, as they consider a wider variety of issues.

Technical driver

Sandia can attempt to set the pace for technology development, by being ahead of the curve technically compared to others in the world. We have achieved this in the past in some areas; maintenance of such a position can be expensive, but prestigious. Such a position is difficult in times of strong opportunity, because there are so many competitors.

Socio-technical driver

Sandia can attempt to set the pace socially and technically. Such a position requires broad knowledge of all the technical and social issues that are relevant to the problem, and a great deal of skill in order to be the best in solving them. The greatest opportunities are here, along with the greatest possibilities for complex entanglements.

It appears that attempts to address the Energy CASoS in a purely technical way is a recipe for social difficulties – the approach attempts to ignore the social issues of the process, then encounters great resistance after significant funding has been spent attempting to devise solutions. If our people and their ability to think and invent are truly our greatest asset, it appears that providing them more degrees of freedom early in the design process is a means of finding the best solutions.

In any of these cases, the high road is most easily found by broadly considering aspects without taking sides, that is, from a perspective of science and engineering. For any given issue, such as climate change, there will be people on both sides of the argument. For engineering purposes, the truth or falsity of any such issue is irrelevant – it is the fact that *people differ in their opinions*, and that we can attempt to evaluate/understand/design/drive solutions that broadly minimize negative impacts and maximize positive impacts, which needs to drive our work, if we are to provide solutions that really work in this complex environment.

One might imagine that there is a “high road” that involves avoiding hot-button issues. Such a path is self-limiting; every decision seeks to avoid pushing hot buttons. Understanding the issues, and how they interrelate, is, instead, a means of reducing limitations – providing more degrees of freedom for the problem, if we’re willing to explore them.

Goals and Outcomes for a High Road in Energy

Independent of the extent of the high road we choose (or are able to follow), we might define a set of goals:

1. To be relevant to the problem of creating energy solutions.
2. To most broadly understand the issues in creating energy solutions.
3. To be honest, objective, and scientific in our work.
4. To make decisions that are good for the whole earth, rather than ignoring problems our solutions might create.
5. To be the best there is in creating energy solutions.
6. To be the best in fielding energy solutions.

Questions to help Frame a Mission

All questions are focused on quantitative analysis independent of specific “paths.” “Path” could be read as “solution” if “solution” is thought of as comprehensive (or multifaceted).

1. Can we evaluate the *goodness and potential success* of proposed transformation pathways? Our goal here would not be to supply exact solutions or pick precise winners. Rather, it would be to evaluate whether a proposed solution is indeed good or bad and whether it can be successfully actualized:
    a. Evaluate given paths (given scenarios) relative to quantitative *metrics* to see if they move us to where we would like to be (good) and not where we don’t want to go (bad); evaluation of unintended consequences is crucial

2. What are the *metrics* for a successful transformation (defining goodness, badness) of national and international energy system?
    a. How are these *metrics defined at various "scales"* (individual, community, corporation, region, nation, groups of nations linked by treaties or agreements, the globe)?

3. How do we combine metrics at various scales to *evaluate goodness* of a given path? A given path may be good at one scale (say individual) but bad at another (say national). How do we get agreement (scientific and social/political) on what good outcomes would look like at various scales so that we could choose?

4. What is the *range of possible outcomes* from wide ranging sets of possible paths? (from do nothing, to engineered outcomes). Can we find good paths that can be successfully actualized?
    a. Systematically evaluate wide ranging sets of possible paths for goodness, robustness and resiliency; identify critical aspects for their actualization.

5. Can we find *self reinforcing paths* which, once entered upon (or proceeded upon far enough), become inevitable or self fulfilling? THESE ARE THE PATHS TO FOLLOW! What situations are required to set them off?

Example evaluation of two *opposing pathways* to understand the appropriate "mix":

6. How much effort should we dedicate toward *reducing climate change versus adapting to its impacts*? Human civilization grew up during the Holocene, a remarkably stable climatic period. It may be that the issue is not so much inducing a new, warmer, different climate state as it is influencing the climatic variability that is imposed along the way. Because of this variability, the costs associated with adapting to the impacts of climate change may be impossible to even ball park; it isn't the cost of going directly to a "final state". Climatic transitions between glacial and interglacial climates have been found to be characterized as "a flickering switch" as the climate varies rapidly between states during the phase transition before ultimately settling into its new state. "The climate is always changing, sometimes very abruptly, so the last thing that mankind should be doing is adding its own forcing actions — like pumping unprecedented amounts of greenhouse gases into the atmosphere. Because you never know — you never know — what will tip the balance and send us hurdling into another abrupt change ... and into another era."[4]

Example evaluation of a *facilitation device* for evaluation, choice and actualization of pathways:

7. Could/Should there be an institution created, analogous to "the Fed" (which manages the money supply, and indirectly, the economy), that is *politically independent and has*

[4] Tom Friedman citing the opinion of climate change experts.

authority to make and implement decisions? Such an institution would navigate the energy transition. Should this institution be international/global?

