SANDIA REPORT

SAND2005-6505
Unlimited Release
Printed October 2005

Multi-Attribute Criteria Applied to Electric Generation Energy Systems Analysis LDRD

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National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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Abstract

This report began with a Laboratory-Directed Research and Development (LDRD) project to improve Sandia National Laboratories' multidisciplinary capabilities in energy systems analysis. The aim is to understand how various electricity generating options can best serve needs in the United States. The initial product is documented in a series of white papers that span a broad range of topics, including the successes and failures of past modeling studies, sustainability, oil dependence, energy security, and nuclear power. Summaries of these projects are included here. These projects have provided a background and discussion framework for the Energy Systems Analysis LDRD team to carry out an inter-comparison of many of the commonly available electric power sources in present use, comparisons of those options, and efforts needed to realize progress towards those options. A computer aid has been developed to compare various options based on cost and other attributes such as technological, social, and policy constraints. The Energy Systems Analysis team has developed a multi-criteria framework that will allow comparison of energy options with a set of metrics that can be used across all technologies. This report discusses several evaluation techniques and introduces the set of criteria developed for this LDRD.

ADKNOWLEDGEMENTS

Thanks to Lorna Greening, Robert Glass, David Borns, Marvin Gottleib, Mark Allen, Marjorie Tatro, Arnold Baker, Rush D. Robinett, Thomas Karas, Kevin Stumber, Thomas Corbet, Keith Vanderveen, Andrew Lutz, Leonard Klebanoff, Donald Hardesty, and Michael Hightower for extensive discussions and interactions with the E-LDRD team during the course of this work.

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ACRONYMS

AEO	Annual Energy Outlook
AHP	analytical hierarchy process
APS	American Physical Society
CDM	carbon development mechanism
CF	capacity factor
CSP	concentrating solar power
DOE	Department of Energy
DSM	demand-side management
EIA	Energy Information Administration
ENRI	Environmental and Natural Resource Impacts
FCR	fixed charge rate
FOM	fixed operations and maintenance
GDP	gross domestic product
GHG	greenhouse gas
GPRA	Government Performance Results Act
IAEA	International Atomic Energy Agency
INGAA	Interstate Natural Gas Association of America
LDRD	Laboratory-Directed Research and Development
LEC	levelized energy cost
LNG	liquefied natural gas
MCDM	multi-criteria decision making
NAS	National Academics of Science
NASA	National Aeronautics and Space Administration
NEMS	National Energy Modeling System
NG	natural gas
NGCC	natural gas combined cycle
NGO	nongovernmental organization
NRC	National Research Council
O&M	operation and maintenance
OECD	Office for Economic Cooperation and Development
OPEC	Organization of Petroleum Exporting Companies

PC	pulverized coal
PV	photovoltaics
R&D	research and development
SFS	Strategic Fuel Stocks
SPR	strategic petroleum reserve
SRI	Stanford Research Institute
TAPS	Trans-Alaska Pipeline System
TEHG	total equivalent heat generation
TMI	Three-Mile Island
TRL	Technology Readiness Level
US	United States
VOM	variable operations and maintenance

SUMMARY

This effort started with a Laboratory-Directed Research and Development (LDRD) project intended to improve the laboratory's multidisciplinary capabilities in energy systems analysis. In this context, participants from various areas of the laboratory collaborated. The initial product is documented in a series of white papers that spanned a broad range of topics, including: the successes and failures of past modeling studies, sustainability, the intersection of power and water, natural gas, oil dependence, energy security, nuclear power, the role of non-governmental organizations in decision making, infrastructure needed if the hydrogen economy were to develop, the process used by the public and others in assessing risk and making decisions, the perceptions of nuclear power and other studies. Several of these studies have been or are being documented as SAND Reports [Karas, 2004; Tatro et al., 2005; Drennen and Klotz, 2005; Brewer, 2005a; Brewer, 2005b]. A group of policymakers and modelers was assembled to discuss ways in which communication and impact between the communities might be improved. Summaries of these projects can be found under "White Paper Summaries" in Appendix L. These projects have provided a background and discussion framework for the team in carrying out inter-comparison of many of the commonly available electric power sources in present use, including consideration of how more advanced versions of these technologies might contribute to our future needs. The inter-comparisons are made on the basis of cost, environmental factors, sustainability, and other characteristics that determine the ability of the technologies to satisfy the required technical and social needs.

A software package, based upon POWERSIM® and containing the salient features of the electric power systems selected for comparison, gives the reader opportunity to learn the consequences of choosing various electric power options by making choices that will be available to future policy makers and the technical and financial communities. This report contains a short summary of the software, which is described in more detail in a self-contained report in process.

INTRODUCTION

This analysis is aimed primarily at understanding how various electricity generating options can best serve needs in the United States. In addition to cost, the report examines various advantages and impediments for implementing electric generation options, such as environmental features, sustainability, technological improvements, or changes in policy or law that may be required, etc. Because energy fuel supplies, the equipment to generate electricity, and effluents cross borders, we cannot completely confine the scope of this work to the United States, but for the purposes of this early modeling effort, we limit ourselves as much as possible to a focus on comparisons only within the United States. Others have produced comprehensive reports to establish international comparisons, primarily focused on energy sustainability issues; a notable report that gives comprehensive reviews of previous studies, covers all energy uses, and goes on to describe the means for measuring several dozen parameters to define sustainability was published by the International Atomic Energy Agency (IAEA, 2005). The IAEA report, like many previous reports, concentrates on metrics of success, but does not fully address impediments to progress and technological maturity. This study reported here focuses on electric power options, comparisons of options, and efforts needed to realize progress toward chosen options. In addition to this report, a computer aid has been developed to allow a non-expert to gain insights by making comparisons of various options based on cost and other attributes such as technological, social, and policy constraints [Drennen, et al., 2005, not yet published].

While cost is currently the dominant characteristic in the adoption of energy technologies, other criteria like environmental and health impacts, energy dependence, and infrastructure vulnerability are becoming increasingly important values in public discourse. Likewise, recent analysis commissioned by the Department of Energy (DOE) has indicated that factors other than cost are important in evaluating energy science and technology programs (National Research Council, 2001). However, there is disagreement with the NRC rules laid out for evaluating technology research and development (R&D) programs (Moore, et al., 2005). Other methods may allow for improved assessment of the benefits of R&D investments. For all of these reasons, the Energy Systems Analysis LDRD team is exploring options for analysis of energy technologies, and has developed a multi-criteria framework that will allow comparison of energy options with a set of metrics that can be utilized across all technologies. This section of the report discusses several evaluation techniques and introduces the set of criteria (embodied in our Star Diagram) developed for this LDRD.

Multi-criteria decision making (MCDM) frameworks have been applied in many decision-making settings where energy and environmental issues are of similar importance (Greening and Bernow, 2004; Pohekar and Ramachandran, 2004). Energy and environmental issues both embody uncertainties resulting from long time frames and capital-intensive investments (Huang, et al., 1995). But the sources of uncertainty can have different time frames (e.g., ecological impacts can long outlive the productive life of an energy technology or infrastructure); differences in geographic and spatial impacts exist; and the scale of required investment and outcome can vary widely (Munda, et al., 1994). As a result, reconciling divergent goals in the nexus between energy production and use and environment (particularly water resources desired for electric power production) is an area of research and continuing inquiry.

A good application of this framework, and the focus of our efforts this year, is science and technology program management. Opportunities for enhancing planning and evaluation functions exist both internally at Sandia and for external customers like DOE. The framework could be used to support both strategic-level technology program decisions and for tactical-level investments in projects within those programs, as illustrated in Figure 1. For planning situations where the goal or mission is somewhat ambiguous, MCDM can play a significant function in assisting the process of technology road mapping. R&D planning (e.g., technology road mapping) exercises where the best means to accomplish the mission is not clearly known at the onset can benefit from the expansion of the process to include a step where the goals or attitudes of the public and of decision-makers or planners toward various technology attributes are assessed. An SNL report produced as a result of this LDRD covers in great detail the ways that people learn, remember, and assimilate knowledge and experiences, assess risks, and make decisions [Brewer, 2005a.].

Task 3 of the LDRD presents a method for interactively and understandably introducing our data to virtually any individual, whether scientifically trained or not. In particular, the computer application POWERSIM® will be applied to the data generated, and the user will be able to interactively vary important factors and gauge the consequences on cost, environmental factors, etc. The application software will graphically depict such factors as whether policies and technology are already available to implement the chosen path, or whether such areas need to be improved.

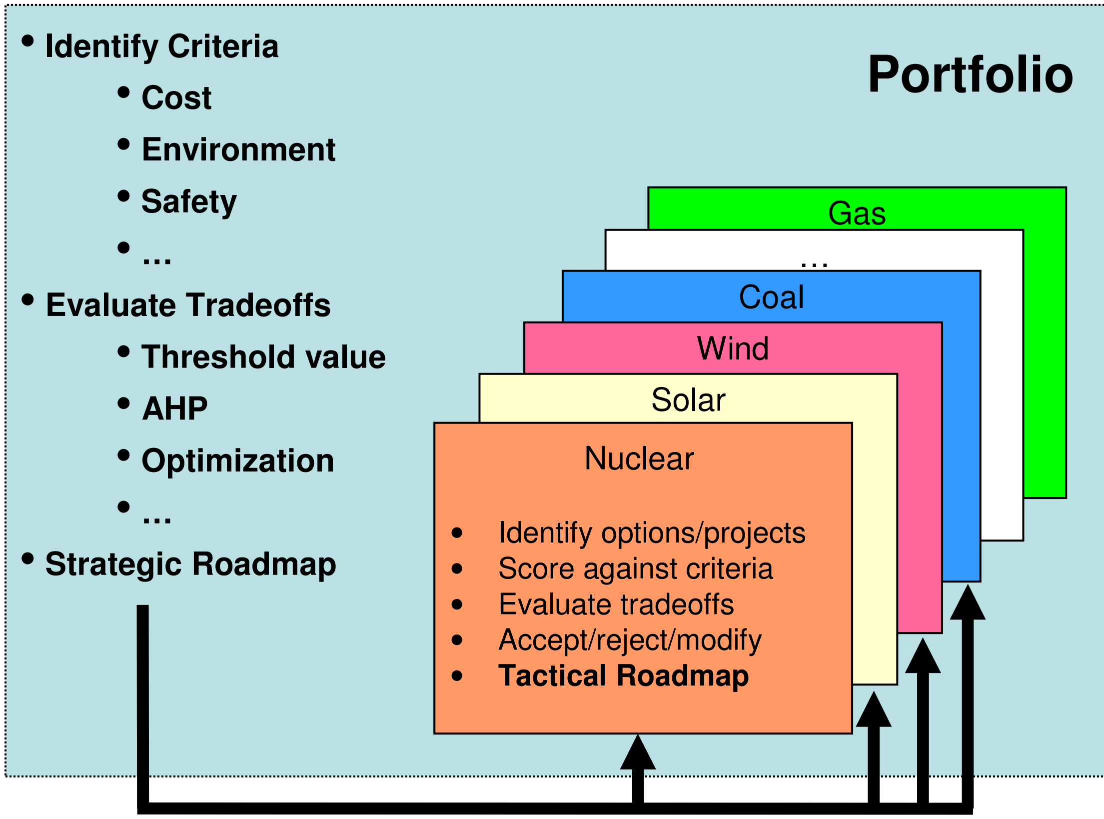

Figure 1. Use of multi-criteria decision making in technology program management.

