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Toward an Energy Surety Future

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Toward an Energy Surety Future

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Abstract

Because of the inevitable depletion of fossil fuels and the corresponding release of carbon to the environment, the global energy future is complex. Some of the consequences may be politically and economically disruptive, and expensive to remedy. For the next several centuries, fuel requirements will increase with population, land use, and ecosystem degradation. Current or projected levels of aggregated energy resource use will not sustain civilization as we know it beyond a few more generations. At the same time, issues of energy security, reliability, sustainability, recoverability, and safety need attention. We supply a top-down, qualitative model—the surety model—to balance expenditures of limited resources to assure success while at the same time avoiding catastrophic failure. Looking at U.S. energy challenges from a surety perspective offers new insights on possible strategies for developing solutions to challenges. The energy surety model with its focus on the attributes of security and sustainability could be extrapolated into a global energy system using a more comprehensive energy surety model than that used here. In fact, the success of the energy surety strategy ultimately requires a more global perspective. We use a 200 year time frame for sustainability because extending farther into the future would almost certainly miss the advent and perfection of new technologies or changing needs of society.

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I. INTRODUCTION

Energy surety is an approach to an "ideal" energy system that, when satisfied, enables the system to function properly while allowing it to resist stresses that could result in unacceptable losses. The attributes of the energy surety model include safety, security, reliability, recoverability and sustainability.

One way to gain insight into energy surety is to study the thermodynamic limitations imposed by well-established physical principles. Seeking sustainability changes the energy perspective from a "scarcity mentality" to one motivated by an "abundance mentality" that seeks to supply energy requirements without damaging the natural environment that supports humanity. The scarcity mentality underlies conventional supply-and-demand economics, and also underlies the philosophy that limiting use will stretch the supply of resources to sustain us. The abundance mentality must include efficiency and conservation, but it also aims to provide as much energy as is required for a prosperous existence. It does so in a responsible manner, making the best possible use of exergy resources, and not necessarily taking the path that would be dictated by purely economic motives. Some regulations and incentives might be used.

From a thermodynamic point of view, sustainability can be described as continuously being able to match exergy sources with exergy needs. Exergy is energy available to do useful work, considering the energy available from a given source within its particular environmental surroundings[1]. Giving full consideration to exergy use includes choosing the best mix of fuels, and applying conservation principles to all steps, starting with energy production and ending with final use, even utilizing what would normally be characterized as waste heat and mass. A high-exergy fuel is optimal for conversion to electricity, while a low exergy fuel might be used for space heating, for example. The optimal exergy solution may not always be the most satisfying economic solution.

This supply-demand matching, if it is to be done without disrupting environmental features valued by society, requires closing the energy cycle by managing emissions and other activities that interfere with the environment. Emissions, water use, and land use changes can adversely influence sustainability and social equity. Matching also requires that we utilize current exergy sources in ways that allow seamless movement toward using other new exergy sources as current ones grow scarce.

Energy is a component required for fulfilling nearly all needs for sustaining society, but much energy is wasted, and little emphasis is placed on guaranteeing sustainable energy supply and on using energy sources to their fullest advantage. To emphasize the need to better appreciate the sustainability aspects of energy, the term exergy is used almost exclusively. The reader who may find that term difficult should recognize that when energy available from any source is

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[1] Exergy is a measure of the usefulness of a unit of energy. The word comes from the Greek elements "ex" meaning "out of" and "ergon" meaning "work." So, exergy means the fraction of the total energy that we can extract to deliver as work. Exergy can also be viewed as energetic order, ordered energy or available energy. It is also important to note that energy contains exergy only when that energy is out of equilibrium with its surrounding environment. For additional insights on exergy, see references [1] and [2].

being utilized to its full advantage, no exergy is wasted. Energy and exergy are often interchangeable in this report. *The working definition is that exergy represents the maximum beneficial use available from an energy source, given the surroundings.* As an example, the exergy available from a given fuel may be greater in a location where plentiful cooling water makes it possible to generate electricity more efficiently. If the waste heat can instead be used for space heating or as part of an industrial process, even greater exergy might be available. What is lowest cost may not best conserve resources, and some advocates of imposing exergy-based mandates propose using taxes or financial incentives to maximize the best use of exergy. This report does not discuss the merits of such measures.

Applying these insights to the U.S. exergy infrastructure suggests several steps in a path toward exergy surety. A national goal should be to use our understanding of exergy to slow the trend of depleting the earth's available limited fuel supplies and to accomplish two other important goals: (1) close or manage the cycle of emissions from energy conversion and reduce the magnitude of such emissions by applying exergy analysis and (2) make possible the use of on-demand exergy resources by future generations. This second goal would use more processes with persistent sources (solar; wind, nuclear—with fuel enhancement such as reprocessing and breeding; geothermal; tides; and coal with sequestration[2]). Fully accomplishing these goals may not be possible, but striving toward them is far better than blindly marching toward energy depletion, environmental exhaustion, and esthetic despair, only to discover that the scarce remaining resources are inadequate to produce the required new infrastructures.

Examining current and future energy options from a surety approach provides some interesting insights and provides one way to understand energy challenges in an uncertain and changing world. A complete application of the surety model can only be valid if all the components of the system (including the earth and biosphere) are understood and quantified. This may be possible in the future as knowledge of the earth's complex systems advances. The attributes of sustainability are complicated, multidimensional, and deserving of additional study, including relationships between exergy usage and population growth.

This report argues that sustainability can be achieved up to some limiting carrying capacity of the U.S. and the world, but carrying capacity also includes some assumptions about living standards, social equity, esthetic expectations, and desires of mankind. The limiting carrying capacity depends upon available exergy supplies and our wiser use of them, including the exergy content of waste streams, but there are other limits based on available land and environmental factors, even if environmentally acceptable exergy supplies are without limit. In other words, if humankind becomes more symbiotic with the earth, future generations will enjoy the same prosperities that we enjoy today. Finally, several aspects of the surety approach warrant additional discussion and study.

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[2] At current use rates, coal use may be sustainable for more than the 200 year time frame we set here. (The Energy Information Administration notes that reserves were sufficient for 250 years.) With that assumption, and also assuming that coal use includes sequestration of carbon dioxide emissions, we include it in the sustainable fuel category, but we recognize that this categorization is debatable. More recent estimates of coal supply at current use rates indicate that the US may have as much as 450 years of reserves [Max Valdez, Sandia National Laboratories, private communication]. See reference [EIA, 1995, Coal Industry Annual, 1994 US Department of Energy Annual report, DOE/EIA-0584 (94), 265 p.].

II. BACKGROUND AND OVERVIEW

Global energy challenges for the mid-term (5–20 years) and the long-term (20–200 years) are different. In the near term, large, growing economies such as China's and India's are expanding their roles in the global economy and are consuming energy at an increasing per capita rate. This means increased competition for materials and energy as well as likely increased pollution of the environment.

In the mid-term, depletion of oil and natural gas[3] may reduce supplies and threaten the global economic expansion. For transportation—which is almost exclusively dependent on oil—the crisis may occur well before most people have anticipated. Potential negative consequences to societies worldwide could be unprecedented. For the U.S., transportation is key to the current way of life, so a fuel disruption would severely impact the economy. Potential consequences may be even more detrimental because oil and natural gas are currently the preferred feed-stocks for most of the chemical industry. Substitutes can be manufactured from coal but are more costly, and if coal were to be used to make synthetic liquid fuels, the sustainability of coal supplies would diminish, and carbon emissions would rise, presenting more need for sequestering or reprocessing emissions.

A re-invigoration of the nuclear fission industry is expected, along with renewed interest in clean coal, renewable and other solar-based energy production mechanisms (hydro, thermal solar, biomass, photovoltaics and wind), and geothermal and tidal energy. A key question for fixed-site energy production is if/when nuclear fusion, which would mimic the processes of the sun using earth-based light isotopes, will become available at costs competitive with various nuclear fission approaches. Fusion could, in principle, avoid many of the contentious waste-management problems of nuclear fission while at the same time posing a much smaller physical footprint than renewable energy production technologies with lower outputs. However, tritium inventory and fusion's neutron-rich environment pose potential weapons proliferation and radioactive materials-management and disposal problems.