Example conceptualization that is possibly *game changing:*

8. Can we create new rights at a global scale that attribute ownership and responsibility for a "commons" that must last into the future across all generations for all time? Through analogy with the "tragedy of the commons" problem (rather a direct analogy at that), we must acknowledge that the highest priority is to focus on ethics, and in particular, transgenerational rights. We must get above the fray of the here and now, business as usual, eye for an eye and tooth for a tooth mindset among those who are currently on the planet. Creation of new transgenerational rights for Climate and resources that are finite (oil) will completely reframe the Energy Mission. See the work of DeCanio[5] and the concept of a Transgenerational Constitution (also referred to in "Design for Crisis" below). Using the current crisis to push this "solution" might have the largest long term payback (greater than an immediate technical discovery that made carbon-emission-free energy free for all and with no investment cost) as it would contribute to the solution of many other global-social problems. Might not this be an area to focus a portion of our effort? SNL has tools and people who can both contribute to and possibly lead quantitative evaluation in this area.

Example evaluation that questions a *fundamental assumption* in the way we live our lives and make decisions for the future:

9. Can there be such a thing as sustainable prosperity in a resource-limited world? Here is where a full evaluation of "Limits to Growth" must be accomplished to understand where effort can be placed to allow development even in context of limited raw materials or resources.[6] What are the true constraints?

Designing for Crisis: a critical component of the "high road"

To find and implement transforming solutions within a CASoS, a pervasive and strong drive is required. The status quo must be broken. In times of relative quiescence, we can think about the design of a smooth transforming course for the future, but such a course is unlikely to be implemented. Friction from the status quo (either a strong monolith or a cacophony of special interests) will dissipate it. A crisis must intervene. When crisis comes, it breaks up established coalitions, forms new one, and imparts a drive that creates pervasive innovation on topics and scales that cannot be predicted before hand. We need this re-organization and pervasive innovation; we must take advantage of it, design for it. As part of this design, we must either enhance the speed of innovation or impart enough inertia to the crisis that innovation can take

[5] "Economic Models of Climate Change, A Critique" by Sephen J. DeCanio, 2003.
[6] An interesting analogy in transcending a resource can be found in the world of money and finance. We once used gold as legal tender, we now have a belief in money that we use for tender instead.

hold before the crisis dissipates. For example, consider the current steep rise in energy prices that we have seen in the past year. The concern for transformative design is not high energy prices, but rather that prices will fall too quickly and the entrepreneurs that invest in innovations will lose their shirts (again). Falls are inevitable because there are so many strong negative feedbacks in energy and energy markets.

The task of policy is two-fold: to channel creative energy (innovation) away from pathways that are “bad” and into pathways that are “good.” Bad and good must be defined and will likely be scale dependent. Something may be good for an individual but bad for a community (i.e., not to the benefit of the whole or create known unintended consequences to others that are bad). Policy should also allow the system itself to find new unforeseen pathways that are not intrinsically bad. But because the system is in crisis mode, these new pathways need to be evaluated quickly to see if they should be pruned. Incentivizing the good requires that good can be determined ambiguously enough that incentivizing it does not obstruct the discovery of new unforeseen pathways that may be better and out compete the incentivized path. Thus, guidance of the CASoS through policy should above all emphasize the pruning of the bad (“drill, baby, drill”). Incentivizing the good, if we could determine “good”, will likely always play a role (given current politics), but it must be done very, very carefully or deemphasized entirely.

To be able to guide the CASoS in crisis mode we need to:

1. build the science of doing evaluation of path
2. build the requisite tools and the groups of people who use them
3. exercise and hone the tools/people

NISAC is an example of where we have tried to implement part of such an approach applied to infrastructure (which if you think about it is really “everything”). In general, it’s an example that “works”. However, recent restricted funding has removed #1, stagnated #2, and focused on #3. By doing this, NISAC stagnates and its ability to design for crisis is being eroded. In our experience, what is transpiring in NISAC is the “natural” life-cycle of such efforts in our current environment of short-sighted, reactionary governance.