Technology road mapping was developed as a process for identifying potential enhancements for a given technology or set of technologies (Bray and Garcia, 1998; Garcia and Bray, 1997). In its original implementation, the mission or stated goal of the technology is known. But, in the broader application of R&D planning, the means to accomplish the mission may be not only uncertain, but may also change over the course of time. For example, R&D for improving electricity delivery focused on demand-side management (DSM) techniques and was initiated in response to increasing dependency on foreign sources of energy, and demands for electricity that were rapidly outstripping generation capacity. With a decline in energy prices (1986 onward), the rationale for use of DSM shifted from addressing these issues to addressing environmental impacts, reliability issues, and similar goals. Application of MCDM to the selection of electricity capacity expansion options has resulted in an increased usage of DSM to meet these types of divergent evolving goals (Hobbs and Horn, 1997). As a result of this type of experience, we know that MCDM can be used to elicit from decision-makers some of the strategic implications and uncertainty of the environment where a technology will be implemented. Both of these factors have also been included in the roadmapping process where appropriate as the method has gained greater acceptance and application (Bonnema, 2002; Bray and Garcia, 1997). These factors have been shown to have significant impacts on the choices made during the R&D planning exercise.

There are several options for evaluating multiple-criteria tradeoffs within technologies and across technologies. One is the threshold filter wherein decision-makers can define limits on acceptable threshold values for various attributes. For example, if costs are a consideration in the generation of electricity, then R&D planners may define a maximum cost per kilowatt hour and focus on technologies that are less than the determined maximum or where R&D would reduce the costs below that value. In the case where multiple attributes are of interest, thresholds may be defined for each attribute; and those technologies where the majority of the attributes are below the threshold for a given attribute would be considered as potential candidates for additional R&D expenditures.

In addition to a simple threshold comparison, several other MCDM methods have been applied to the selection of projects and the design of R&D portfolios (Kagazyo, et al., 1997; Lootsma, et al., 1986; Saaty and Bennett, 1977; Stewart, 1991). Perhaps the most common method used is the analytical hierarchy process (AHP). During the AHP, decision-makers are asked to compare every possible pair of criteria and give a ratio of importance for each pair. As an example, decision-makers might be asked to give a ratio for the importance of air quality impacts to costs. A suggested scale for AHP assessments is provided in Table 1 (Hobbs and Meier, 2000).

Table 1. Suggested scale for AHP ratio assessments.

The ratio for attribute I (e.g., cost) over attribute II (e.g., air quality impacts) should be:	
1	If the two attributes are judged to be equally important
3	If attribute I is judged to be slightly more important than Attribute II
5	If attribute I is judged to be moderately more important than Attribute II
7	If attribute I is judged to be strongly more important than Attribute II
9	If attribute I is judged to be extremely more important than Attribute II
2,4,6,8	If intermediate values between two adjacent judgments are needed

After the pair-wise comparison of attributes is completed by each decision-maker participating in the R&D planning process, an aggregate set of importance weightings of attributes can be derived. Then each alternative (i.e., a potential technology for R&D funding) may be scored by using this set of weights to combine attribute scores. Different groups of decision-makers at different periods of time may have different attribute weightings. One approach would be to assemble different groups of experts to provide weightings. Once technologies have been identified based on this process, the standard technology road mapping process can be undertaken identifying those components for additional R&D development.

MCDM techniques (including AHP) are complementary to more conventional techniques such as the monetizing of non-market valued benefits and damages (Hobbs and Meier, 2000). However, MCDM is not restricted to a single metric as are more conventional economic methods, and therefore measurable physical quantities (e.g., grams of a pollutant) can be used directly in the analysis. Often though, the best practice is the combination of the two methods. Monetizing in an MCDM framework is defensible when market-determined costs truly reflect the economic benefits/damages (e.g., compliance costs with no additional externalities) or defensible estimates of benefits/damages exist. Monetizing is arguably inappropriate when fundamental value conflicts might be hidden by the process; or when the decision process involves the public sector; or where unique local issues exist such that value judgments from other areas are not relevant; or when dollar values do not exist for social costs or are controversial. One of the main arguments for MCDM is that its use avoids some of the uncertainties associated with a decision-making process and reduces the problem to a clear choice (e.g., more or less tons of CO_2).

The primary benefits of adding MCDM to a decision process, including an R&D road-mapping exercise, are as follows (Hobbs and Meier, 2000):

- MCDM helps to structure a decision process, particularly the reconciliation of divergent views.
- MCDM allows for the display of tradeoffs between very different evaluation criteria.
- MCDM includes a "learning" component where alternatives previously not considered can be evaluated in the light of new information.
- MCDM methods help people make more consistent and rationale evaluations of risk and uncertainty.
- MCDM methods facilitate negotiations: (1) quantify and communicate the priorities held by different stakeholders; and (2) move the discussion away from alternatives and towards fundamental objectives and tradeoffs among those objectives.
- MCDM methods assist in the documentation of how decisions are made.

The Star Diagram

All MCDM processes or methods begin with the same step of the selection and definition of attributes. For the LDRD effort, the LDRD team has selected attributes that have or have had significant importance to the planning of national or local energy policy, infrastructure expansion, and similar undertakings. Nine criteria were identified as being significant in the definition of a portfolio of technologies for a technology road mapping exercise:

- Cost
- Service Limitations
- Environmental and Natural Resource Impacts
- Infrastructure Vulnerability
- Energy Dependence
- Policy Needs
- Science and Technology Needs
- Health and Safety Impacts
- Sustainability Limitations

Definition of these attributes is key to a successful MCDM process. Attributes are chosen to reflect important planning objectives or other concerns, and as a result the selection determines the success of the evaluation. In defining these attributes, six main issues needed to be addressed: boundary setting, double counting, value independence, specification of attribute definition, attribute quantification, and the proliferation of attributes (Hobbs and Meier, 2000). Expanded discussion of these issues can be found in Appendix A. The attributes (or vectors of characterizing criteria) selected by the LDRD team are summarized in a table in Appendix B, and more detailed discussions for each attribute appear in the subsequent appendices.

To summarize a technology succinctly, criteria scores obtained through technology attribute characterization can be converted to vectors and displayed on a "star" diagram. Figure 2 shows fictional current and advanced technology options for illustration purposes. For all criteria, a lower score indicates better performance or greater desirability—closer to the bull's-eye. Other presentation methods such as line shading or error bars can be used to illustrate some of the uncertainty in the vectors. Interactive graphical interfaces provide a good platform for multi-criteria scoring, and such an interface has been suggested from a previously developed Sandia model (Baker, et al., 2002). In any event, any number of options exist for effectively incorporating an MCDM process into a technology road mapping exercise.

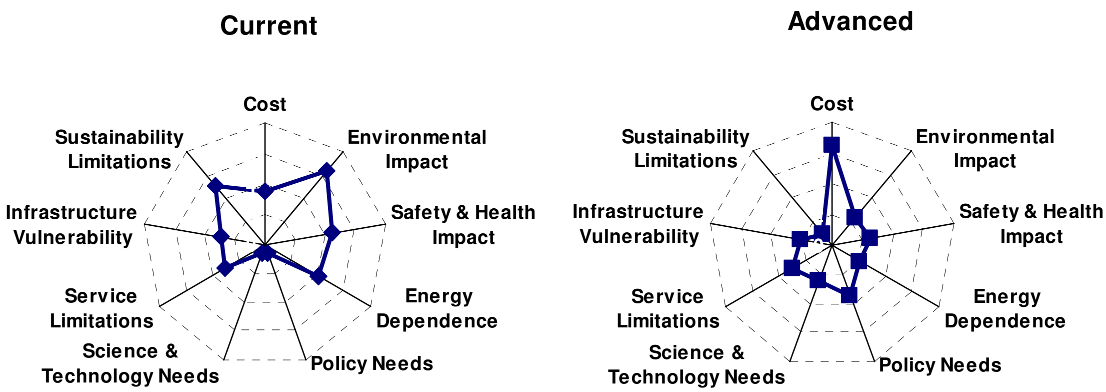

Figure 2. Star diagram of fictional current and advanced energy technologies. Scores closer to the origin are better. Note that here we connect the dots with lines for better visibility, but we emphasize to the reader that the area enclosed is not indicative of the relative merits, because area depends upon placement of the vectors as well as their magnitude.

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APPENDIX A. Definition of Attributes for Technology Characterization

Before any multi-criteria decision making effort can be undertaken, the attributes for consideration must be defined. Attributes are chosen to reflect important planning objectives or other concerns such as environmental and natural resource impacts or the sustainable use of non-renewable energy resources. For this effort, the LDRD team has selected attributes that have or have had significant importance to the planning of national or local energy policy, infrastructure expansion, and similar undertakings. In defining these attributes, six main issues needed to be addressed: boundary setting, double counting, value independence, specification of attribute definition, attribute quantification, and the proliferation of attributes (Hobbs and Meier, 2000).

<u>Setting boundaries</u>: How boundaries are drawn depends upon the perceptions of the definers as to what is important. For the LDRD, we are emphasizing the perceptions of US decision-makers. However, this strict interpretation of the defined boundary has been relaxed so that trans-boundary pollutants such as CO_2 can be included in the analysis. Although some attributes are purely local in nature such as land usage or footprint of a facility, in the aggregate this attribute can be significant in the decision to pursue the development of a technology.

<u>Double counting</u>: Double counting may not always be undesirable. For example, there may be a cost assessment for emitting a pollutant. The same pollutant may influence climate or health. It would be appropriate to count all of the effects. We list a few examples of double counting that need to be considered in an MCDM problem.

1. The first relates to double counting in the attributes (e.g., for an electricity expansion planning problem, "monthly bills" and "total resource cost" would double count cost).

2. A second double counting issue concerns the extent to which pollutant emissions are subject to tradable emissions allowances, and to the extent these emissions should also be used as an attribute (e.g., levels of SO_2 where a viable emissions market exists). In the case of SO_2 in the United States the total quantity emitted is fixed under the emissions allowance system, and the cost of purchasing attributes is already included in the cost attribute. However, the locality of emission does matter for this pollutant; therefore, whether to include SO_2 as an attribute would depend upon whether a case can be made that there is a differential locational effect *in addition.* If the costs of the locational effect are greater than the cost of allowances which are included in the cost attribute, then the incremental impacts of emissions of SO_2 should be counted as an attribute.

3. The third double counting issue is the comparison of means and ends. Attributes (the ends) should represent fundamental objectives and concerns. They should not be confused with the means for accomplishing those ends (e.g., including coal consumed and SO_2 emissions as attributes would penalize coal twice if coal's pollution is considered during weighting).

Conceptual independence: Attributes should be conceptually distinct. Strict conceptual independence is called "preference independence" (e.g., preferences on costs of reduction of one type of emissions is independent of preferences for reduction of another). Decision analysis differentiates between statistical independence ("facts") versus preference independence ("values"). A possible approach to avoiding problems with conceptual independence is to define an attribute that is the product of the two dependent variables.