Uncertainty in a continually changing environment makes it difficult for analysts to recommend or influence policy to achieve acceptable futures. A few of these uncertainties are depicted in Figure 1. Note that many of the factors in Figure 1 are interdependent, though these interdependencies are not illustrated here. For example, the availability of fossil fuel and the type used influence how much carbon dioxide is emitted. Also, the amount and distribution of energy to poorer nations has been shown to influence birth rates. Other uncertainties include climate responses[4] to CO_2 production; future exergy demand; fossil fuel depletion rates; and

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[3] In the 1960s, U.S. geophysicist M. King Hubbert correctly predicted the peaking and subsequent decline of domestic oil production. Others predict a "Hubbert peak" and subsequent decline for worldwide oil production, see reference [3]. By one estimate, production will decline to 1950s levels by the turn of the century. However, the use of new technologies for exploration and production could effectively modify such predictions.

[4] A major factor controlling whether the earth is in an Ice Age or a warmer, inter-glacial period, that we are arguably currently enjoying, is full functioning of the Great Ocean Conveyor (GOC), a global system of ocean currents carrying solar heat from equatorial to polar regions. Previous Ice Ages have correlated to abrupt disruption of the GOC. Climatologists fear increased man-made CO_2 production can disrupt the GOC, sending the world prematurely and rapidly into another ice age. See references

expectations for developing persistent, exergy production mechanisms that could complement fossil fuel supplies. What is needed to support such analyses is a dynamic surety model incorporating metrics that can evaluate and discriminate among alternatives for sustainable futures. We recommend using a 200 year time frame for sustainability because extending farther into the future would almost certainly miss the advent and perfection of new technologies or changing needs of society.

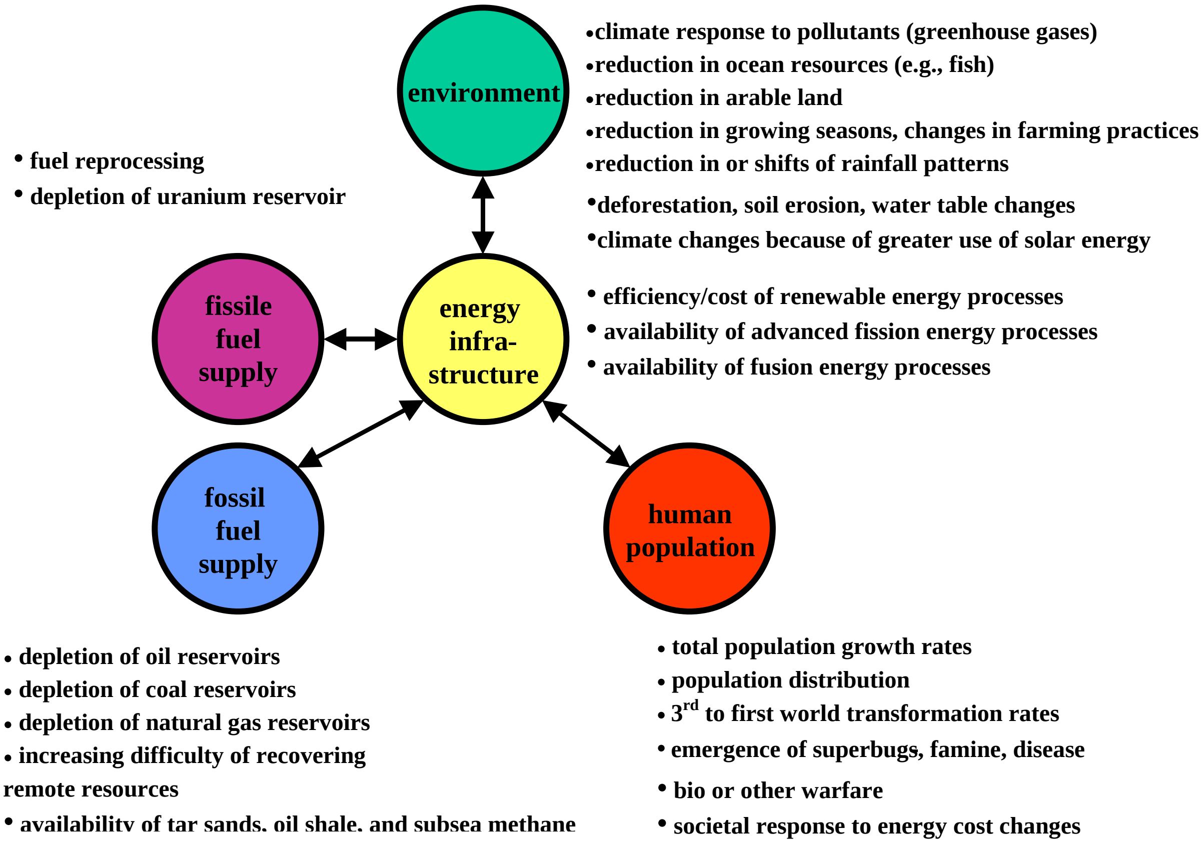

Figure 1. Uncertainties affecting energy futures.

There are three considerations related to the quest for maximum thermodynamic sustainability:

1. An exergy surety plan must include some estimate of consumer needs and capacity for using exergy. The traditional view of an expanding world population and economy must at some point level off, or it could surge to the point of resource exhaustion, social upheaval, or disease epidemic, and then collapse.[5] An ultimate energy surety plan must have at its core some international commitment to hold growing populations in check; without this measure,

[http//www.sspi.gatech.edu/weatherchg.pdf or http//news.nationalgeographic.cm/news/2005/06/0627_050627_oceancurrent.html.].

[5] For an interesting perspective on the issues of societal success and collapse, the reader is referred to Jared Diamond's two books that examine the contributing factors to such over thousands of years, see references [8] and [9].

no technical solution can be assured. Science cannot solve sustainability issues without help from world leaders in managing the overpopulation question.

2. The use of fossil fuel resources must be considered as limited, although the magnitude of potentially recoverable fossil fuels may never be precisely known. Fossil resources may be treated as a capital pool that allows us to transact the business of society in the near term, and which forms the basis for constructing the energy systems needed for the future. Conservation methods to save resources may also draw on this capital (construction of more efficient generating plants, projects aimed at improving the environment, etc.), and conservation may itself serve to reduce stress on this capital, but conservation alone is not sufficient. Conservation employs principles of reducing exergy expenditures. Exergy, as noted, is a concept that challenges societies to obtain the maximum benefit from any energy resource, and this includes optimizing the match of available energy sources with specific applications using the energy. In other words, if one carries out efficiency measures to the extreme, considering all aspects to wring out the most benefit from available energy sources, and considering what is possible, given the surroundings (surroundings include such factors as availability of cooling water, uses for water heat to be used for heating buildings, etc.), then exergy use will be optimized.

3. Because of the reliance on the use of fossil energy, changes in the environment could threaten the surety of the system. For example, carbon dioxide emissions have to be managed, as well as other factors that could trigger environmental changes that would spoil sustainability. For example, building roads, damming rivers, converting natural terrain into farmland, cutting down forests, and irrigating land are all activities that have potential for driving climate changes. A complete and comprehensive view of climate change and issues is not possible here, but some of the uncertainties are identified. These uncertainties make it impossible today to apply the surety model to energy systems and the environment with the highest degree of confidence. However, understanding the uncertainties should lead to development of options and contingencies that provide the best opportunities for a sustainable future. See Appendix C for a discussion of some features of climate science and the need to manage other factors in addition to carbon dioxide.

The goal of a thermodynamic sustainability model is to understand what exergy practices can best answer our current needs, while not compromising opportunities for future generations. Thermodynamic principles are used to convert as much as possible of the available heat or chemical energy in a fuel into desired end results; this lightens the anthropogenic footprint. In the usual engineering context, the costs of extracting more value from the available energy of fuel is traded with the costs of higher efficiency technology and the cost of capital for implementation. Capital expenditure often implies more up-front energy use to build facilities, and this one-time energy expenditure must be included in the bookkeeping. Appendix A contains an example that illustrates some of the trade-off considerations.

There is already some regulation and accepted methodology in place to assure that the decisions made are in the best long-term interests of society. For example, the Energy Star program and lighting standards place ratings or requirements on appliances and certain lighting fixtures, and fuel efficiency standards set limits on fleets mileage for the automotive industry. These simple programs aimed at the consumer, who may not have the tools and understanding to make detailed analyses, work well, and the energy savings are impressive.

Regulations aimed at saving exergy have to be very carefully crafted to achieve the desired goal. An example of a simple regulation proposed by some exergy proponents to move in the right direction would be to provide incentives to encourage using the most appropriate fuel matched to a given application. For example, with current technology, when compared to coal, one can convert a larger fraction of the energy available from natural gas into electricity, and based on an exergy analysis, the use of gas for electric generation should be incentivised. However, as a matter of economics and fuel availability, such incentives would not make sense.