In what we have stated above, it is important to stress that we are imposing “command and control” to constrain or guide the system away from known bad while allowing the system itself to find good pathways. Overall, the market is generally efficient at picking winners, but it, too, is imperfect. There is no such thing as an entirely free market; some rules/constraints are always needed. The key is to impose additional/different constraints through policy that help correct for what the market doesn’t do well – namely considering externalities and looking beyond the immediate future. Examples include the inter-generational aspects of climate change and depletion of finite resources such as fossil fuels. Can one monetize that aspect to bring these externalities into the market? Here the issue is one of “rights” for people who are not yet “at the table.” Bringing them to the table might require an Intergenerational Constitution that spells out the rights of future generations, a constitution that the present generation is committed to abide by (DeCanio, 2003, p160).

Defining more General Outcomes where Energy is a Component

The overall outcome should be “self-actualization” at all scales from the individual to the global community of humans on earth. The concept of self-actualization was introduced through the humanistic psychology of Abraham Maslow[7] where he developed it for the individual. We must define it at higher scales and evaluate its metrics. Here is a first shot at the BASIC NEEDS.

- Air, water, food, shelter, sleep, sex, *and energy* for all…
- Safety and security for all
- Peace for all (if all nations were independently “secure” would we have peace? If all nations were inextricably connected through the process of “globalization” would we have peace, at least off the soccer field?)
- Prosperity for all (an end to poverty)
- Opportunity for all (to improve their standard of living, to move up Maslow’s hierarchy of needs and become self-actualized)
- Equity across humans now and into the future (geopolitical and transgenerational ethics)

While we might try to order these in terms of priority, they are all inextricably intertwined: all are required to enable movement up the hierarchy to *growth needs* and on to *self-actualization*. Further thought along these lines (defining Maslow’s hierarchy of needs at a variety of scales) we believe would be very fruitful to set the Energy Mission in context of a much greater whole.

A General CASoS Engineering Framework

Engineering within CASoS spans a wide functional space. CASoS are *complex*, often complicated, large and irreducible; their dynamics have a wide range of time scales. As a result, interpretation and quantification of the impacts of modification are difficult; these systems are *adaptive*, often hysteretic and/or recursive, so building understanding through testing is difficult because repeatable initial conditions are generally not possible and simultaneous tests are often not independent. Additionally, many critically important CASoS are *socioeconomic-technical* in nature, so a wide range of “physics” apply that must address technical concerns, economic concerns, political concerns, and the interface between. Because socioeconomic-technical CASoS embed people, experimentation within them is risky and costly, often leaving modeling as the only practical option. All these factors encourage widely different opinions on what the problems are, how big the problems are, and how to go about solving them.

As engineers, our Aspirations *are to influence* (design, control, manipulate) CASoS to solve problems, exploit opportunities, and/or achieve goals. A focus on Aspirations breaks us out of the endless cycle of leaning more and more about the details of individual CASoS. Aspirations fall into a set of clearly identified categories: Predict; Prevent or Cause; Prepare; Monitor; Control; and Recover or Change. Within each category, three sets of similar questions naturally emerge that encompass: *Decision*, determining *Robustness of Decision*, and *Enabling Resilience*. In context of socioeconomic-technical CASoS, all of these *Inform Policy*. Through such systemization, we argue that the requisite theories, technologies, tools, and approaches for

[7] For a good discussion of Maslow’s concepts of hierarchy of needs and of self-actualization see Frank G. Goble’s book “The Third Force, the Psychology of Abraham Maslow”, 1970.

Aspiration-focused CASoS Engineering are similar across many CASoS and can be organized within a *CASoS Engineering Framework.*

A general *CASoS Engineering Framework* must be wide and deep to cover the many potential opportunities for unexpected, nonlinear, interconnected behavior. We envision the framework to contain three phases applied primarily in succession but with some overlap and blending to deliver CASoS engineered solutions:

4. **Defining** (blackboard to details) 1) the CASoS of interest, 2) the Aspirations, 3) Choice of Aspirations based on constraints and impact, 4) Choice of appropriate methods and theories from the full space of those possible based on Aspirations chosen, 5) Appropriate conceptual models, and 6) Required data to support conceptual model development and validation. Possible methods, theories and fields of contribution include analogy, dimensional analysis and similitude, experimental design, system dynamics, non-equilibrium thermodynamics, complex adaptive systems, game theory, percolation phenomena, agent-based modeling, networks, system optimization and control, and many others.
5. **Designing and Testing Solutions** using computational models, data mining/integration, experiments, etc, within a common quantitative analysis environment. Designing and testing solutions will be problem-dependent, it will focus on answering the three general sets of questions relevant to any Aspiration: 1) What are *feasible choices* within the multi-objective space, 2) how *robust* are these choices to uncertainties in assumptions, and 3) what are the critical enablers that increase system *resilience*. Included in this process is the delineation of unintended consequences and their amelioration/mitigation.
6. **Actualizing** the engineered solutions devised above within the real system. The engineered solution may be a concept, a computational tool, a sensor, a control policy, etc. This activity involves working with decision makers (change the world), other researchers (change the field) and people affected by the change (understand the impact). This involvement requires a long term commitment: these are high-consequence systems that adapt to change. Any change makes us part of the system with concurrent obligation through a solution's lifecycle.

As in classical engineering, iteration and blending among the phases is intrinsic. Actualization will require designing and testing to suggest future steps, and adaptations of the system might require us to return to fundamental thinking to understand the adaptations and possibly reformulate our Aspirations as the system changes.

Evaluation of Energy Plans

One of the most pressing needs to engineering better solutions to the GES, is a means to evaluate the myriad of energy policies being proposed for the GES. A great deal of effort is focused on generating solutions with all kinds of claims that one has found the "right" answer. But without a clear "apples to apples" evaluation criteria for these solutions, companies, consumers, and governments have little to go on but hunches on what they think will work (politics plays a huge role in what gets adopted). A very useful tool that Sandia could develop is to provide a complete system-wide (e.g. GES) evaluation of the impacts of various proposals. The impacts would look at technical, economic, social, and political aspects of these proposals. The goal is not necessarily to pick the "right" answer but rather to see how many different options impact the

GES along with their unintended consequences. Such a tool would require CASoS engineering techniques to create. It will also help policy makers evaluate solutions before committing huge resources and time on questionable policies. Of course, policy makers will have other criteria that we may not put into the tool in how they make their decisions. But at least, they could be warned as to what might go wrong. But how can the vitality of these plans be evaluated?. That's where Sandia can help. This does not mean that Sandia can't propose its own plan(s), but it is helpful for us to produce the tools to evaluate proposed plans. This would include the evaluation of the consequences of plan adoption both intended and unintended. Towards this end, there are 6 key priorities to consider in the evaluation of GES energy plans (in no particular order).

- Markets
- Scale of the GES problem
- Lessons learned from the past
- Apples to Apples comparisons
- Necessary Infrastructure to deliver the energy solutions
- International (e.g. nation-state) consequences

Starting with markets, one must evaluate whether a plan is realistic from a market adoption standpoint. This does not mean that the market is ready for the plan now. But one must ask how much government assistance is needed to get the plan adopted by the global energy markets. Too much government help and long term assistance (e.g. taxpayer help) may not be a good investment if it can't stand on its own in the marketplace. Likewise, there may be societal benefits to some plans that do require longer term government help that would be worthwhile to the taxpayers (Example: Carbon Market or Tax). Sandia can assist in this analysis by looking at market economic simulations for a particular plan.

When proponents of a particular energy plan state their case, it is often true that the proposed energy solutions are far from capable of producing the amounts of energy needed nationally let alone globally. The sheer scale of the GES makes it unlikely that new energy choices can be scaled up quickly, if ever. Thus, it is important that one evaluate how much energy is being supplied now by current sources, and what it would take to replace these sources with up and coming candidates. Further, one must consider that energy demand is likely to increase steadily worldwide due to economic development and increasing reliance on new technology, much of which relies heavily on electricity. Some of the renewables (e.g. wind, waves) will be hard pressed to produce more than a couple percent of the needed power. This does not imply that they are not important. They most certainly are. But one has to be realistic about how soon they can replace current sources (e.g. wind for gas-fired power plants), if ever. Another problem is that some energy choices would require large quantities of a scarce material in order to be implemented on a large scale. This might make some energy ideas useful on a smaller scale but not on the large scale being proposed unless some basic materials problems are solved.

Some energy plans are mere variations of old ideas. Again, this may be appropriate considering new technology and new discoveries. But, it is also worthwhile to ask why the old plans were not adopted or why they didn't work, and what makes these new plans different. It may be well worthwhile to pursue them, but be sure it is in the context of understanding what has worked in the past, what hasn't, and why.