Specificity of attribute definition: The rationale for selection of a specific attribute needs to be clearly specified. Does the attribute clearly reflect the problem under consideration? Or is there a clear linkage between the attribute and the problem? For example, is there a clear linkage between the quantity of solid waste generated (in tons) and the impacts of solid waste disposal? In the case of the LDRD, for example, do the tons of CO_2 emissions from an electricity generation technology clearly impact or relate to global climate change? As another example, do levels of imported fuels clearly impact economic security?

Quantification of attributes: Definition and quantification are interwoven. MCDM methods require that attributes must be quantified. However, not every important attribute may be given a number. There are four ways of dealing with attributes that are difficult to quantify.

1. Indirect valuation methods can be used without direct impact quantification. For example, "hedonic pricing" methods can be used to estimate the impact of existing power facilities (i.e., comparing property values between properties near a power plant with those at a distance).

2. Costs of mitigation scenarios can be used as a proxy (e.g., the costs of sequestering CO_2 could be used as a value for avoiding a ton of emissions).

3. Effects that are difficult to quantify, such as some ecological impacts, can be described categorically (e.g., "mild/beneficial impact" to "severe impact").

4. A proxy attribute may be selected (e.g., tons of a pollutant emitted may be a proxy for health effects of the pollutant). However, scientific validity for the linkage between the actual impact and the proxy needs to be established.

Attribute proliferation: A proliferation of attributes tends to make weighting more difficult. Further, proliferation may introduce a bias simply because of the reluctance to weight any particular attribute as near zero, which results in an under-weighting of truly important attributes. The guiding principle ought to be that one starts from those impacts which are the most important, and then, if at all possible, one attribute is selected for each of those concerns.

APPENDIX B. Summary Table of Criteria and Defining Attributes

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
COST (description found in Appendix C)			
Unit Overnight Capital Cost (C) is the total up-front cost of a technology if it could be built instantly	Constant $/kW (e.g., year 2003 $1800/kW)	Cost to society and market penetration. Increased capital cost increases cost to society and reduces market penetration.	Full fuel cycle investment costs including contingencies, owner and developer costs, etc. (everything but the construction loan)
Fixed Charge Rate (FCR) represents the cost of financing a project using a levelized annual fraction of capital	Real (inflation adjusted) %/yr	Capital recovery, financial risk, and taxation, relative importance of fixed versus variable costs. Increased FCR means higher costs of capital recovery, financial risk, or taxation and lower market penetration and increased importance of fixed costs relative to variable costs.	EIA estimates for the US including the construction loan
Unit Fixed Operations and Maintenance (FOM) cost is the minimum cost of operating the facility	Constant $/kW-yr	Cost to society and market penetration. Increased FOM results in decreased market penetration.	National electricity generation system
Capacity Factor (CF) is the fraction of rated output produced annually and may be constrained by economic or physical traits (see Service)	%	Relative importance of fixed versus variable costs (see also Service). Increased CF means decreased importance of fixed costs relative to variable costs.	National electricity generation system
Unit Variable Operations and Maintenance (VOM) cost is the marginal cost of operation, incl. fuel	Constant $/kWh	Cost to society and market penetration. Increased VOM increases cost to society and reduces market penetration.	National electricity generation system
Unit Levelized Fuel Cost (F) in real (inflation-corrected) terms	Constant $/kWh	Cost to society and market penetration. Increased VOM increases cost to society and reduces market penetration.	National electricity generation system

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (description found in Appendix D)			
Global Climate Change (summation of CO_2, methane, N_2O, CO with possibly a reduction for aerosols such as SO_2)	Grams of all greenhouse gas (GHG) per kWh normalized to CO_2 utilizing the 3rd IPCC Assessment for reactive forcing effects and $/kWh for combining into a scalar; each species needs to be broken out, e.g., grams CO_2/kWh; costs will be the marginal costs of damage (offset by benefits) above and beyond sequestration costs or market value of carbon credits from carbon development mechanism (CDM) activities	Increases in global temperature, and climate change resulting in changes in sea-level, land-use, sustainability of life on the planet as we know it. Increases in concentrations of CO_2 and other GHGs in the atmosphere are hypothesized to lead to increases in global temperature, and climate change.	Global (i.e., transboundary) Note: Accounting done at point of emission (or fuel use).

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (continued)			
Acid Rain Effects Other than Human Health	Grams of SO_2 per kWh and grams of NOx normalized using coefficients from Contadini, et al., and combined into $/kWh for combining into a scalar; each species needs to be broken out, e.g., grams SO_2/kWh; costs will be the marginal costs of damage above and beyond costs of pollution control measures.	Acid rain (changes in ecosystems and wildlife, damages to buildings). Atmospheric chemistry results in transformation of SO_2 into sulfuric acid and NOx into nitric acid that is then deposited on various surfaces; increases in SO_2 and NOx emissions result in greater levels of acid deposition.	Local and regional; due to the uncertainty of the dose-response relationships and other potential indicators of damage, accounting is done at point of emission (or fuel use).
"Eutrophication" Effects	Grams of NOx per kWh and $/kWh for combining into a scalar; costs will be the marginal costs of damage above and beyond costs of pollution control measures.	Nutrient overload that deteriorates water quality and destroys aquatic ecosystems. Increased nitrogen loading into waterways results in “eutrophication.” Increased levels of NOx emissions result in increased nitrogen concentrations.	Local and regional; due to the uncertainty of the dose-response relationships and other potential indicators of damage, accounting is done at point of emission (or fuel use).

APPENDIX B. Summary Table of criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (continued)			
Visibility Impacts	Summation of grams of SO_2, NOx, P2.5 and P10 per kWh using coefficients from DeLuchi, et al. or Contandini, et al. and $/kWh for combining into a scalar; each species needs to be broken out, e.g., grams of P2.5/kWh; marginal costs will be the marginal costs of damage above and beyond costs of pollution control measures with some of these costs measured in terms of reduced tourism, etc.	Impaired visibility such as haze over the Grand Canyon. Increases in particulate matter are known to reduce visibility.	Local and regional

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (continued)			
Particulates Damage (major constituents include heavy metals, radioactive isotopes and hydrocarbons, sulfates, and nitrates)	Grams of P2.5 and P10 per kWh normalized using coefficients from Contadini, et al., and $/kwh for combining into a scalar; each species needs to be broken out, e.g., grams P2.5/kWh; costs will be the marginal costs of damage above and beyond costs of pollution control measures.	Materials damage due to soiling and possibly corrosion, damage to foliage, and possible health effects to animals. Increases in particulate matter are known to reduce visibility.	Local and regional; due to the uncertainty of the dose-response relationships and other potential indicators of damage, accounting is done at point of emission (or fuel use).
Airborne Heavy Metal Contamination of the Ecosystem	Grams of mercury per kWh and $/kwh for combining into a scalar; costs will be marginal costs above and beyond costs of pollution control measures.	Causes birth defects, reduced reproduction, organ (brain, heart, kidneys, lungs, and immune system) damage, and death in domesticated and wild animals. Mercury concentrations (as with other heavy metals) increase through the food chain. Elemental mercury is converted to methylmercury (a highly toxic form) in organic systems, and builds up in fish, shellfish and animals.	Local and regional; due to the uncertainty of the dose-response relationships and other potential indicators of damage, accounting is done at point of emission (or fuel use).

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed	Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (continued)				
Water and Ground Contamination Damage to Ecosystem from Disposal of Waste Products	Grams of ash (fossil-fuel combustion) or heavy metal (nuclear spent fuel) per kWh and $/kwh for combining into a scalar; each physical component needs to be reported separately, e.g., grams of ash per kWh; costs will be the marginal costs of damage above and beyond costs of pollution control measures.	Special facilities must be constructed to contain waste products to avoid impacts on ecosystem. In the case of ash, these facilities must be RCRA compliant. In the case of nuclear spent fuel, these facilities must meet the requirements under the Nuclear Waste Policy Act of 1982 (e.g., Yucca Mountain). Ash generated during fossil-fuel combustion contains high concentrations of heavy metals (e.g., cadmium, zinc, lead). If leached into ground water, these constituents pose hazards to the ecosystem. Spent nuclear fuel poses a radio-toxicity problem resulting in “flu-like” symptoms or death in animals, and potential genetic damage.		Local and regional; due to the uncertainty of the dose-response relationships and other potential indicators of damage, accounting is done at point of waste generation (or fuel use).
Land Use and Landscape Degradation	Acres of land included in a footprint per kWh (Note: landscape or visual degradation is highly variable and is excluded) and $/kwh for combining into a scalar.	Land-use impacts evolve primarily from the conversion of land from other purposes such as agriculture, recreation, or commerce. Greater land usage for power production means less for other purposes; as populations increase or in already densely populated areas, levels of impact increase accordingly.		Local

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENVIRONMENTAL AND NATURAL RESOURCE IMPACTS (restricted to non-human health environmental impacts) (continued)			
Water Consumption for Generation	Acre-feet of water consumed per kWh and $/kwh for combining into a scalar.	Additional water usage in areas of short supply impacting ecosystems and agriculture; and aquatic organism "impingement." Diversion of water to power generation results in reduction in the availability of water for other purposes. Heavy dependence upon water requires the intake of water from streams, rivers, and lakes with the added risk of damage to wildlife (e.g., salmon on the Snake River, the snail-darter, etc.).	Local
Thermal Hazards to the Ecosystem	Acre-feet of water released per kWh generated and $/kwh for combining into a scalar.	Thermal pollution resulting in damage to flora and fauna. Thermal pollution may occur as a result of the discharge of heated water into streams; thermal pollution can also occur as a result of the release of steam into the local climate (i.e., changes in micro-climes).	Local

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SAFETY AND HEALTH (description found in Appendix E)			
Construction and Transportation of Materials Hazard	Fatalities/Injuries per kWh	Size and number of plants/pipes and other energy infrastructure needed for each energy technology. Construction injuries and fatalities have a direct effect on productivity, facility construction costs, and societal welfare on lives and health of citizens.	National
Mining of Materials Hazard	Fatalities/Injuries per kWh	Number of plants/pipes, amount of fuel needed to meet energy needs. Mining/Refining injuries and fatalities have a direct effect on productivity, facility construation costs, and societal welfare.	National
On-the-Job Hazard	Fatalities/Injuries per kWh	Number and safety of plants. On-the-job injuries and fatalities have a direct effect on productivity, facility operating costs, and societal welfare.	National
Sabotage/Terrorism	Risk per kWh*	Vulnerability of plants and other infrastructure aspects – pipes, power lines, etc. Power sources have particular appeal among the terrorist enemies to the US. In addition to disrupting the economy and energy infrastructure, the possibility for instant death to those in the plant's vicinity adds more value as a terror target.	National
Energy Transportation Hazard	Fatalities/Injuries per kWh	Miles of human-facilitated energy transportation. Energy transportation injuries and fatalities have a direct effect on productivity, facility operating costs, and societal welfare.	National

* This will be difficult to quantify, as there is no experience base, but the total risk would rise in proportion to installed capacity.