The optimal solution gets more complex because it is very convenient to use natural gas to heat water and homes, but using natural gas to produce electricity that would, in turn, perform the same heating function is decidedly less efficient. However, if there were economic means to produce electricity and, at the same time, obtain other value from natural gas combustion in a combined heat-and power unit for home use, utilizing the otherwise wasted heat to warm homes and to provide hot water, exergy use could be maximized. There are some devices on the market that accomplish this exergy-saving goal, but the costs and/or operating complexity are currently too high for widespread domestic application, and more work needs to be done to couple such devices to the power grid to achieve full benefits. We already have some installed capacity of combined heat and power systems in apartments and business complexes, some many decades old.

There is no doubt that the exergy concept has proven merit and was practiced even before the term exergy was coined. Note that a full exergy analysis must take into account the cost of resource extraction, processing, transportation to the point of use, and waste disposal. In some cases, economics will self-select the optimal use of fuels, but this is governed by factors beyond exergy, such as ease and cost of extraction and transport and the cost of capital. Regulations requiring exergy analyses before building permits are issued could help to close the energy-biosphere cycle by getting the most value per unit of fuel consumed, and this increases sustainability. Already, many communities require building window area and insulation analysis as part of the permitting process, so this suggestion is not particularly radical. The extent to which regulation can be effectively applied needs careful consideration. For example, if regulations were to require extensive costs associated with energy use in a new building, that has a short service life, more exergy might be invested in the construction process than would be saved over the life of the project. It is not always possible to have the necessary data available to conduct an exergy analysis in a rapid changing society.

III. THE ENERGY SURETY MODEL

Ideally, engineers and economists working together can articulate the characteristics of a dynamically optimized energy infrastructure, and the next step would be to convince the users and politicians to act on the findings. Optimization would include attributes of *safety, security, reliability, recoverability,* and *sustainability* (all of which can be translated to economic units[6]) while striving for a robust system. These attributes must be understood, measured, and traded off among each other to find a desirable future end state or point of optimization for the world as now envisioned. Of course, as events unfold and time passes, one would expect adjustments and new optimizations and if done properly, the energy infrastructure would be dynamically optimized.

The Surety Model Concept

Surety is a collection of system attributes that allows a system to function properly while resisting stresses that could result in unacceptable losses. Surety in the energy context differs from the more conventional definition of "certainty" or an absolute guarantee. Approaching certainty is desirable, but is not often affordable because absolute reliability is too costly.

Surety comprises several interdependent elements that describe the features of a system. Several elements relate to functionality, and others relate to prevention or containment of loss. Functionality elements include reliability, availability, maintainability, affordability, reconstitutability, recoverability, and durability. (Sustainability is implied in the larger sense.) Loss-control features include safety[7], security[8] and emergency response measures. Systems subject to high-consequence losses must be designed, manufactured, emplaced, and operated to have verifiable and acceptable surety.

A key element in providing surety is the limit on available resources. Resources comprise not only the fuel and the infrastructure for beneficially using the energy from the fuel, but also the responses to the environmental consequences of these activities. This limit spawns the need to allocate scarce resources and the need to accept some risks. Because limited funds generally do not allow full prevention or mitigation of every risk, some so-called "residual" risks (risks that remain after the expenditure of funds) must be acknowledged and accepted by system managers. Small systems can be designed and certified to a high level of surety because it is possible to identify all possible failure modes, and to thoroughly understand all interactions between the

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6 For a description of several approaches for translating sustainability concepts into economic terms, and emphasizing the ethical and moral issues involved with using some of the resources available to present generations to protect and serve the needs of future generations, see reference [5]. This report was a result of two organizations, Resources for the Future and the Stanford Modeling Forum, convening a group in 1996 to explore the issue of discounting (a technique used by economists to compare present with future costs and benefits on an equal basis.)

7 For our purposes, a safe system is one that is robust to inadvertent stresses like human error, accidents, aging or other natural disruptions.

8 For our purposes, a secure system is one that is robust to malevolent stresses like terrorism, vandalism, theft, or intentional disruption.

elements that comprise the system. This is less true of large systems because the interactions between various subsystems become too complex to model thoroughly.

> **Surety Definition:**
>
> Surety is an approach that blends risk analysis and engineering to
>
> • Assure performance in intended environments,
> • Reduce or eliminate the possibility of failure under any foreseeable circumstance, and
> • Manage the consequences of unintended events.

The Nuclear Weapons Example

Of what value is a "surety model" to system owners? The value lies in maximizing confidence that the system will continue to function without unacceptable loss. We illustrate the surety model by describing the system for which it was developed (nuclear weapons), which demanded a very high level of surety and a formalized approach for its attainment. Obviously, as a high-consequence system, U.S. nuclear weapons require a firm basis in surety. Some of the system needs or outcomes are described as "must-have/must-not-have" attributes in Table 1.

Table 1. Surety Requirements for U.S. Nuclear Weapons

Must-Have Attributes	**"Must-Not-Have" Attributes**	
reliably function when authorized and delivered	prematurely detonate in accident environments	be too difficult to recycle at end of life
maintain required shelf life with a minimum of maintenance	be subject to use by unauthorized persons	be overly consumptive of radioactive materials
require infrequent testing	disperse radioactive materials in a fire	contain excessive quantities of hazardous chemicals
resist enemy countermeasures	suffer unacceptable age-related degradation	pose unacceptable hazards to custodians

Surety requirements for the entries in Table 1 are partly qualitative and partly quantitative. The most important requirements tend to be quantitative (e.g., reliability and resistance to unauthorized or unexpected activities) and performance based, as opposed to prescriptive. Furthermore, detailed descriptions of stress environments accompany the requirements. Examples are vibration spectra for flight environments and temperature profiles for credible accidents such as fires. As shown later, this seemingly esoteric example can be used to guide surety considerations for more general cases, including energy production and distribution systems.

Defining Surety Model Requirements

A comprehensive and well-crafted set of requirements is essential for a high-surety system. Such requirements drive systems that are comprehensible and thus analyzable.[9] Comprehensibility, in turn, demands simplicity of architecture, limits on functional complexity, and reliance on interdependent sets of positive measures. It is this requirement for simplicity that makes it difficult or impossible to use the word surety in its true sense when considering a complex system of many energy systems coupled with an environment that is even more complex. For designed systems, such as weapons, the system is intentionally reduced to easily understood functional requirements so that surety can be designed into the system. There are significant challenges in making a similar adjustment to a complex natural system, such as the climate. This brings attention to one limitation with the surety approach—we can define features for a model system that strives for surety only to the extent that we can understand the model.[10]

Within the context of the nation's energy situation, the generalized definitions of surety are placed into an energy infrastructure context. Thus, Table 1 has been modified to be more specific to the needs of an energy infrastructure as shown in Table 2. One important constraint in the energy infrastructure is affordability.

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9 In our opinion, most large, existing systems (e.g., an older chemical plant) are not practically analyzable with high confidence—as a system—because of their great complexity and highly evolved and interconnected nature. Therefore an analyst will not only have trouble quantifying how often known failures can occur, but may also fail to recognize certain failure modes entirely.

10 For example, incomplete knowledge of the physical principles that determine climate change may limit the ability to design energy systems that place any guarantees on climate outcome. (See Appendix C for additional data on climate.) However, there is an understanding of many of the energy systems currently in use and this understanding allows informed trades between cost and reliability, and at least, short-term projections of fuel availability and cost.

Table 2. Surety Requirements for the U.S. Energy Infrastructure.
(Note that it has global interdependencies.)

"Must Have" Attributes	**"Must Not Have" Attributes**	
function reliably and continuously for long periods (decades) under uncertain and changing conditions	be too easily sabotaged	be too difficult to recycle at end of life (rely solely on the biosphere to close the cycle)
require a minimum of maintenance, testing and calibration	distributed, interconnected units must not be subject to propagating failures	suffer catastrophic damage when subjected to credible abnormal environments (e.g., earthquake, flood)
be economical to build, maintain and operate	be harmful to wildlife or the environment	be so complex or poorly documented that surety analysis cannot be done with confidence
resist environmental stresses (corrosion, fatigue, etc.) or be designed with planned obsolescence within a closed cycle system	suffer unacceptable age-related degradation over the designed lifetime	pose unacceptable hazards to custodians or bystanders
be available to deliver energy when needed at a predictable price (have excess capacity for adaptability)		

An example of applying the surety approach to a specific energy system component (in this instance, a river lock admitting a gasoline tanker) is summarized in Table 3.