One of the biggest problems in evaluating energy ideas, is that it is difficult to determine the economic and environmental impact of a new energy plan. That is even true for existing energy sources. For instance, the economic benefits of biofuels have been difficult to determine. Although, it can replace imported oil, it does require the production of more crops which use scarce resources such as water and natural gas-based fertilizers. A complete life cycle cost analysis of any energy idea is needed to compare the benefits of one energy choice to another. Some choices may appear to be more cost effective, but are propped up by tax credits and government subsidies where other choices may not be. Equally as important is the analysis of environmental impact. Though coal generated electricity is fairly inexpensive compared to other generation means, it does carry a high environmental cost. Its carbon output can be measured. Other environmental costs such as damage to land in its extraction, may be much harder to quantify. But a tool to do such analysis is needed and currently missing. Pieces of such a tool do exist and are used by electric utilities in deciding what new plants to build. But for transportation energy, the analysis is not as far along. Sandia can assist in developing such tools which would help policy makers decide on what energy choices are good taxpayer investments.

The delivery of an energy plan is very important. Many good ideas on electricity generation fail to account for the lack of transmission capacity. Conversely, this may argue for an overhauling of the nation's electric power grid. Energy choices that alleviate the need for a large overhauling of the power grid should also be considered. Likewise, in transportation energy, the delivery of these fuels to dispensing stations that are conveniently located has hampered the development of the so-called Hydrogen economy. The need for infrastructure development must be included in the evaluation of any energy plan as well as the understanding that the building of new infrastructure such as pipelines and overhead transmission lines has a strong NIMBY component that may force non-optimal implementation from a technical standpoint.

Finally, international consequences of energy choices must be considered. The world's dependence on petroleum has resulted in a large wealth transfer from oil importing nations to oil exporting nations. This alters the balance of world power and most definitely drives military doctrine for the U.S. and much of the rest of the world. It is important to consider, how this dynamic might change depending on new energy scenarios. Which countries would benefit, which countries would suffer? What effects would this have on U.S. foreign policy, and how would our allies, trading partners, and enemies react over time? The analysis of balance of power is key in any consideration of new energy plans. Of course, this would be mostly hypothetical as actual energy adoption may be a hybrid of several plans, but it is a good idea for policy makers to be aware of potential consequences of new energy choices. What new material will be key? What countries have this material? Will the withholding of this material cause economic chaos? How can this be mitigated? What impact is global climate change going to have on energy supply and availability? These are some of the questions that need to be addressed in such an analysis.

APPENDIX F: THOUGHTS ON FOLDING CLIMATE INTO THE GLOBAL ENERGY SYSTEM CASOS

The evidence strongly supports the anticipation of societally-important climate change on a time scale of decades, driven primarily by the accumulation of greenhouses gases in the atmosphere and human-caused change in the surface optical characteristics of the planet (deforestation, desertification, etc).[8] Those changes will have a major influence on the economic as well as the physical environment going forward[9], and will impact decision-making about national security and many other aspects of society[10]. The issue facing us here is how to incorporate anticipated climate change and its impacts into a GES CASoS in an interactive way – that is, so that influences can flow back and forth between the climate system and other relevant elements of the GES. We review the options.

The most straightforward and, in principle, most desirable option would be to run a well-validated Atmosphere/Ocean General Circulation Model (GCM; or Global Climate Model) at an appropriate resolution interactively as part of a system of models representing the GES, incorporating feedbacks between the modeled climate and other elements of the GES. However, AOGCMs are extremely computationally intensive. Non-interactive AOGCM runs covering a century at useful resolutions typically take weeks to months on the largest computers. However, computers are getting bigger and faster all the time, and techniques are being developed to make better use of their size and speed for climate modeling.[11] In the longer term, this approach will likely become viable. In the near term, however, there are much simpler climate models which could play that role for now.[12] Unfortunately, the results are not likely to be sufficiently detailed or accurate for policy making. For example, Radiative –Convective models are readily available, but typically provide no geographic resolution – the earth is treated in one dimension (height) only. There are also Energy Balance Models that provide a two dimensional description (height and latitude), but these are clearly inadequate for policy making as well. Nevertheless, these simpler climate models could provide some insight as to how specific policy options might interact with climate. They have the advantage of being available and usable now.