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SAFETY AND HEALTH (continued)			
Availability/ Reliability	Proportion of time system is available	Steadiness and reliability of energy system. During times of medical or meteorological necessity, the lack or intermittency of an electricity source can have dire consequences on those that have been depending on it to provide them energy for necessary processes (cooling, medical equipment, etc.). This impact could also be included in infrastructure vulnerability.	National, by Region
Malfunction/Disaster	Risk per kWh	Robustness of safety controls of plants and other infrastructure aspects. Akin to the terrorism/sabotage criterion – were a power source to malfunction, economic and infrastructure disruptions could occur along with injury and death.	National
Proliferation Threat	Fissile material per kWh	Nuclear material produced during energy generation. Unsecured energy by-products can be a cause for concern if it fell into the wrong hands.	International

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SAFETY AND HEALTH (continued)			
Pollution Effects	Fatalities/Injuries per kWh	Amount of air pollution created during energy production; causes human respiratory health problems. There are established links between airborne particles and chemicals and decreased health of individuals in their general vicinity. Moreover, the public perception of this problem is immense. If we are to be concerned with the public's opinion, then a cleaner energy system would have to be valued much more highly than a dirty one, were all things equal or negligibly different.	National, by Region
Contamination Effects	Fatalities/Injuries per kWh	Amount of soil/water contamination created during energy production; mercury and other heavy metals causes birth defects, reduced reproduction, organ (brain, heart, kidneys, lungs, and immune system) damage, and death. Akin to pollution effects – contaminated soil and water have direct impacts on human life, and an even bigger impact of human opinion.	National, by Region
Decommissioning Effects	Fatalities/Injuries per kWh	Size and number and design life of plants and other energy infrastructure needed for each energy technology. Deconstruction injuries and fatalities have a direct effect on productivity, facility operating costs, and societal welfare.	National

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
ENERGY DEPENDENCE (description found in Appendix F)			
Dependence by US on Foreign Imports of Fuel	Share of imports of a fuel (e.g., oil, LNG, or yellow cake) to US over time projected using AEO 2005, and $/kWh; costs calculated from a range of sources as per the bibliography at the end of the attribute description.	Concerns over increasing or potential increases in foreign dependence for energy supplies. Increased dependence on foreign energy supplies represents a security threat.	Global. Accounting done at point of use.

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
POLICY AND MARKET NEEDS (description found in Appendix G)			
Price Regulation: Government regulations of prices, or prices being set by a monopoly or association	0 to 10 scale indicating the estimated levels of policy intervention to encourage market penetration of a technology. A score of 0 indicates that the technology is viable without any regulatory price support, and 10 indicates that strong price support is a must.	Price regulation can help establish a new technology or can accomplish various social objectives. Often, regulation will cause market distortion, and can have unintended consequences. The final cost of power can also be influenced by other types of credits or regulations, some of which are listed in this chart.	Prices may be set by using governments or entities, as well as by cartels, such as OPEC.
Production Credits or Use Taxes: Use taxes internalize some of the externalities associated with the use of energy; production credits reduce energy costs	0 to 10 scale indicating the estimated levels of policy intervention to encourage market penetration of a technology. No production credit needed is scored with a 0, and a strong need for such credit earns a score of 10. No use tax needed earns 0, and a high use tax could earn a score of 10.	Levels and types of energy consumption: Production credits reduce the relative costs per kWh, and thereby increase demand for a given type or technology; use taxes internalize some of the externalities of energy consumption and result in reductions in demand. An example of a use tax is the federally imposed tax on nuclear power for waste management. Use taxes may also be placed merely to raise revenue, with no direct intent to shape electric usage.	Taxes may be imposed at many points, from producing country or region, to the user.
Regulation for reliability or security reasons – or insistence by users for certain standards	0 to 10 scale indicating the estimated levels of policy intervention to encourage market penetration of a technology, with 0 being no intervention and 10 indicating an overbearing regulation program.	Economic and social concerns requiring the ready and consistent availability of electricity. Properly designed regulation can achieve social and economic goals for areas where markets fail, for example in allowing utilities to charge rate-payers for the cost of excess capacity to help assure reliability.	US electrical generation system, and associated markets.

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
POLICY AND MARKET NEEDS (continued)			
Environmental Regulation, including waste disposal and decommissioning. This can include international agreements or treaties, such as Kyoto, or agreements concerning mineral rights in Antarctica.	0 to 10 scale indicating the estimated levels of policy intervention to encourage market penetration of a technology. A score of 0 denotes no intervention, and 10 a high level of binding intervention.	Health or environmental concerns unaddressed in existing regulation. The impact may be direct or indirect. Policy may regulate by direct regulation, or may be indirect. For example, although the US does not subscribe to the Kyoto accord, some European businesses are interacting with US businesses in a manner dictated by Kyoto, and some groups of states, such as in New England, are moving ahead with independent carbon dioxide management efforts.	US and global in the case of transboundary pollutants.
Regulations on rights of way and land use	0 to 10 scale indicating the estimated levels of policy intervention to encourage market penetration of a technology. A score of 0 indicates either that adequate right-of-way exists, or can easily be obtained, and 10 indicates extreme opposition.	Land use and planning for the benefit of the public, for example the development the Alaskan oil fields and concerns about ecological preservation. Properly designed regulation can achieve social and economic goals for areas where markets fail.	US and where appropriate globally.
Regional Concerns, Public Perceptions, Social Equity, and Public Trust	The units and quantification are often qualitative, but should be reduced to technical specifications early in any dispute.	The impacts are high, and may make the difference between opening a new mine or power plant, for example. The links are often indirect, because here many emotional concerns are likely to arise.	
Power structure represented by various lobby and interest groups	Dollars or influence from lobby groups in favor of a technology would win a score of 0, and funding and activity against an activity could produce a score of 10, if such efforts make it essentially impossible to deploy a technology.	Perhaps more than any other single factor, influence peddling spells success or failure for a technology. The links here are sometimes technical, but more often are founded on economic self-interest. Understanding the strategy behind alliances can give invaluable perspectives.	Influence peddling certainly extends to area of foreign diplomacy; there appear to be no well-defined boundaries.

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
POLICY AND MARKET NEEDS (continued)			
Jobs, and Economic Development	0 to 10 scale indicating the estimated levels of policy intervention that would be required to encourage market penetration of a technology. For example, a score of 0 indicates that no new policies are required to cause wide use of the technology, and that jobs and economic development are likely to follow. A 10 would indicate that there is no hope of development without extensive intervention.	Economic growth and expansion of the labor pool. New technologies maintain world competitiveness, can result in the development of new industries, often result in a more skilled work force, and can result in the expansion of the work force.	National markets
Propensity to introduce legislation calling for research and development or special studies to address a problem that that may not be satisfied by normal free market dynamics.	0 to 10 scale, with 0 denoting ample funds available with good political support for continuation, and 10 indicating great public and congressional resistance and no effort for support. A score of 5 would indicate bills have been submitted and there is some likelihood of passage.	This metric is designed to gauge the likelihood that Congress will make public funds available to pursue a given technology.	

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed	Linkage between Attribute and Impact	Boundary
SERVICE (description found in Appendix H)				
Economic Duty Limitations impact the desirable capacity factor and are a function of the cost attributes (see Cost)	Qualitative scale of 0 to 5 with 0 as best or no constraints	Economic market share limitations. For a constant levelized energy cost (LEC), higher fractions of variable costs increase market share potential, but normally high fixed-cost technologies are lowest total cost in base-load duty. Because the potential market share for a particular technology depends upon the economic duty of other technologies in the portfolio, complex analyses (or expert estimates) are needed.		National (may require regional analysis)
Load Following Limitations indicate how well a technology can adjust output to meet time-variant loads and include factors such as ramp rate and efficiency at part-load or in small plant sizes	Qualitative scale of 0 to 5 with 0 as best or no constraints	Physical market share limitations. For example, hydro can be dispatched at a high ramp rate to “regulate” rapidly intermittent wind. Higher ramp rates and part-load or small-size efficiency indicate increased capacity to follow loads and regulate intermittent generation and larger market share potential. Because the potential market share for a particular technology depends upon the physical limitations of other technologies in the portfolio, complex analyses (or expert estimates) are needed.		National (may require regional analysis)
Peak Period Capacity Credit (the capacity factor during the peak demand period)	%	Economic market share limitation applicable to technologies with time-dependent resources like many renewable energy technologies. The value (not cost) of power varies with economic duty. Increased peak periods capacity credit results in a potentially greater share of a critical market served.		National (may require regional analysis)

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SCIENCE AND TECHNOLOGY NEEDS (description found in Appendix I)			
TML 10 – Nothing known about how to solve the problem* **TML 9** – Basic principles observed and reported **TML 8** – Technology concept and/or application formulated **TML 7** – Analytical and experimental critical function and/or characteristic proof of concept **TML 6** – Component and/or breadboard validation in laboratory environment **TML 5** – Component and/or breadboard validation in relevant environment **TML 4** – System/sub-system model or prototype demonstration in a relevant environment—for example, in a power plant on a simulated power grid **TML 3** – System prototype demonstration in the power grid environment, but using a cadre of special experts	The units are descriptive of how close to maturity a technology lies. One may in some cases make some estimates of the time and cost expected to be involved in advancing to a higher maturity status. This would most likely be placed in text describing a technology option.	Commercial viability of technology. Time to commercial viability indicates levels of R&D expenditures that must be made before commercialization.	We will emphasize technology as it is practiced and is familiar to the US national community, but we note that we must consider international technologies, to the extent that technologies are usually fairly easy to import. For example, if we consider breeder reactors, one would be remiss not to use French operating experience.

* These definitions are adapted from the NASA definitions of technological readiness.

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SCIENCE AND TECHNOLOGY NEEDS (description found in Appendix I)			
TML 2 – Actual system completed and qualified through test and demonstration and used on the grid in a commercial application* **TML 1** – Actual system capable of turn-key operation by generally available operations personnel **TML 0** – The technology is so mature that substantial improvement seems unlikely			
* These definitions are adapted from the NASA definition of technological readiness.			

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
INFRASTRUCTURE VULNERABILITY			
We use the Herfindahl index that establishes vulnerability by assessing the multiplicity of supply sources, or may also be applied to other "bottlenecks," such as critical terminals or transmission lines.	$H = 10 \sum_{i} X_i^2$ where X is the fraction of one type of energy from source i, or the fraction of energy entering a system through a portal i. We multiply by 10 to make the number consistent with other metrics.	The impact of a supply disruption may be very large if one or a few major suppliers are disrupted. An example would be the profound effect of electricity disruption if all the power for a city were to arrive via a single transmission line.	National, but will extend across borders, particularly for petroleum products, and increasingly for natural gas.

APPENDIX B. Summary Table of Criteria and Defining Attributes (cont.)