Table 3. Application of Surety to an Energy Subsystem
(a river lock admitting a gasoline tanker)

"Must-Have" Attributes	**"Must-Not-Have" Attributes**	
maintain availability of the lock	suffer extensive downtime or closure of the lock	allow sinking of the ship at or within the lock
maintain affordably (low lock passage fees and insurance premiums)	allow complete breach of the lock (implying local or regional flooding)	suffer loss of customer confidence (all shipping that uses the lock)
maintain an acceptably short transit time	suffer damage to the lock supporting equipment (power, control systems, etc.)	allow breach of the cargo containment to release damaging volumes of gasoline
be compatible with physical design parameters of the tanker (e.g. length, draft, etc.)	damage river environment by uncontrolled release of gasoline	allow personal harm to ship crews, lock workers, bystanders, or the nearby residents and their property

The requirements illustrated in Tables 2 and 3 can be quantified and incorporated into the design specifications of the components and the full system. The resulting system features produce outcomes that lead to benefits to the system owner and the entities served by the system. Note that when the ship is in the lock, there cannot be an absolute guarantee that the gasoline will not ignite. The designers must do what is deemed practical to mitigate the impact of a possible fire by including features such as exclusion zones and fire-control equipment and processes, but full surety cannot be guaranteed, unless alternative delivery options are readily available.

In every system there are components (or subsystem elements). These components have certain properties and work together with other components to produce certain system features. The features cause certain outcomes to emerge. These outcomes create certain benefits (in our case societal benefits).

When this model is applied to our country's energy system, energy surety is an outcome. The level or amount of energy surety in our society produces a number of benefits, including a sense of security in the public, the creation of wealth (because disruptions do not waste money), and safety (because the power will probably not fail during emergencies). *Thus, the higher the level of energy surety, the greater the societal benefits*, at least up to the point that the cost of additional surety measures would bring less return.

Energy Model Attributes

In general, *safety* is defined as the state of being secure from harm, danger, or evil.[6] A safe system is defined as one that is robust to *inadvertent* stresses like human error, accidents, aging, or other natural disruptions. It is important to distinguish between safety criteria and safety consequences of an energy disruption. For energy discussions, safety consequences are measured in units of lives lost from energy accidents, energy outages, and energy construction, operations, and maintenance activities.

Security is defined as freedom from risk or danger and freedom from anxiety or fear.[6] In a surety context, a secure system is one that is robust to *malevolent* stresses like terrorism, vandalism, theft, or intentional disruption. A qualitative metric for a combination of safety and security is the "must-have" attribute in Table 2 that energy must be available when needed at a predictable price, even in changing conditions. Full attainment of a robust energy infrastructure independent of world events is unlikely and is probably not an optimal solution because the economic requirements would be far from a free-market situation, and the nation's competitiveness would probably be compromised to a crippling degree. Nevertheless, it seems desirable to move in a direction that reduces the risk, danger, or anxiety of the public (and those commercial or industrial consumers) that could result from an energy disruption or price shock, whether it be caused by an inadvertent or malevolent stress.

Reliability is defined as dependability or the ability to place one's trust in something. In an energy context, reliability is the ability for the energy infrastructure to operate under any condition. Reliability can be measured in terms such as mean time between failures, and time to restore following a disruption.[11] *Recoverability* is related to reliability, and for energy systems,

[11] Three nines of reliability means the system is available 99.9% of the time, 4 nines translates to system availability of 99.99% of the time, and so forth.

it means the ability to return to normal operation following some disruption. Recoverability can be measured in time, resources (labor or money), or some other unit of effort required to put a system back into operation after service or functionality has been lost or to substitute another system. Recoverability (and reconstitutability), maintainability, affordability, durability, and availability are all functionality attributes or features of the system. These attributes are likely to have different levels of acceptability, depending on whether the system is operating within normal, off normal, or emergency conditions.

Sustainability is defined in both qualitative and thermodynamic terms. Qualitatively, sustainability is accomplished when energy needed to do work is available when needed. In other words "meeting the needs of the present without compromising the ability of future generations to meet their own needs"[12] or a less stringent criterion, "saving all that is practical when doing otherwise would leave future generations at a disadvantage." For some, sustainability is thought of as economic and environmental objectives. A 200-year time frame was chosen for sustainability in this report because extending farther into the future would almost certainly miss the advent and perfection of new technologies or changing needs of society. By staring with a 200-year horizon (approximately 7 generations[13]), ample opportunity exists to make mid-course changes that will extend sustainability to a much longer period.

In the past 100 years, there has been considerable change in the way civilization derives its energy, but there is nearly a century of experience with electric power and with transportation dependent on liquid fuels. By most estimates, supplies of petroleum will run short, and there will be increased pressures on coal and the uncertain supplies of natural gas to derive replacement synthetic liquid fuels, or possibly hydrogen. One potential development, fusion power, could change the energy equation considerably in a 200-year time frame, but it is not included in the projections here because its progress has been slow.

Thermodynamically, sustainability is achieved when some persistent supply of exergy (available energy coming from the sun or gravity or cooling of the earth, which owes some of its energy to nuclear decay) offsets or compensates for the "exergy" now drawn from the finite pool of fossil fuels. Exergy is energy available to do useful work considering the energy available from a given source.[14] This matching, in the full context of sustainability, requires closing the energy cycle in terms of emissions that interfere with the environment, minimizing waste heat that

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[12] Sustainability as defined by the 1987 Brundtland Commission Report, see reference [7].

[13] The use of seven generations was used as a standard by the Iroquois Nation in making important decisions that would influence the tribes' future [www.sevengenerationsahead.org].

[14] Note that exergy analyses must be conducted by applying the second law of thermodynamics. The second law of thermodynamics gives the theoretical maximum amount of work that can be extracted from a source of heat. This efficiency increases as the heat source temperature becomes higher, for example, by using fuels that burn hotter, and efficiency also increases when the sink to absorb exiting heat has a lower temperature. Another efficiency measure using the second law derives from how closely the theoretical efficiency is attained. Unwanted heat loss and friction commonly degrade this efficiency. Contrast this with a first law efficiency which is the ratio of energy out to energy in reference [2]. As defined by the first law of thermodynamics, energy is not a scarce resource; it is neither created or destroyed. However, exergy or energetic order is scarce and the cost of continually ordering energy is significant. For a more complete discussion of these concepts in a global economy which is becoming increasingly dependent on the most highly ordered form of energy, electricity, see reference [2a]. Also, see Appendix A for a second law thermodynamic efficiency calculation example.

results from the conversion of energy and closing the cycle with respect to waste materials that still contain useful exergy. In short, sustainability can be described as continually striving to match exergy sources with exergy needs.

Other Considerations

Having described some individual features or attributes of energy surety, integration with other considerations that determine feasible technological solutions is now appropriate [4]. The nine factors considered are c*ost*, *environmental impact*, *safety and health*, *energy dependence*, *policy and market needs*, *science and technology needs*, *infrastructure vulnerability*, and *service sustainability*.

Figure 2 represents how one might summarize a select set of energy surety attributes of two different energy systems. It helps to visualize the attributes, with the center of the chart representing the ideal situation with all attributes optimized. The ideal situation at the "bull's-eye," where all of the metric factors indicate perfection, is unlikely, but at a glance, one can make some comparative judgments. A note of caution is needed because the area enclosed in the chart does not represent a reliable measure of "unworthiness." The attributes have various units that are normalized to allow representation, and the order in which the attributes are arrayed can influence the appearance of the chart and the area enclosed. In this representation, security and reliability are quantified in terms of energy dependence, cost, and infrastructure vulnerability. Sustainability is described directly and by the measure of environmental impact. Recoverability is not represented in this particular example. The goal of this methodology is to design a system that approaches the bull's-eye.

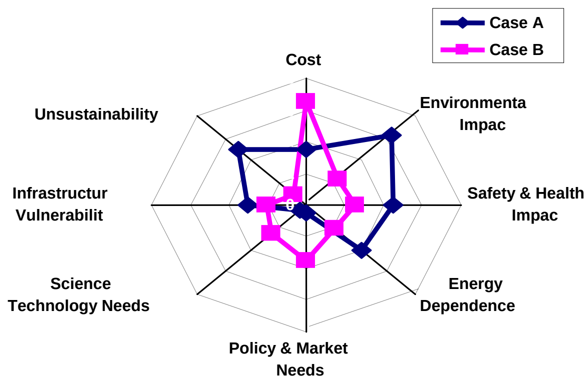

Figure 2. Example of Energy Surety Attributes for Two Systems

Social Benefits

The surety energy model will help produce an energy system that possesses the appropriate properties and features to effect certain outcomes (such as high levels of energy surety) that produce benefits to society. The problem of bringing this about is more difficult today than it was in the past for electricity because deregulation has taken place in the utility market. In the past, when electric and natural gas markets were highly regulated, obtaining high levels of surety for the public good was the responsibility of lawmakers and regulators. Power or electric companies could remain profitable if they maintained excess capacity or used environmentally friendly fuel and technology. With the lessening of regulatory control in recent decades, environmental protection has been a matter of direct regulation, and excess capacity has been left up to the market.