One potential intermediate term approach that may be sufficiently accurate to be useful for policy making is to parameterize the output from the ensemble of models run for the IPCC Fourth Assessment Report (FAR) over the range of GHG emissions scenarios used therein so as to create a relatively simple, deterministic (or probabilistic) interactive climate model based on existing AOGCM output. Creating a parameterized interactive 4D climate model from the existing IPCC model output would likely be very challenging, but it may be the only viable option in the intermediate term for credibly dealing with climate in the GES CASoS.

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[8] Intergovernmental Panel on Climate Change, Climate Change 2007: Working Group I Report “The Physical Science Basis”; Working Group II Report “Impacts, Adaptation and Vulnerability”; Working Group III Report “Mitigation of Climate Change”; http://www.ipcc.ch/ipccreports/assessments-reports.htm
[9] Stern, Nicholas, *The Economics of Climate Change*, *The Stern Review*, Cambridge (2006
[10] CNA Corporation, *National Security and the Threat of Climate Change* (2007); http://securityandclimate.cna.org/.
[11] Mark Taylor, private communication
[12] W.A. Robinson, *Modeling Dynamic Climate Systems,* Springer, New York, 2001; K. McGuffie and A. Henderson-Sellers, *A Climate Modeling Primer, 3rd Edition,* John Wiley, West Sussex, England, 2005.

A major difficulty would arise in the suggested intermediate term approach if the actual emissions scenario that plays out is not spanned by the range of emissions scenarios for which the ensemble of AOGCM model output is available. In fact, this is already happening. Global GHG emissions are already exceeding the most pessimistic "business as usual" scenario for which the IPCC models were run. However, in the near term, we have probably not so greatly exceeded the range of existing emissions scenarios that extrapolations are meaningless. For the future, the IPCC models can be run for additional emissions scenarios. In fact, given recent experience, it seems likely that this will be done for the IPCC Fifth Assessment Report, due out in about 2012. Furthermore, the models used for the next IPCC report are likely to have been improved in many ways over those used for the FAR. So shifting the basis of the intermediate term model to the newer AOGCM model outputs as each successive IPCC report comes out makes good sense.

A more fundamental difficulty is that the existing ensemble of IPCC models very likely do not contain all the physics, chemistry and biology necessary to make accurate long-term climate predictions. There are likely to be "black swans" – climate phenomena and/or climatically-relevant events the occurrence and/or importance of which are largely or entirely unanticipated, and hence not adequately reflected in the models[13]. There are already a variety of such potential black swans under discussion – tipping points for global climate that could greatly accelerate (or possibly retard) the rate of change. Possible slowing of the thermohaline circulation is a potential black swan; another is the possible release of massive amounts of methane from the warming of the tundra and/or from the breakdown of methane hydrates. A third might be a return of a period of slightly lower solar radiative output such as occurred during the Maunder Minimum, believed to be responsible at least in part for the Little Ice Age.[14] There are numerous rapid and dramatic changes in global climate reflected in the paleoclimate record, most of which were caused by phenomena that have not yet been convincingly identified. The Holocene (the period since the end of the most recent glacial period which spans the entire history of civilization) appears to have been unusually climatically quiescent[15] for reasons that remain the subject of speculation. Impact of unusually large meteors, massive volcanism, and changes in the circulation of the oceans may all have been causes of rapid climate changes in the prehistoric past, as may other events not yet even suspected.

So, even given future emissions scenarios, our ability to predict future climate is limited. None the less, existing capability is likely useful for policy making. As has been pointed out,[16] there is reason to believe that the uncertainties in climate impact projections are asymmetric. For any given GHG emissions scenario, minimum impacts can be predicted with substantially greater confidence than maximum impacts. So for any GHG emissions scenario, there is greater risk for under-prediction than would be the case if the uncertainty were symmetric. This is yet another reason that risk minimization requires holding GHG emissions to the lowest feasible levels.

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[13] N.N. Taleb, *The Black Swan, The Impact of the Highly Improbable,* Random House, New York, 2007.
[14] Wikipedia, Maunder Minimum
[15] R.B. Alley, *The Two Mile Time Machine, Ice Cores, Abrupt Climate Change, and Our Future*, Princeton Univ. Press, Princeton, NJ, 2002.
[16] G.H. Roe and M.B. Baker, "Why is Climate Sensitivity so Unpredictable," *Science* 318, 629 (26 October, 2007).

Taking into account the influence of climate on other elements of the GES (global and regional economies, for instance) and vice versa will not be straightforward either. However, a start has been made upon which one can build.[17]

[17] Stern, Nordhaus

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