Definition of Attribute	Units of Quantification	Impact Addressed Linkage between Attribute and Impact	Boundary
SUSTAINABILITY LIMITATIONS (description found in Appendix J)			
Persistence: Length of time of supply of a given resource at current technology and use	ratio of time scaled between 0 to 10	Concerns over long-term energy supply, prices, and economic growth and maintaining a standard of living Utilizing persistent energy sources expands the time horizon over which less persistent sources are available without sharp price increases.	National; domestic production and use rates; current production efficiencies; and domestic pop growth.
Capacity Matching: Compares the net exergy produced in a system with the exergy needs of the consumer	# ratio of unmet needs scaled between 0 to 10	Maintaining a certain way or quality of life requires continuous exergy production. Matching exergy sources with exergy needs can sustain a way of life.	National; domestic exergy applications.

APPENDIX C. Cost Criterion

Definition

The cost of energy from a technology strongly correlates with its penetration into a competitive market. Costs also impact the quality of life and national economic competitiveness in global markets. Higher energy costs relative to other costs would reduce the share of income available for other goods and services that are deemed to promote the quality of life, for example, by increasing the cost of travel the share of personal income available for medical services is reduced. Further, higher energy costs relative to global competitors makes energy-intensive products less competitive in the global market. To address the aforementioned issues, the Levelized Energy Cost (LEC) is used as the figure of merit.

Importance

Currently and historically, cost is the dominant criterion in energy system evaluation and deployment. Often, consideration of alternative technologies is framed as a trade-off between societal benefits and private or internalized costs. While opinion varies about the monetary value of the other criteria, cost reduction is almost always a key R&D goal for energy technologies. Lower costs encourage broader acceptance and wider market penetration.

Impacts

Costs directly impact the market penetration of new technologies. Costs also determine the order of dispatch and preferred operating capacity factor. Lower costs result in increased use whether in a regulated environment or in a competitive market. Even in the case of renewable portfolio standards, cost is a major consideration in setting targets. Therefore, the cost attribute is a driving factor for the acceptance of a new technology.

Attributes Quantification

The key attributes for calculation of LEC are listed in the table included in Appendix B. In order to fairly compare technologies, it is important to consider the service provided (see Service criteria in Appendix H). In the case of electricity, this means the duty cycle (as captured by the capacity factor) as well as the transmission requirements. Distributed generation may avoid the need for additional electrical transmission. However, it may require additional fuel transportation infrastructure or local storage for distributed resources like solar photovoltaics. Generally, the infrastructure requirements used in this analysis should reflect a scenario wherein the energy technology is at least half its potential market penetration (Nth plant installed). Further, emissions mitigation measures such as scrubbing equipment are included in the cost vector; marginal environmental damage costs for emissions above scrubbed levels are used in the calculation of the environmental and natural resource vector.

The fixed charge rate is the percentage of capital costs per year allocated to the LEC and includes all financial costs such as capital recovery, taxes, construction loan, etc. The fixed charge rates used in this study vary by technology and are based on DOE/Energy Information Administration (EIA) estimates from National Energy Modeling System (NEMS). Documentation is available on the web at www.eia.doe.gov:

- Annual Energy Outlook 2005 with Projections to 2025. DOE/EIA-0383(2005).
- Electricity Market Module of the National Energy Modeling System, Model Documentation Report 2000. DOE/EIA-M068(2004).

The EIA fixed charge rates include current tax law and trends in power plant finance.

Constraints

The costs should include the full life cycle when data are available (decommissioning costs are often difficult to estimate). The costs should also be compared on an equal basis of service (utility) delivered. For example, the costs of transmission and distribution of electricity (and fuel) must be considered when comparing distributed generation with centralized generation options.

Mathematical Model

The LEC in \$/kWh is calculated as follows:

$$\mathrm{LEC} = \frac{\mathrm{C} \bullet \mathrm{FCR} + \mathrm{FOM}}{\mathrm{CF} \bullet 8760} + \mathrm{VOM} + \mathrm{F}$$

where

C = Unit overnight capital cost, including project development and contingencies in \$/kW
FCR = Fixed charge rate in real terms (inflation-adjusted) in fraction/yr
FOM = Fixed real annual operation and maintenance (O&M) cost in \$/kW-yr
VOM = variable real O&M cost (including fuel) in \$/kWh
F = levelized fuel cost in constant \$/kWh
CF = percentage of full-load annual energy production as a fraction
8760 = hours/year.

Uncertainty

In reality, costs are not known precisely, particularly estimates for future technology costs. There are several reasons that quantifying this uncertainty is useful, but basically it helps one understand the system and better compare options and potential outcomes.

Much of the energy infrastructure in the United States is built, owned, and operated by private industry. Different companies have different risk tolerances and targets, but all want to maximize return for a given risk level and make their investments accordingly. For example, some estimates of the LEC from nuclear power plants is competitive with coal. However, the uncertainty in the nuclear power costs is much greater than that for coal. The majority of power plants built from 1990 to early this decade were fueled with natural gas because new technology made them less expensive, cleaner, and easier to site than several competitors and their low fraction of fixed costs seemed to reduce financial risk (due to discounting future fuel costs). However, natural gas prices have increased several fold and appear likely to remain volatile for some time. Some plants had contracts that transferred this fuel cost risk to a customer. Since someone is always left holding the bill, these increased risks have led to an environment where other plant types are being deployed in greater numbers.

In managing research and development (R&D) programs, such information is useful in developing appropriate portfolio diversity. A sensitivity analysis provides valuable information on the key drivers and key unknowns. This can be used to tailor R&D programs and individual projects to maximize benefits. For example, reducing the LEC is a prime objective of the DOE Solar Energy Technologies Program. Having a good knowledge of the impacts of various inputs and uncertainties on the LEC permits better evaluation of programs or individual projects to reduce the cost or uncertainty. Another important aspect of uncertainty in this context relates to risk management of R&D projects that themselves have uncertainty related to cost, duration, and ability to meet technical objectives. The combination of uncertainty information about both the system in question (e.g., cost of solar) and the R&D projects under consideration (e.g., cost, duration, impact or probability of meeting goals) provides program managers insights that help make difficult funding decisions and achieve the desired portfolio diversity.

Crafting public policy in the energy arena is a difficult task; there are so many divergent perspectives that can often be effectively argued. Energy infrastructure typically also has a long lifetime, from ~15 years for autos to ~30 years for power plants and refineries to 70+ years for pipelines, dams, etc. Once infrastructure is installed, the investment cost is stranded, making a change to a different approach that much more expensive to society. However, predicting that far into the future, the inputs most valuable for infrastructure decisions are rife with uncertainty. Policymakers benefit from better understanding these uncertainties, and from approaches that help them create robust or "no-regrets" solutions. Such solutions, while maybe not optimal for all futures, are often good solutions, and rarely bad solutions. An example of current interest is the hydrogen economy that offers the potential for domestic production of energy and low environmental impacts[1]. However, the hydrogen economy faces a common conundrum for energy technologies. Costs are currently much higher than current approaches and are predicted to decrease with further development and deployment, but deployments are unlikely until costs become competitive with current approaches. Furthermore, it is uncertain when, if ever, costs would become competitive with other options. This is important because global economic competitiveness can be impacted by local energy costs. Conversely, the energy infrastructure cannot be changed quickly to respond to a problem such as rapid climate change or an oil production rate peak. If changes do not start before economic competitiveness is reached, it may be too late.

[1] Not all hydrogen-related technologies offer these potential advantages, but several do.

Scoring

The impact of uncertainty on LEC was investigated for several electrical generation technologies using a Monte Carlo analysis approach. Tables C-1 and C-2 list low, most likely, and high estimates and the sources for these estimates. Triangular distributions were used to represent the attribute uncertainty. While this diminishes the tails of the results distribution, it was deemed appropriate for this application where the input distributions are essentially opinion and the 5- and 95-percentile bounds are probably the best fidelity that might be achieved. Commercially available @Risk software was used to perform the Monte Carlo analysis. Figure C-1 shows the capital cost distribution for residential photovoltaics (PV) in 2004.

Table C-1. Cost attributes for current (2004/2005) and future (2020) concentrating solar power (CSP), residential and commercial photovoltaics (PVr, PVc), pulverized coal (PC), and natural gas combined cycle (NGCC).

Technology	Overnight Capital Cost, $/kW			Real Fixed Charge Rate, %			Fixed O&M, Constant $/kW-yr		
	Low	Most Likely	High	Low	Most Likely	High	Low	Most Likely	High
CSP 2004[4]	$ 3,582	$ 3,980	$ 5,174	8.0%	12.5%	16.0%	$ 65	$ 71	$ 85
CSP 2020[3]	$ 2,270	$ 3,102	$ 4,653	8.0%	12.5%	16.0%	$ 49	$ 64	$ 79
PVr 2005[1]	$ 8,000	$ 8,470	$12,770	3.9%	4.3%[1]	5.2%	$ 92	$ 102	$ 305
PVr 2020[1]	$ 2,250	$ 2,500	$ 5,000	3.9%	4.3%[1]	5.2%	$ 9	$ 10	$ 92
PVc 2005[1]	$ 6,830	$ 7,440	$ 9,500	4.5%	5.0%[1]	6.0%	$ 37	$ 42	$ 83
PVc 2020[1]	$ 1,999	$ 2,221	$ 4,442	4.5%	5.0%[1]	6.0%	$ 8	$ 9	$ 37
PC 2004[2]	$ 1,115	$ 1,239	$ 1,363	15.5%	17.0%	18.0%	$ 22	$ 24	$ 27
NGCC 2004[2]	$ 521	$ 579	$ 637	14.5%	16.1%	17.5%	$ 9	$ 10	$ 11

1 DOE, 2006, Solar Energy Technologies Multi-Year Technical Plan (Draft September, 2005). Costs are per nameplate power rating in peak Watts DC. Year 2004 low, most likely, and high capital costs are from DOE data. Year 2020 low and high costs are 90% and 200% of 2020 DOE goal that was used as the most likely value.

2 EIA, 2005, Assumptions to the Annual Energy Outlook 2005. www.eia.doe.gov. Low and high capital cost estimates are 90% and 110% of most likely.

3 Sargent & Lundy LLC Consulting Group, 2003, "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts," NREL/SR-550-34440. This is the Solar 220 plant. Low, most likely, and high capital costs estimates are from SunLab, S&L, and 150% of most likely.

4 Stoddard, L., B. Owens, F. Morse, D. Kearney, 2005, "New Mexico Concentrating Solar Plant Feasibility Study. Draft Final Report." Prepared for New Mexico Energy, Minerals and Natural Resources Department. This is a 50 MW trough plant with 6 hours of thermal storage. Low and high capital costs are estimated at 90% and 130% of most likely.

Table C-2. Cost attributes for current (2004/2005) and future (2020) concentrating solar power (CSP), residential and commercial photovoltaics (PVr, PVc), pulverized coal (PC), and natural gas combined cycle (NGCC).