The balance between the risks of maintaining a reliable grid and the benefits to the profit bottom line is now left in the hands of a collection of individual entities. As the excess capacity of past years is reduced from increases in demand and plant retirements, the surety situation has become increasingly precarious, even though the tools to manage power flow have improved. This may be especially acute in view of increasing terrorist threats, a subject that was not strongly considered in the days of regulation. A successful surety program will doubtless require certain regulations or incentives because a migration to "just-in-time power production" will lead to tensions between those who want low costs and those who are willing to pay more for a more secure energy system. To maintain a fair playing field, regulations will have to be uniform across all suppliers to the grid.

It is important to recall here that the benefits of the energy surety model are assumed to be beneficial in a global context. The problems inherit in reconciling competing interests globally will be more complex than those discussed for the example subsystem of the U.S. energy infrastructure, but the U.S example is sufficient for demonstration purposes.

IV. THE PATH FORWARD FROM AN ENERGY SURETY PERSPECTIVE

Society can achieve energy sustainability when it is able to match all exergy needs with available exergy sources while simultaneously providing exergy sources for future needs. Exergy sources come from a mixture of depletable and sustainable resources. Analogous to a long-term financial strategy in which our daily expenses would be met by the interest earned on investment resources without depleting the corpus, *our goal is to satisfy our daily energy needs from an exergy account that can adjust to meet population changes, using technology that is already available*. We must also assure that the environment account stays sufficiently in balance at any particular time so that the needs of nature and humanity are satisfied. This "matching" challenge is easiest to accomplish in the presence of stable population, but may still be possible if some dramatic change in population does occur.

As humans, we are in a never-ending battle with the second law of thermodynamics,[15] constantly using exergy to support ourselves and our surroundings in an environment in which we are in nonequilibrium. This activity (which consumes exergy) is in keeping with nature's biological tendency to use resources to create "order" around us. This consumption expands until the resources become exhausted and equilibrium with competing life forms is reached, but to let this natural process run to its normal conclusion would not be consistent with our current view of "civilized societies" because of the implications of societal collapse upon complete resource depletion.

We offer a three-step strategy for moving toward better matching of our exergy resources with our exergy needs. As a first step, we must improve the second law efficiency of energy conversion, transport and use processes. Secondly, we must attempt to close the cycle of the same processes taking into consideration the interactions with the earth's biosphere, at least when open cycles provide undesired consequences. The final step to obtain true sustainability into the indefinite future would be to harvest the earth's persistent exergy sources at no greater rate than which they are being made available to us. The three steps are further described below.

Step 1 – Close the Cycle, Starting with Improved Second Law Efficiency.

To begin to close the energy conversion cycle, we must squeeze every unit of available exergy from our current supply sources. This goes beyond the implementation of higher efficiency electricity consuming devices (such as lighting, appliances, motors, etc.) and vehicles (diesels, hybrids, etc.) to include waste-to-energy options such as the extraction of methane from landfills and the conversion of biomass wastes to liquid fuels. Combined heat and power technologies, regenerative braking (such as is used in hybrid vehicles), gas wellhead burn-off capture, appliance "sleep mode" features, and motion detectors for turning off lights when not needed and

[15] First and second laws of thermodynamics simply state that energy cannot be created or destroyed and the entropy of the universe tends to a maximum. These laws imply that the usefulness of energy is always declining. Fortunately, we have persistent sources such as the sun, and to a lesser extent nuclear energy, to carry on civilization for eons even though these energy sources will ultimately decline.

more efficient lighting devices such as light-emitting diodes are just a few of the technological opportunities to make better use of limited exergy resources.

Our technical foundations for closing the cycle are equilibrium thermodynamics and the first and second laws. Our goal is match exergy sources with exergy needs, thereby minimizing irreversible entropy production at each stage of the energy conversion and use process. Simply stated, this essentially means using energy sources best matched to particular needs, and reducing waste heat.

We must close the energy conversion cycle by trapping wasted products such as carbon dioxide, or by using systems that produce fewer contaminants. We also seek to reduce environmental impact by using as much wasted low-grade heat (low exergy content) for space heating, air conditioning using an absorption cycle, for heating greenhouses, etc, and then assure that wasted heat is discharged in ways that least harm the environment. Opportunities for efficiency improvements in the U.S. abound. Even incremental improvements in electricity production, distribution, and use—most notably in lighting efficiency can have a significant effect. In transportation, improving fuel economy through technological improvements and by more effective fuel economy legislation would be very effective in improving energy dependence, because about 60% of transportation fuel is imported. The concept of extracting higher value from fuels, such as natural gas that directly provide heat for water, buildings, and processes could be useful, but its application is difficult, because of the capital expense for equipment and the complexity of operation and providing a power grid that accommodates power transfer from many small entities that are capable of delivering power, but may also draw energy for peak usage. For an example of a second-law efficiency analysis, see Appendix A.

Step 2 – Invent and Adopt Sustainable Energy Storage Systems and Closed-Cycle Systems.

We must be able to store exergy for later use (e.g., when there is no wind, the sun is obscured, or an energy supply is disrupted.). Currently, energy storage technologies are used in a limited way, ranging from battery-powered units to manage brief interruptions to the strategic petroleum reserve to provide energy surety features for economic security or system reliability and recoverability. However, looking at storage from a broader perspective can provide sustainability features as well. For example, without storage capability (or a massive transmission system that links light and dark regions of the earth), wind and photovoltaic options cannot supply more than about 50% of power requirements. The goal in storing excess energy by using persistent exergy sources is to begin to more closely match the time constants of the earth's receipt of exergy with human consumption of exergy. Examples that could provide such energy storage include solar production of hydrogen for fuel cells or solar-powered conversion of CO_2 and water to liquid fuels and exergy storage from solar thermal collectors in molten salt that can power generators throughout the day. Hydroelectric power is an example of a natural storage process, augmented by dams, that allows us to release and use energy that periodically appears as rain and is stored for consumption over days or years.

Step 3 – Harness Fusion Energy by "Moving the Sun to Earth."

The first two steps described above may provide new insights, but as with fossil-based energy resources, implementing them allows us to "buy time" to learn how to replicate the sun's fusion process on earth in a safe, secure, reliable, and sustainable way. While nuclear fission fuels can arguably replace fossil fuels for centuries, it seems desirable to seek less exhaustible and evenly distributed fusion fuels. All water contains such a fuel, deuterium that would serve as the primary fuel feedstock for fusion reactors. The other fusion fuel ingredient is lithium, a substance that is very common. In addition, some fusion proponents propose using helium-three, an isotope found in moon surface rocks. While the nuclear physics makes this task enormously difficult, problems of induced radioactivity in reactors would be reduced or eliminated.

Understanding and possibly replicating the sun's energy conversion process is highly desirable for long-term energy supply options, and it must extend beyond the study of heat engines. While the precise nuclear physics details of the energy that powers the sun are unlikely to be replicated on earth, the basic principles of fusion are understood and have been demonstrated in laboratory experiments and in the destructive bursts of thermonuclear weapon tests. If we can harness this exergy source, only limited storage would be necessary; exergy could always be produced on demand with a virtually inexhaustible fuel, deuterium from water. This source would also be used to synthesize transportation fuels, which might be very similar to today's liquid fuels, or may possibly be hydrogen or light hydrocarbon gases such as methane or propane. Though we do not know if fusion can succeed as a practical terrestrial energy source, we believe that its promise is worth extensive investment.

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V. CONCLUSIONS

Modeling current and future energy options from a surety approach provides some interesting insights and provides one way to understand energy challenges in an uncertain and changing world. A complete application of the surety model can only be valid if all the components of the system (including the earth and biosphere) are understood and quantified. This may be possible in the future as knowledge of earth's complex systems is developed. The attributes of sustainability are complicated, multidimensional, and deserving of additional study, including relationships between exergy usage and population growth. Sustainability can likely be achieved up to some limiting carrying capacity of the U.S. and the world. The limiting carrying capacity depends upon available exergy supplies and our wiser use of them, including the exergy content of waste streams. In other words, if humankind is capable of being more symbiotic with the earth, future generations can enjoy the same prosperity that we enjoy today.