Technology	Capacity Factor, %			Variable O&M, constant$/kWh			Fuel, constant$/kWh		
	Low	Most Likely	High	Low	Most Likely	High	Low	Most Likely	High
CSP 2004[4]	32%	34%	36%	$0.003	$0.003	$0.004	$-	$-	$-
CSP 2020[3]	40%	70%	73%	$0.001	$0.001	$0.001	$-	$-	$-
PVr 2005[1]	14%	16%	20%	$-	$-	$-	$-	$-	$-
PVr 2020[1]	14%	16%	20%	$-	$-	$-	$-	$-	$-
PVc 2005[1]	14%	16%	20%	$-	$-	$-	$-	$-	$-
PVc 2020[1]	14%	16%	20%	$-	$-	$-	$-	$-	$-
PC 2004[2]	81%	85%	89%	$0.004	$0.004	$0.005	$0.011	$0.012	$0.014
NGCC 2004[2]	81%	85%	89%	$0.001	$0.001	$0.001	$0.028	$0.037	$0.056

1 DOE, 2006, Solar Energy Technologies Multi-Year Technical Plan (Draft September, 2005). Costs are per nameplate power rating in peak Watts DC. Year 2004 low, most likely, and high capital costs are from DOE data. Year 2020 low and high costs are 90% and 200% of 2020 DOE goal that was used as the most likely value.
2 EIA, 2005, Assumptions to the Annual Energy Outlook 2005. www.eia.doe.gov. Low and high capital cost estimates are 90% and 110% of most likely.
3 Sargent & Lundy LLC Consulting Group, 2003, "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts," NREL/SR-550-34440. This is the Solar 220 plant. Low, most likely, and high capital costs estimates are from SunLab, S&L, and 150% of most likely.
4 Stoddard, L., B. Owens, F. Morse, D. Kearney, 2005, "New Mexico Concentrating Solar Plant Feasibility Study. Draft Final Report." Prepared for New Mexico Energy, Minerals and Natural Resources Department. This is a 50 MW trough plant with 6 hours of thermal storage. Low and high capital costs are estimated at 90% and 130% of most likely.

Overnight capital cost includes all development, construction, and owners costs, but assumes the plant is built overnight. The fixed charge rate includes capital recovery costs, interest during construction (because large facilities cannot be installed overnight), and tax effects.

The most likely FCR values are based on the average used in the EIA NEMS model over the calculation horizon of 2005 to 2031 that is based on project finance, a 20-year project life, and US tax law in effect at the time of the analysis. The PV most likely FCR values are based on the DOE solar program financial assumptions such as adding the residential system cost to a 30-year home mortgage. High and low FCR estimates are from the author. In the case of concentrating solar power (CSP) technologies, the range is large to represent the impact of different financing approaches (e.g., utility, municipality, etc.) and possible incentives (taxes, loan guarantees, etc.) or lack thereof.

Fixed O&M, variable O&M, and fuel costs are levelized constant dollar (real) costs over the project life. CSP variable O&M costs are assumed to be 10% of total O&M, which appropriately yields similar costs to gas and coal plants. While the CSP values have greater uncertainty, variable O&M contributes little to the LEC of any of these technologies. Most likely fossil fuel costs are assumed to be the mean EIA estimate over the period 2005-2025; coal bounds are assumed to be 90% and 115% of most likely, while more volatile natural gas cost bounds are assumed to be 75% and 150% of most likely.

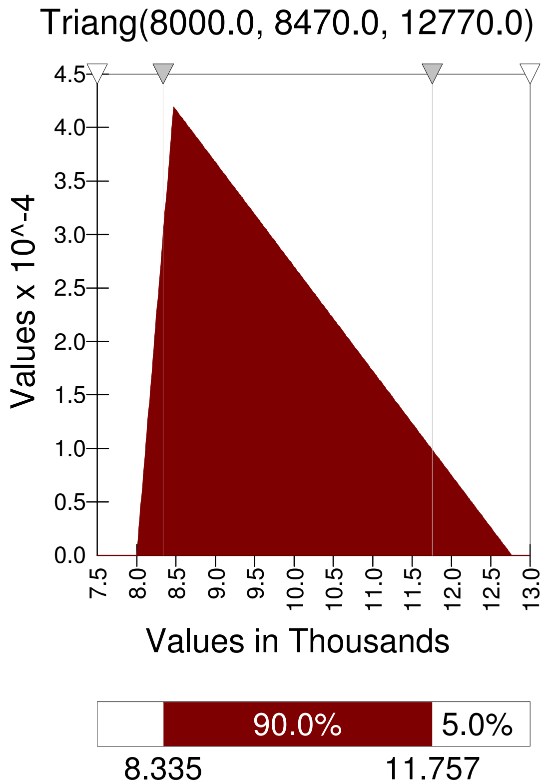

Figure C-1. 2004 residential photovoltaics triangular distribution of overnight capital cost ($\$/kW_{peak}$) used in Monte Carlo modeling. The 5% and 90% probabilities are indicated.

The most likely capacity factor of the fossil plants reflects how new plants are typically run. Upper bounds are typically constrained by planned and forced outages for maintenance and repair, while the lower bounds represent the potential for lower utilization. The capacity factor of the PV technologies depends on local resource conditions, primarily solar insolation and temperature. To be consistent with the PV cost attribute, capacity factor is the estimated annual production in useable Watt-hours AC per Watt DC peak system nameplate rating. The most likely capacity factor is from the best data available for Phoenix, Arizona (Moore et al., 2005a), the site selected by the DOE solar program for use in program planning and evaluation. The high bound is for Prescott, Arizona, a cooler site than Phoenix and one for which good experimental data also exists (Moore et al., 2005b). The low bound estimate is 90% of most likely. Less desirable solar sites may actually have lower values. Year 2020 capacity factor estimates are the same because it is assumed that the convention used in rating nameplate power and relative performance impacts of temperature and part-load operation remain unchanged.

The results of LEC calculations using 10,000 samples[2] from these distributions for attributes are shown in Figure C-2. Several items are noteworthy. First is that there was no attempt was made to address the potential non-uniformity in optimism or pessimism of estimated inputs obtained from the various sources. For example, one could argue that estimates taken from program goals could represent an optimistic or advocate position.

[2] The Latin hypercube sampling methodology was used.

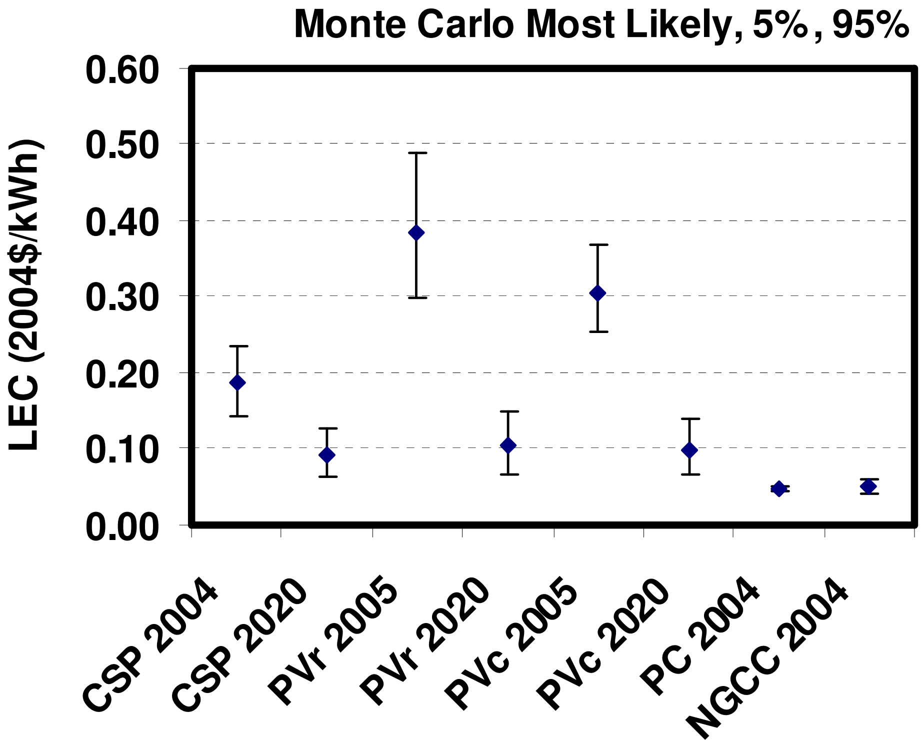

Figure C-2. Levelized energy cost (electrical generation) estimates for current (2004/2005) and future (2020) concentrating solar power (CSP), residential and commercial photovoltaics (PVr, PVc), pulverized coal (PC), and natural gas combined cycle (NGCC) facilities. The diamonds represent the most likely cost, while the whiskers show the 5% and 95% probability bounds. No attempt was made to address the potential non-uniformity in optimism or pessimism of estimated inputs obtained from the various sources.

The current and future PV generation costs are higher than the solar and fossil central generation technologies. However, photovoltaics generally compete with retail electricity costs,[3] not wholesale generation costs. In 2003, the average residential cost of electricity[4] was $0.087/kWh including an average cost of transmission and distribution of $0.026/kWh (EIA, 2005a).

The uncertainty of future CSP and PV cost estimates is less than for current costs, which seems counterintuitive. However, the uncertainties actually increase from 2004 to 2020 as a fraction of the mean cost estimate. The ratio of 2 standard deviations to mean for CSP, PVr, and PVc increases from 25% to 45%, 25 to 41%, and 22% to 39% respectively. This still implies that solar cost reductions will definitely occur during this period. While not certain, a history of prior cost reductions, likely continued R&D, and increasing deployments make this likely. The fossil technologies included here are mature, so potential future cost reductions likely have a modest

3 Local generation that offsets power produced. Excess generation that is returned to the grid is currently often also priced at retail rates in "net metering" contracts. However, photovoltaics without storage are intermittent, so it does not eliminate the need to construct generation and transmission facilities as backup. Consequently, only a small fraction (currently 0.5% in California) of total capacity is often allowed in net metering agreements.

4 Prices can vary significantly, typically between $0.05-0.15/kWh.

impact on LEC, especially when compared with future fuel costs. More environmentally friendly fossil technologies under development have larger uncertainties on cost and performance and would certainly be interesting to evaluate in a similar manner.

The lower uncertainty in LEC of pulverized coal (PC) compared to natural gas combined cycle (NGCC) is reflected in industry trends. The number of NGCC plants proposed for construction has declined while increases have occurred in proposed PC plant construction. While nuclear power is not shown, it also competes with coal power and has higher uncertainty for several reasons beyond the scope of this section.

In this study, as is often the case, some input distributions were skewed with the most likely value closer to the best case. This leads to the interesting result that using the most likely point estimates for each input yields a resultant that is *not* the most likely LEC. For example, Figure C-3 shows the resultant LEC distribution for residential PV in 2004. The most likely cost from Monte Carlo analysis is \$0.38/kWh, whereas using the most likely point estimates for each input yields \$0.33/kWh, a 13% error.

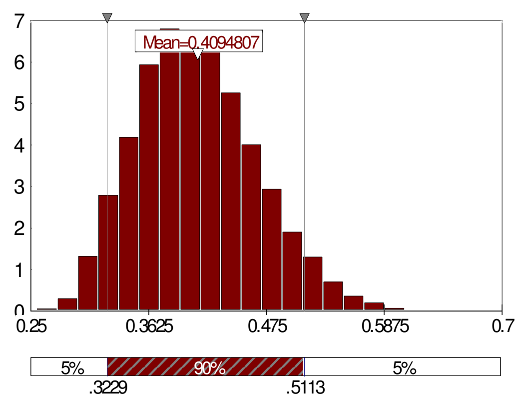

Figure C-3. Resulting LEC (\$/kWh) distribution from 10,000 samples. The most likely value is \$0.38/kWh, whereas using the most likely point estimates for each input yields \$0.33/kWh, a 13% error.

Another benefit of sensitivity analysis is the identification of key inputs, in this case that impact LEC. Table C-3 lists the top three drivers for each technology and their regression sensitivity. Positive values indicate that an increase in that input increases LEC and vice versa.

Table C-3. Top three regression sensitivities for calculation of LEC for current (2004/2005) and future (2020) concentrating solar power (CSP), residential and commercial photovoltaics (PVr, PVc), pulverized coal (PC), and natural gas combined cycle (NGCC). FCR is the fixed charge rate.

Technology	Top Sensitivity	Value	Second Sensitivity	Value	Third Sensitivity	Value
CSP 2004	FCR	0.84	Capital cost	0.50	Capacity factor	-0.14
CSP 2020	Capacity factor	-0.60	Capital cost	0.58	FCR	0.52
PVr 2005	Fixed O&M	0.59	Capital cost	0.57	Capacity factor	-0.49
PVr 2020	Capital cost	0.75	Fixed O&M	0.52	Capacity factor	-0.34
PVc 2005	Capacity factor	-0.63	Capital cost	0.58	FCR	0.49
PVc 2020	Capital cost	0.87	Capacity factor	-0.35	FCR	0.28
PC 2004	Capital cost	0.68	FCR	0.51	Capacity factor	-0.38
NGCC 2004	Fuel	0.99	Capital cost	0.09	FCR	0.08

Some technologies are dominated by one factor, such as the NGCC plant dominated by fuel cost, while others are more evenly impacted by several factors, such as the 2005 residential and commercial photovoltaics.

Simplified Uncertainty Analysis

The preceding analysis was performed using the Monte Carlo approach. In some cases, a simpler, faster analysis methodology may be desirable. Initially, a first-order analytical approach was investigated. In this approach, a Taylor-series expansion is constructed around the mean value and the higher-order terms are discarded. This provides estimates of the mean and variance (σ^2) of the output distribution from knowledge of the mean and variance of the input distributions (Ang and Tang, 1975). This results in nine algebraic equations that could easily be implemented into software such as EPSim.

Table C-4 compares the accuracy of this first-order approach with the Monte Carlo results. The 5^{th}-percentile and 95^{th}-percentile estimates for the first-order approach were assumed equal to the mean $\pm 2\sigma$. In most cases, the errors were optimistic (lower LEC), but sometimes they were pessimistic. While the error in standard deviation was sometimes large, the error in 5^{th}-percentile and 95^{th}-percentile estimates was typically less than 10% in magnitude. This first-order approach should be sufficient for the application illustrated here given the level of confidence in the input distributions. If the application requires more accuracy in an analytical approach, several options exit. Higher-order terms could be added to the Taylor series expansion. First- or second-order reliability methods could be used. Finally, the input distributions could be selected to make analytical solution easier, which would provide the full output distribution, not just mean and variance. For example, the input distribution for the ln(CF) could be used to simplify the LEC equation to a linear form.

Table C-4. Error of first-order method compared to Monte Carlo results for current (2004/2005) and future (2020) concentrating solar power (CSP), residential and commercial photovoltaics (PVr, PVc), pulverized coal (PC), and natural gas combined cycle (NGCC).

Technology	**Error Mean**	**Error σ**	**Error 5th-percentile**	**Error 95th-percentile**
CSP 2004	-0.1%	-3.6%	-5.6%	2.4%
CSP 2020	-1.6%	-45.6%	7.8%	-12.7%
PVr 2005	-0.5%	-28.9%	0.9%	-4.3%
PVr 2020	-0.5%	-13.0%	-8.6%	-1.4%
PVc 2005	-0.5%	-55.0%	8.3%	-8.3%
PVc 2020	-0.5%	-14.2%	-9.3%	-2.1%
PC 2004	0.0%	-15.4%	-0.3%	0.1%
NGCC 2004	0.0%	-0.2%	-6.1%	1.9%

APPENDIX D. Environmental and Natural Resource Impacts Criterion

Definition

As the energy infrastructure in the United States has developed, it has been recognized that production and use of energy has significant impacts on environmental and natural resource quality. This criterion is defined to capture those effects above and beyond (or in addition to) the environmental effects currently mitigated under various types of environmental regulation. Current mitigation or control measures that require additional investment are captured in the cost vector. Further, this criterion is restricted to the non-human safety and health aspects of a technology; human safety and health aspects are considered separately under the safety and health criterion.

Importance

Electricity generation has a major impact on the US and world environment. Perhaps the biggest environmental challenge is the emission of greenhouse gases. With approximately 4 percent of the world's population, the United States currently accounts for about 24 percent of total global emissions of greenhouse gases; the United States now emits greenhouse gases at levels more than 13% above levels mandated by the Kyoto Protocol. US power generation is responsible for approximately two-thirds of all domestic SO_2 emissions and approximately one-third of US nitrogen oxide emissions, both of which are precursors to acid rain, cause materials damage and visibility impairment, and, in the case of NO_x, contribute to eutrophication. Power generation also results in the emissions of mercury and other heavy metals that have been shown to cause serious damage to ecosystems. Finally, power generation results in land use, landscape degradation, and additional demand for water. Particularly, in the case of water in semi-arid regions such as the southwestern United States, this increasing demand could result in an environmental crisis exceeding current proportions before mid-century.

Impacts

New technologies would be expected to effect significant reductions in environmental loadings or natural resource degradation. Those improvements might include: (1) mitigation of global climate change; (2) further reduction in the precursors of acid rain; (3) lessening of eutrophication; (4) improvement in visibility; (5) further reductions in particulate damage resulting from materials soiling, corrosion, and damage to foliage; (6) reduction in airborne heavy metal contamination of the ecosystem; (7) further reduction of water and ground contamination from disposal of waste products; (8) lessening of land use and landscape degradation from the installation of power generation facilities; (9) reductions in water consumption for electricity generation; and (10) lessening of thermal pollution caused by the discharge of heated water or the release of steam.

Attributes Quantification

Several different physical measures of quantification will be used for this metric: (1) grams of a pollutant per kWh; (2) in the case of land use, acres of land included in a facility footprint per kWh; (3) in the case of water consumption, acre-feet of water consumed per kWh; and (4) in the case of thermal pollution, acre-feet-degrees of water per kWh. These rather disparate units are still usable since they will be combined only after being mapped to a scoring system common across the different attributes. The table in Appendix B provides a listing of the attributes for the environmental and natural resources (non-human-related effects).

Constraints

This measure will be restricted to impacts in the United States. In the case of cross-boundary impacts (e.g., greenhouse gases), generally accepted levels of importance will be employed; these levels will have appropriate international concerns taken into account.

Mathematical Model

The Environmental and Natural Resource Impacts (ENRI) criterion contains many possibilities for scoring. This is because many well-defined types of data are at our disposal, particularly when it comes to different emissions and pollutants that are often tabulated for the spectrum of technologies. From this wide selection, one can easily choose which factors appear to have the greatest impact on the environment, although in some cases, the choice is not so simple and may involve subjective judgments.

Unfortunately, this wealth of information can be distracting when it comes to finding an aggregate score for a technology's ENRI variable. Determining a per-kilowatt value of carbon dioxide or mercury emissions for a technology is straightforward, but combining the two into a cohesive number is a more difficult proposition, due to (among other things) their disparate impacts and scales.

To combat this problem, these quantities will be compared on a relative scale to benchmarks that are easily determined and can be consistently applied across different categories, both within and outside of the environmental criterion. The following rubric will be employed to produce a score for categories (such as pollutants) that cannot otherwise be combined very easily:

Physical Data

The first key step towards determining an aggregate criterion score is to find the physical information related to each constituent factor in the analysis. During the selection of these factors, one must ensure that no quantities are double-counted. For this reason, care has been taken to use unambiguous chemical formulae instead of more generic terms such as "greenhouse gases."

For the ENRI criterion, the following environmental quantities have been chosen for the study:

Emissions
CO_2 produced (g/kWh)
SO_2 produced (g/kWh)
NO_x produced (g/kWh)
$PM_{2.5}$ and PM_{10} produced (g/kWh)
Mercury produced (g/kWh)
VOC produced (g/kWh)

Water Use
Water consumed (acre-feet/kWh)
Water released (acre-feet/kWh)

Land Use
Land used in fuel harvesting and plant footprint (acres/kWh)

It is understandable that there may be some uncertainty inherent to these numbers. This uncertainty is welcome and can be effectively propagated through the subsequent steps, after which uncertain physical quantities will be converted to an uncertain criterion value.

Preliminary Scores

While the physical data should certainly be the true determining factors in the scoring, some work is needed to get a better grip on these numbers. It is desired that all scores be between 0 and 10, so clearly some normalization is needed. Moreover, this normalization should somehow be hardwired to realistic values; in other words, there should be a clear reason why a technology received a particular score in a category, and the more obvious and sensible the reason, the better.

In a sense, it would be best to map the continuum of possible physical quantities to the continuum that runs from 0 to 10. This works perfectly at the lower bound, where a quantity of zero corresponds directly to a preliminary score of zero – both being the ideals in their respective categories. However, these quantities, by their very nature, have no absolute maximum values. Furthermore, even if there were a theoretical maximum value in any of these categories, it could possibly be so far detached from today's realities of relatively clean and environmentally friendly energy sources as to render the score worthless.

However, since this project is intended to determine sensible alternatives to today's current energy policies, it is appropriate to use today's energy portfolio in this part of the analysis. Since data collection is already being performed for the technologies that comprise the bulk of US electricity generation, it is possible to use these numbers to derive a logical benchmark. For this, the following is proposed:

(To see a more detailed concept for normalizing category values within a criterion as well as then combining these criteria scores into an overall portfolio number, please see *Concepts for Determining an Overall Technology Score and Portfolio Mix* in Appendix L.)

A preliminary score of 0 will be earned for a technology in a particular metric if its corresponding physical quantity value is identically 0.

A preliminary score of 5 will be earned for a technology in a particular metric if its corresponding physical quantity value is the same as the weighted average of the physical quantities for the five most dominant electricity-producing technologies. This average is determined by using the weights listed in the following table, which lists the national share of the electricity portfolio for these technologies.

Table D-1. Proportion of current electricity portfolio devoted to five largest sources.

Coal	Nuclear	Natural Gas	Hydropower	Oil
53%	21%	15%	7%	3%

Note: These values only sum to 99%, so the results will need to be normalized by division by 0.99 to find the true weighted average.

Preliminary scores not identically equal to 0 or 5 will have their value determined by either linear interpolation or extrapolation through use of this weighted average and the zero-score value.

Weighting of Metrics

At this point, it is desired to combine the 10 to 12 preliminary scores into one criterion value. It is here where the importance of the physical quantities will be taken into account. This is done by multiplying each preliminary score by the weight for that category.