A number of topics raised our curiosity but are left to future investigations, perhaps by others. These include:

- A robust methodology for integrating safety, security, reliability, reconstitutability and sustainability and for providing measures of these attributes;
- A full treatment of the issues posed by conventional supply-demand economics, and the ability of such economies to support smooth transitions from fossil exergy to other sources;
- Specific application of the surety model to the nation, continent and globe – which requires a robust understanding of the relationship between climate and human activities;
- A more complete study of entropy, exergy, and recent discoveries in the information technology and bioscience fields;
- Uniform guidelines for measuring sustainability, which takes on various meanings beyond maintaining status quo, including social equity; and
- Studies of the dependencies between demographics, social structures and related social values, and energy consumption.

The appendices contain materials that start to examine some of these problems.

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REFERENCES

1. Scott, David Sanborn, "Exergy," *International Journal of Hydrogen Energy* 28 (2003) 369-375.

2. Simpson, Mark and James Kay, *Availability, Exergy, the Second Law and all that…*, 1989.

2a. Huber, Peter W. and Mark Mills, *The Bottomless Well*, Cambridge: Basic Books, 2005.[16]

3. Goodstein, David, *Out of Gas: The End of the Age of Oil*. New York: Norton, 2004.

4. Jones, Scott A., draft internal document resulting from laboratory directed research and development project entitled "Energy Systems Analysis," Sandia National Laboratories, 2005.

5. Portney, Paul R. and John P. Weynat, *Discounting and Intergenerational Equity*, Resources for the Future, Washington, DC, 1999.

6. *Webster's II New Riverside Dictionary*, 1984: Houghton Mifflin Company.

7. Bruntland, G. (ed.), (1987), "Our Common Future: The World Commission on Environment and Development," Oxford: Oxford University Press.

8. Diamond, Jared, *Guns, Germs, and Steel*. New York: Norton, 1999.

9. Diamond, Jared, *Collapse.* New York*:* Viking Penguin, 2005.

10. Brander, J.A. and M.S. Taylor, "The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use," *The American Economic Review*, Vol. 88, Issue 1, Mar. 1998, 119-138.

11. Arrhenius, S., "On The Influence of Carbonic Acid Upon the Temperature of the Ground," *London, Edinburgh, and Dublin Philosophical Magazine* and *Journal of Science*, vol. 41, 237-276 (1896).

12. *Climate Change 2001: Synthesis Report Summary for Policymakers*, Summary approved at IPCC Plenary XVIII (Wembly, UK, 24 September 2001).

13. Cox, Peter M., Richard A. Betts, Chris D. Jones, Steven A. Spall, and Ian J. Totterdell, "Acceleration of Global Warming due to Carbon-cycle Feedbacks in a Coupled Climate Model," *Nature* vol. 408, November 2000, 184-187.

14. Houghton, J.T, G.J. Jenkins, J.J. Ephraums, editors of *Climate Change: The IPPC Assessment*, Cambridge University Press: Cambridge, UK (1999) 38.

15. Spencer, Roy W., Testimony to the United States House Science Committee—Subcommittee on Energy and the Environment—by Roy W. Spencer, Senior Scientist for Climate Studies NASA Space Flight Center, Huntsville, Alabama on 7 October 1997. Can be found at http://www.house.gov/science/spencer_10-7.html

16. Pielke, Roger A., Gregg Marland, Richard A. Betts, Thomas N. Chase, Joseph L. Eastman, John O. Niles, Dev Dutta S. Niyogi, and Steven Running, *The Influence of Land-use Change and Landscape Dynamics on the Climate System: Relevance to Climate-change Policy Beyond the Radiative Effect of Greenhouse Gases*, Phil. Trans. Royal Society of London (2002) 360, 1705-1719.

17. Australian Coal Association Research Program Project 8049, "*Environmental Credentials of Coal,*" http://ciss.com.au/ref/static/reports/public/acarp/acarp.html

18. Andrew McKillop, *Energy Transition and Final Eenergy Crisis*, published on internet site VHeadline.com---http://www.vheadline.com/readnews.asp?id=23067, October 10, 2004.

[16] The authors believe that this reference is interesting and informative, but they do not necessarily subscribe to the conclusions that energy supplies will not run out.

19. Prescott-Allen, Robert, *The Wellbeing of Nations*, 2001, Island Press, Washington, D.C.

20. Pimentel, David, *Energy and Dollar Costs of Ethanol Production*, Hubbert Center News Letter #98/2 (1998), available at http://hubbert.mines.edu/news/Pimentel_98-2.pdf. Also see Comparison of USDA and Pimentel Net Energy Balances at: http://www.ncga.com/public_policy/issues/2001/ethanol/08_22_01b.htm

21. EIA, 1995. Coal Industry Annual, 1994 US Department of Energy Annual Report, DOE/EIA-0584 (94), 264.

22. http://www.sspi.gatech.edu/weatherchg.pdf

23. Our Common Journey: A Transition Toward a Sustainability (1999), National Academy of Sciences. Executive Summary available at http://books.nap.edu.catalog/9690.html. See also "Long-Term Trends and a Sustainability Transition." Robert W. Kates and Thomas A Parris, PNAS, July 8, 2003, vol. 100, no. 14, 8062-8067, www.pnas.org/cig/doi/10.1073/pnas.123133100

APPENDIX A. Demonstration of a Second-Law Efficiency Impacts

Below is a simple demonstration of a second-law efficiency impacts:

Engineers Larry and Mo want to heat their houses with solar energy. Neither had the foresight to build a passive solar home, so they must retrofit their current systems. The only constraint is that each is limited to using 10 m^2 of solar collector area in a region with solar insolation of 1000 W/m^2. Both live in an ideal world in which the sun shines all day, every day and the outside temperature is always cold. Larry opts to use flat plate solar collectors that are 50% (first law) efficient. Mo opts to use a concentrating collector with a Stirling engine that is 35% (first law) efficient. Which one can produce the most heat?

Larry is an industrious chap who carefully designs the plumbing system such that there are not any extraneous line losses. Therefore, the heat that is introduced into his house is:

$$\left|\begin{array}{l} \varepsilon \leftarrow 0.5 \\ Area \leftarrow 10 \cdot m^2 \\ q_{solar} \leftarrow 1000 \cdot \frac{W}{m^2} \\ q_{solar} \cdot Area \cdot \varepsilon \end{array}\right. = 5000\ W$$

Mo is distraught when at first glance as it looks like she struck a bad bargain. Not only did she choose a technology with a lower (first law) efficiency, but the end product is electricity, not heat! What is poor Mo to do?

Well, Mo calls up the local HVAC contractor and orders a heat pump with a coefficient of performance (COP) of 5. She powers it with the electricity from her solar-powered Stirling engine. Therefore, the heat introduced in her house is:

$$\left|\begin{array}{l} \varepsilon \leftarrow 0.35 \\ Area \leftarrow 10 \cdot m^2 \\ q_{solar} \leftarrow 1000 \cdot \frac{W}{m^2} \\ COP \leftarrow 5 \\ q_{solar} \cdot Area \cdot \varepsilon \cdot COP \end{array}\right. = 17500\ W$$

Mo chose the technology with the lower first law efficiency and ended up with over three times the heat output compared to Larry's system. Mo spells energy with an "x."! Of course, the second law thermodynamics worked in Mo's favor. However, neither Mo nor Larry followed the ideal path. Their friend, Curly chose to use an absorption-cycle heat pump powered by the solar panels, and saved the energy losses that would result from making electricity with the Stirling engine, realizing even higher heating performance, with a significantly smaller collector area. Curly saved money and roof space to accommodate his new star-gazing observatory. (The proof of Curly's solution is left to the reader.)

Of course, we have not considered the relative costs of these technologies, nor have we considered the need for heat storage to keep our subjects warm through the nights. Even this seemingly simple example immediately becomes quite complex.

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APPENDIX B. Limitations and Improvement Opportunities for Current U.S. Energy Systems

Today's energy systems are usually open cycle and wasteful. Average first law conversion efficiencies of heat engines, combustion of fossil fuels, conversion of heat to electricity, and many other energy-related processes rarely exceed efficiencies of 33%. In some cases, such as combined-cycle natural gas generating plants, systems produce electricity with about 60% efficiency, and if the plants are co-located where the waste heat can serve air conditioning or heating needs, the total energy utilization can exceed 80%. Merely by using more efficient technologies based on simple application of first and second laws of thermodynamics, the impact on the environment could be cut in half, but the capital investment may be great. The availability of natural gas (already in great demand and increasing in use) would be in doubt. The byproducts of these conversion processes (heat, air, and water emissions) are left for the earth's biosphere to absorb and recycle, making today's energy systems open cycle.

This open cycle philosophy is supported by economic principles that largely neglect the biosphere. In actuality, the biosphere has limitations on its carrying capacity and should be a recognized externality. In some cases, the environment handles contributions to such externalities gracefully, and there would be little merit in closing the loop. For example, in any electric generation plant, waste heat must be dumped into the environment. There is no way to prevent this, but waste heat can be minimized through efficient design and conservative use policies. The quantity of this heat is small in comparison to the additional solar heat trapped from carbon emissions, and in some cases might be unimportant. However, the intensity of the heat locally deposited, such a nonpermissible warming of a river can be a problem.

An example of closing a cycle that was open until a few decades ago is the use of high-sulfur coal in heating and generating plants placed near populations. Until the 1970s there were few restrictions on this health-harming pollutant. Laws were enacted that limited emissions, and electric generating utilities installed scrubbing equipment. A market emerged that allowed electricity generators to trade the right to emit and to earn additional revenue by lowering emissions. However, short-term economics continue to dominate the operation of such plants. If emissions penalties are low compared to the price of electricity, such laws could be ineffective. At some point, carbon dioxide and other greenhouse gases may be treated similarly, thus exposing an additional set of externalities.

Although U.S. exergy consumption per person is 6% lower today than it was in 1979,[17] widespread opportunities exist for making better use of resources in the electricity and transportation sectors[18]. (See Table 4 for tabular data.) Experience between 1979 and 1983 demonstrated the nation's ability to reduce exergy consumption per person by 13%. Some of

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[17] Energy Information Administration data from the Annual Energy Review 2003 show energy consumption per person as 360 million BTU in 1979, 313 million BTU in 1983, and 338 million BTU in 2003. Energy intensity data reveal a continuous reduction from 15.6 to 9.4 quadrillion BTU/$ GDP between 1979 and 2003. See reference [Energy Information Administration Annual Energy Review 2003 DOE/EIA-0384 (2003) available at www.eia.doe.gov/emeu/aer/contents.html].

[18] EIA's Annual Energy Review 2002 also reports that of the roughly 96 quads of current US energy consumption, 56 quads (or 60%) are wasted. See reference [Energy Information Administration Annual Energy Review 2002 DOE/EIA-0384 (2002) available at www.eia.doe.gov/emeu/aer/contents.html].

this difference results from improved efficiency, but doubtless, the migration of manufacturing activities to off-shore locations has also contributed to this trend. More progress is possible, but future improvements may not be as dramatic or as cost effective. Also, the risk of decreasing exergy consumption per person could postpone the urgency of addressing population growth because any excess available exergy could be consumed by a growing population. In some sectors, certain exergy consumption trends are worsening.

Table 4. U.S. Energy Statistics from EIA Annual Energy Outlook (2003)

	Energy Consumption, BTU	Energy Con. Per person, million BTU	GDP, trillion 2002$	Energy consumption per $ of GDP, QBTU/$ GDP	Vehicles Miles/ Vehicle	Gallons of gas per vehicle	MPG, all vehicles
1973	75.7	358	4.3	17.4	10099	850	11.9
1979	80.9	360	5.2	15.6	9722	776	12.5
1983	73.1	313[19]	5.4	13.5	9760	686	14.2
1990	84.7	340	7.1	11.9	11107	677	16.4
2002					12172	715	17
2003	98.2	338	10.4	9.4			

Some improvements that reduced energy intensity involved improving efficiency and therefore helped improve the exergy ratings. Many more changes would be required to make full use of the exergy available. For example, although the miles per gallon indicator for all vehicles in the U.S. have continued to improve (11.9 MPG in 1973 and 17 MPG in 2002), the number of miles driven per vehicle has risen 21% between 1973 and 2002, and the number of vehicles has increased significantly. In addition, the gasoline use per vehicle declined between 1973 and 1990, but this trend reversed between 1990 and 2003, likely from worsening traffic congestion and the public's craving for large vehicles. It is not unusual for efficiency or performance improvements to cause actual increases in consumption; greater efficiency means lower unit cost, and the consumer may then consume more, in some cases displacing less efficient systems and, in other cases, merely increasing demand for fuel consumed by more use of the more efficient technology. High fuel costs may set the trend back to more frugal gasoline use. When assessed against 180 other countries in the world, the U.S. ranks among the 18 worst with regard to energy resource use wellness.[20] We will likely be forced by rising energy costs and

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[19] Lowest value in the 83-86 timeframe.

[20] In a study of (14 different) ecosystem wellness indicators assessing the land, water, air, species and resource use health of 180 countries, 18 countries received the lowest score for the ability to match energy consumption with the carrying capacity of the ecosystem. The U.S.'s rating (based on 1997 measures) was due to a high rate of energy use per person (101 GJ) and high rate of energy use per hectare of land area (350 GJ). The other 17 countries were Barbados, Canada, Trinidad and Tobago, Belgium, Germany, Luxembourg, Malta, Netherlands, United Kingdom, Bahrain, Brunei and Darussalam, Japan, South Korea, Kuwait, Qatar, Singapore, and United

environmental concerns to become better stewards of energy use, and similar forces will likely lead to more use of renewable (solar, wind, tidal and geothermal) energy and nuclear energy.

Renewable and nuclear sources now represent a fraction of what is feasible, but there are limitations. For example, some scholars have examined the total energy cycle from biomass and conclude that biomass raised expressly for energy is frequently close to energy break-even, when energy costs for irrigation, fertilizer production, harvesting, and processing are all included. In addition, sustainability is called into question because the biomass cycle results in soil erosion and currently uses fossil fuel.[18] The sun, a fusion energy source that is sustainable within the likely time constant of human activity, is the predominant persistent energy source for the earth.[21] Solar energy absorption results in biomass or enables other energy conversion processes, including wind or hydropower. It is possible to convert solar radiation to electricity with either photovoltaic or thermal generators with a conversion efficiency of tens of percent, which is orders of magnitude more efficiency than capturing solar radiation for the production of plants for biomass, and without a continual need to conduct energy and labor intensive farming.

Fossil resources provide most of our energy today and play a critical link to the future. We presumably will depend greatly on current world reserves of fossil fuels to build the initial infrastructure of more efficient fossil plants, nuclear plants, and renewable energy installations. As these latter sources get a stronger foothold, the reliance upon fossil reserves will, of course, lessen, at least for nontransportation fuels. (We might assume that the renewable sources of energy will be used partly to produce synthetic transportation fuels.)

The transition to other than fossil energy should be accomplished before fossil reserves become so expensive that the transition becomes too painful or economically impractical. The extent of this problem seems to be unquantified, but it has received some attention.[23] One measure of the transition difficulty is the energy replacement time for a new source to provide the quantity of energy needed to construct the new source.

The energy replacement time for photovoltaic technology is a few years, in comparison with a typical service span of thirty years, and wind generators have an even more rapid energy replacement time, so the transition to these renewable technologies is unlikely to be a problem if energy costs increase in an orderly manner. Whether the inevitable transition away from fossil energy can arise gracefully through normal economic forces or whether governmental and international interventions will become necessary is not known. The topic of smooth transition from fossil to other exergy sources should receive more attention from policy makers, economists, and from the scientific and engineering communities.

Arab Emirates. Countries with the best combination of human wellbeing and moderate energy use (one measure of ecosystem wellbeing) which may warrant further study are Portugal (at 70 GJ/person and 75 GJ/hectare), Ireland, Spain and Cyprus. See reference [19].

[21] Inertial energy from the moon-earth rotational system is transported by gravity and is another persistent source of energy for the earth. The available energy from this transfer of inertial energy is much smaller than the solar energy flux incident on the earth; however, in certain locations, such as water inlets and bays, this energy is conveniently concentrated. It is possible that intensive use of this energy source could impact marine life. Thermal energy from the earth's crust also constitutes a very persistent source, but it also is not free of pollutants, because water and steam used for heat transfer also carry minerals and thermal pollution to the surface.

Given the numerous options listed above and the large number of uncertainties previously mentioned, our hope for the energy surety approach is to define possible end states and paths to achieving those end states, despite great uncertainty.

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APPENDIX C. Climatic Effects of Carbon Dioxide: Control of Carbon Dioxide Alone Will Not Stabilize Climate

The effect of carbon dioxide in trapping some of the sun's energy and causing temperature rises is much-studied and well established. In fact, the importance of carbon dioxide in the energy balance of the earth was noted in a lengthy article by S. Arrhenius in 1896 [11]. The problem is fairly complex in some of the atmospheric science details, but some simple average calculations are easy to carry out. The following are a few facts that are generally accepted [12] and will help the reader understand how the sun's increased warming of the earth can be far more potent than the heat directly generated when fuels burn. The residence half-time of carbon dioxide released into the atmosphere is not precisely known, but is thought to lie in the range between five and two-hundred years; we assume a conservative ten-year residence time. (In the sense of the simple calculation made here, shorter residence time means less solar energy trapped.) The increase in carbon dioxide since the industrial age started about 250 years ago is about 31%, a peak level unprecedented over many millennia. The concentration of carbon dioxide is still increasing.

If we assume that an average grade of coal is burned, and the residence time of the carbon dioxide in the air is conservatively set at ten years, the added solar heat to the environment would surpass the combustion heat generated by a factor of about 59, a number that is derived below.[22,23] Of course, the heat from combustion would be deposited locally at the power plant or factory, and where any generated electricity is consumed, while the solar energy uptake is collected slowly over the entire earth. (The carbon dioxide emission of natural gas power plants is estimated to be approximately one quarter that of coal plants per unit of produced electricity

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[22] According to reference [12], table 6.1 and nearby text, the solar energy retained on earth, as a consequence of the increased carbon load, has increased by 1.46 watts per square meter (W/m^2), out of an incident flux at the outer atmosphere of 1370 W/m^2. While such a change seems minor, the effect on temperatures at the surface is thought to be about 0.6 degrees centigrade over the last century, and there is a long list of undesirable consequences. If we calculate the total annual excess energy retained on the earth as a result of the 1.46 W/m^2, we merely multiply by the area of the earth times the number of seconds in a year of twelve-hour days, or $3.14 \times (12.7 \times 10^6)^2$ square meters $\times 12 \times 3600 \times 365$ seconds $= 1.16 \times 10^{22}$ watt-seconds or joules per year. The total amount of carbon in the atmosphere is quoted as 5.15×10^{18} Kg, (reference: www/cdg.ucar.edu/cas/abstracts/files/kevin2003_6.html) and the current mole fraction of carbon at the concentration of 372 ppm is 3.72×10^{-4}, so the entire carbon inventory in the atmosphere is 5.22×10^{14} Kg or 5.22×10^{11} metric tons. The fractional change in carbon inventory responsible for the change is obtained by multiplying the atmospheric carbon load by the difference in current concentration and pre-industrial age concentration, divided by current concentration, or (372.3ppm – 280ppm) /372.3 ppm = 1.29×10^{11} metric tons. The solar heat added per year per metric ton is given by the total excess solar energy retained divided by the change in carbon inventory responsible for the change, or $1.16 \times 10^{22} / 1.29 \times 10^{11} = 1.24 \times 10^{11}$ Joules per metric ton of carbon per year. If we add more carbon to the atmosphere and assume its residence time is ten years, this number must be multiplied by ten to obtain 1.24×10^{12} joules retained solar energy per metric ton of carbon emitted. If we wish to compare the heat value from a metric ton of carbon, we can to first approximation examine the energy liberated by burning one metric ton of coal, which is 2.1×10^{10} joules. In other words, about 59 times more energy is retained from sunlight incident on the earth than from the burning of the coal itself. If we were to take the high estimate of 200 years for carbon dioxide atmospheric residence time, the multiplying factor would be approximately 1200.

[23] The assumptions concerning greenhouse gas potency and longevity used in these calculations can be found in the references [12], [13], and [14].

because of the lower carbon content of natural gas compared with coal and plant efficiency differences.)

There are contrary views suggesting that water vapor could have a mitigating effect that would stabilize the effects of carbon dioxide, and this is mentioned briefly several paragraphs below. Carbon dioxide is trapped in ocean water, and ocean temperature increases trigger some release. Other changes, such as warming in the Arctic, cause more tree growth that would at least temporarily absorb carbon dioxide, but the thawing of the perma-frost leads to accelerated release. Climate models generally predict that at some point, carbon sinks will become carbon sources, driven by temperature rises, and a system that has tended to be stable over the centuries will likely become unstable, triggering rapid rises in carbon dioxide levels. Reforestation to help re-capture carbon dioxide has become a topic for industrial investment, and some non-profit organizations obtain funds from industry to preserve forests with the intent of gaining future carbon emission credits. It is not clear that this practice is truly sustainable, as an equilibrium between storage and release may be reached as the forests mature. However, the carbon retained in equilibrium would have a beneficial effect.

Although the greenhouse effect of carbon dioxide is strong, the entire climate change problem is far more complex than the carbon-dioxide model would alone predict. In fact, efforts to control carbon dioxide emissions may not provide the most efficacious means to stabilize the climate. For example, water vapor is a greenhouse gas with a half-life residence measured in weeks, rather than decades, and the clouds themselves can lead to strong energy trapping or reflection, depending upon their detailed nature. In addition, the evaporation of water and its subsequent transport to high altitudes offers an important heat flow mechanism from the earth's surface, providing a strong modification to the radiation heat flow balance [15]. The amount of water in the air and its correlation with human activity, such as irrigation and change in forest cover is known with high precision only since satellite and modern instrumentation became common (within the last five decades) but there are studies that estimate the history of land use changes.

It is thus possible to estimate non-CO_2 greenhouse gas anthropomorphic changes to the environment that would influence climate[24]. In an elegant set of experiments, Roger Pielke and collaborators used satellite and historical data to determine the current vegetation patterns worldwide, and using current climate data, determined what changes in vegetation and resulting water vapor emission would be expected.[16] Computer climate models then calculated the consequence of the return of the terrain to vegetation patterns presumed to reflect those that existed when populations were much smaller. A metric other than uniform global radiation is required, because land use change and its release of water vapor can engender very strong local or regional effects that eclipse the effects of greenhouse gases. In fact, the Pielke paper notes that local climate effects can easily be stronger than global effects, and can be of either sign!

[24] We plan to examine the effects of water, a greenhouse gas as well as a generator of clouds, and its impact on radiation reflection and trapping properties, but water is usually not popularly considered to be in the same group as carbon dioxide and other so-called greenhouse gases. See reference [Discussion Forum Global change Newsletter, N059, pp 16-19, September 2004. Roger A. Pielke Sr., "A Broader Perspective on Climate Change is Needed," published by IGBP International Geosphere-Biosphere programme. Available at www.igbp.kva.se/cgi-bin/php/go.php? Section_id = 188 article_id = 89 – 17k – alternative www.igbp.kva.se/uploads/NL_59_10.pdf].

The Pielke paper advocates the use of ‘regional climate-change potential’ (RCCP), and specifically expresses the opinion that greenhouse gas mitigation is an inadequate currency for satisfying the aims of the Kyoto accord on global warming. These climate impact issues, though full of uncertainty, provide a useful context for the sustainability dimension of the surety model.

Whenever energy finds application, whether to move cars, make fertilizer, or heat and light our homes, there is heat loss to the environment, both where the energy is produced, such as at a power plant or where it finds its end use. In the process of using energy, a quantity called entropy[25] always increases, and the world gets warmer as a result, but the primary entropy production increase (from the burning of fossil fuels) results from secondary causes brought about from greenhouse gases such as carbon dioxide that influence the solar energy balance. When nuclear energy or renewable energy is used, some greenhouse gas is emitted in the process of mining and manufacturing for plant construction and maintenance, because fossil fuel still provides most of the energy supply for building and servicing the infrastructure.[26] However, the net effect of renewable energy sources on carbon dioxide levels is very small in comparison with energy sources that consume fossil fuel.

[25] Entropy is a measure of the decrease in the amount of energy available to do work due to the irreversible nature of a process. When energy is used, not all of it is available to perform useful work, some is unavailable and must be discarded. Entropy is the subject of the second law of thermodynamics, paraphrased, “any spontaneous process will proceed in such a direction as to result in a net increase in entropy.” A study of entropy quickly takes one to the topic of available energy or exergy.

[26] For an interesting summary of life cycle resource use, efficiency and environmental impacts of all major electricity production technologies, see reference [17] by the Australian Coal Association.

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