This is the appropriate time to bring scientific considerations into place to determine and utilize natural weightings among the variables. As an example, while one may find both CO_2 and NO_x to be pollutants that one should seek to limit, that same person may find NO_x to be a more dangerous contributor; this is generally the scientific consensus on the issue as well. As such, by including a sensible weighting scheme, the program will have taken the metric scores and combined them properly into a criterion score.

What follows is a description of the areas of impact for each of the categories mentioned above as contributors to the environmental criterion. There is a weight listed for each of the categories as well. Clearly, this is a subjective judgment on the part of the author, but it is based on the severity of the environmental damage that is caused by the existence of or an increase in the size of a physical quantity.

(Note that these weights are based on how much of an issue the quantity is *currently* in the United States. This distinction is needed because not all of these categories endanger the environment at the moment. Put another way – were this to be a ranking of diseases and their threat to society, while polio is more debilitating than the common cold, it would not be ranked very high because it is mostly eradicated. The same concept applies here.)

CO_2 – primary contributor to global warming; 20%

SO_2 – leads to the formation of acid rain and regional haze, inhibits cloud formation; 25%

NO_x – leads to the formation of smog, acid rain, and ozone, decreases crop yields, causes eutrophication; 25%

$PM_{2.5}$ and PM_{10} – decreases visibility, causes corrosion to metal objects, leads to damage of vegetation; 10%

Mercury – negatively affects bird and mammal reproduction, makes fish toxic; 6%

VOC – secondary contributor to global warming, contaminant of soil and groundwater; 6%

Water consumed – damages ecosystems in excess; 5%

Water released – leads to thermal pollution; 2%

Land use – restricts land from other purposes; 1%

These weights are subject to change as perception is altered or the environmental opinion adjusts. If acid rain were to become a larger nuisance, for example, then categories like SO_2 and NO_x would get a larger share of the weight. The weights listed above are adequate for finding a reasonable ENRI score, but should be open to adjustment based on the feelings of the researcher.

Finding the Criterion Score

With the above steps completed, finding the ENRI score is straightforward. One first takes the intermediate values, determined through interpolation or extrapolation based on the physical data and the current portfolio's weighted average, and multiplies them by the corresponding weightings, found in the previous section. These numbers are summed to find the criterion score, which will be a positive value; all values larger than 10 should be rounded down to 10 so as to keep the criterion scores within the desired range.

Conclusion

There is much debate about the importance of environmental issues with respect to other worldly concerns. Among those that put a high value on the environment, there is still discussion about which factors are more important than others. The methods described herein do not seek to define importance, but rather to allow all researchers to use their own (or someone else's) trusted judgments to determine it for them. With these weights now in place, the process computes a normalized ENRI score, which can safely be compared with the ENRI scores from other technologies for ranking purposes. Since care was taken in the criterion formulation, these results will add value to those wishing to compare technologies.

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APPENDIX E. Safety and Health Impacts Criterion

Definition

The availability of energy is sometimes seen as a quality-of-life issue; in the United States, on-demand available electricity is so common as to be taken for granted. On the flip-side of this issue are the negative health effects, often unseen or indirect, that come along with the generation and distribution of the aforementioned electricity. This criterion will be defined as the amount of risk to the public that results from the creation and distribution of electricity. It will consider issues encompassing the excavation to post-processing of fuel, the creation to removal of specific electricity transportation means, and the creation of the materials used to make an electricity-generating mechanism (e.g., power plant) through its decommissioning. As an example, safety issues relating to the making of steel or the drilling of oil will be considered here, while issues relating to the creation of steel-making machinery or oil rigs will not.

Importance

It is reasonable to assume that it is in the best interest of the country to take steps so that its citizens' lives are not unduly threatened by death or harm on account of the nation's energy infrastructure. As such, limiting the risk associated with the creation and maintenance of the national energy infrastructure is of the utmost importance, as this has a most direct impact on the lives of citizens.

Impacts

It is understood that there will always be some degree of risk associated with the production of electricity. The impact this criterion will have on the selection of an energy technology will be to bring attention to those methods that carry with them an inherent risk *far beyond* that to which the public has become accustomed. Energy-related fatalities, injuries, and debilitations are not likely to be an overwhelming factor in the selection process – even the most risk-prone technologies tend to have strikingly low numbers of incidents – but will instead play a role in the trade-off phase of the analysis. Providing values for this criterion for each technology will allow for a greater flexibility of choice, depending on how risk-tolerant the country is at the moment of decision.

Attributes Quantification

The units of interest, at least initially, will be the frequencies with which certain incidents (injuries, deaths, instances of disease/illness) occur as a result of a technology and its associated aspects, as well as the risk of certain incidents (e.g., reactor meltdown) that carry significant enough consequences to merit mention. In order to come up with a measure that fits onto our overall "target" graphic, these disparate units will have to be combined into one number. This can be accomplished in several ways, such as providing a dollar value for each expected instance of injury/illness/death, or accumulating the expected number of years of life lost as a result of the technology choice. It should be stressed that monetizing lives or the quality of life is to be avoided in the overall analysis of an energy technology, and that the above suggestion of monetization is merely to be used for comparisons of technologies within the Safety and Health criterion. The attributes used in the definition of this criteria are described in the table presented in Appendix B.

Constraints

The boundary for this metric should rest between those living in the United States and those outside of this country's borders. It is believed that safety and health issues affecting residents of other countries are implicitly reflected in the cost or availability of the goods and services from those countries.

Mathematical Model

The mathematics behind calculating the safety and health incidents involving a given energy technology will be rooted in pragmatism more than anything. The data expected to be found and used in this analysis will most likely be based on national levels of incidents. A simple ratio method, such as the following, will be the most useful way to incorporate some of these data:

$$\text{Incidents}_{\text{Technology}} = \frac{\text{MaterialsNeeded}_{\text{Technology}}}{\text{AnnualMaterials}_{\text{Produced}}} * \begin{array}{c}\text{Total Incidents related to}\\ \text{production of material}\end{array} \quad \text{(E-1)}$$

where Materials Needed = amount of material needed in extraction, production, and construction.

In this manner, it will be possible to estimate the materials-related safety and health factors. Harmful pollution levels will be treated in a similar way, with an expected increase in pollution leading to an expected increase in incidents.

In the case of other contributing factors (such as those risk related, or the threat of proliferation), a general risk analysis paradigm will be followed. In these instances, the generic product of consequence and probability will be considered and used as a proxy for actual occurrences. This methodology may at first appear to be directed against the nuclear technologies, but in reality all possible events with a substantial enough risk term will be considered in this analysis.

Challenges

We can find some of the raw data needed for evaluating this criterion. Because such small numbers are expected, it is vital that the data that are found be viewed with close scrutiny, or else one stray source may greatly skew the relative ranking of these technologies. If sufficient and sufficiently accurate data are found, melding the disparate units into one overall number will present a challenge of its own. However, this latter challenge is subject to discussion, while potential data-related issues provide a possibly insurmountable impediment.

APPENDIX F. Energy Dependence Criterion

Definition

In the United States much of the rationale for energy research, energy policy, and the US DOE evolves from concerns about dependency on foreign sources of energy. As a result, this criterion is defined as the share of imports serving the demand for a specified fuel, e.g., imported oil as the share of total oil consumption in the United States.

Importance

Since before the initial oil price shock in October 1973, and then reinforced by the second oil price shock in 1979, US policy-makers have been very aware of the consequences of a disruption of foreign oil supplies. Political uncertainty and conflict in the primary petroleum-producing regions of the world have heightened this awareness. Most recently, this awareness has been demonstrated by an active military presence in the Middle East; this region has been prone to continuing political and social upheaval since the collapse of the Ottoman Empire at the end of World War I.

Disruptions of supplies of energy can depress macroeconomic activity and overall growth, and pose threats to human health, safety, and security. Supply disruptions may evolve from a number of sources including loss of foreign supplies, and domestic infrastructure damage due to weather, hostile incursions, and mechanical failure. With the anticipation of apparent increasing dependence on imports of oil for US transportation needs, and the potential increasing dependence on imports of liquefied natural gas (LNG) to satisfy the demand for natural gas, impacts of R&D and new technologies on reducing levels of imports is assuming new importance. This importance is reflected in the use of this criterion by several offices at US DOE in the fulfillment of their Government Performance Results Act (GPRA) requirements.

Impacts

New technologies focused on energy import reduction would be expected to either shift consumption from fuel types with high levels of imports to indigenous or domestic fuels, or reduce consumption of an imported fuel type through gains in efficiency, i.e., less input per unit of output. In either case, a new technology would be expected to reduce the requirement for imported fuels and the corresponding risk.

Attributes

Six attributes will be used for this criterion:

- Versatility of technology
- Impact of fuel on GDP
- Value of import and percentage of total consumption

- Portfolio diversification
- Strategic Fuel Stocks
- Surge Capacity

These attributes will be rated on a scale between 0 and 1.0, and then summed up to a combined score. This implies each attribute used to determine energy dependence has equal weight in the combined score. This method of simple summation will give some qualitative measure of dependence. We realize that this is a simplification and that dependency has many aspects that are being force-fit into a simple metric as a starting point for discussion.

Versatility of Technology*

The key to enabling a competitive and stable market is the use of substitutes. If a given electricity-producing technology is able to easily switch to substitute fuel when the primary fuel source has become economically unstable, this technology can reduce the impact of foreign dependence of a resource, providing there is a substitute fuel readily available. Versatility will be scored either as a 0 (zero) if a technology has fuel switching capability or a 1.0 if it does not. A score in mid-scale would result if the substitute fuel use results in secondary shortages.

** This attribute may not be used in the final quantification of this criterion.*

Impact of Energy Type on GDP

This attribute measures the relative impact a fuel has on the production of goods and services. Changes in the cost of resources ripple throughout the economy and create price changes with other goods and services. The greater the percentage of a resource reflected in the GDP, the greater the impact on the economy. This attribute will be reflected in decimal form of the monetary value of fuel consumed/GDP.

Percentage of Net Imports

The net amount of imported resource as a percentage of the total resource supplied reflects the relative impact importation may have on the economy. Although modified from gross imports to net imports in 1982, this attribute has been regularly published as a measure of oil import dependence used by the Energy Information Administration since 1979 (Kendall, 1998). We note that fuel imports currently account for about 25% of our exchange deficit, so the entire picture of economic impact must be considered.

This attribute will be reflected as a proportion of net fuel imported/total fuel supplied. Physical units, such as million cubic feet for natural gas and barrels for oil rather than Btu's, will be used because a physical measure of dependence should use physical units rather than a heat value because producers and consumers typically sell and buy fuel in barrels or cubic feet, not in Btu's (Kendall, 1998).

Portfolio Diversification

Kendall (1998) suggests that oil dependence does not necessarily indicate vulnerability to a disruption. He further explains that if "supply came from many small producers and one of them suddenly stopped exporting oil, it would have little effect on U.S. and world supplies and prices, even at a high rate of U.S. dependence." Kendall (1998) contends that resource concentration is a key factor in the security of our oil supply and has been a commonly used measure by the GAO in measuring energy security.[1]

The resource concentration of a given supplier identifies the relative impact one supplier may have on the economy regardless of the diversity. To account for this, a common approach used in the financial markets and in antitrust law is the "Herfindahl Index." This index is a measure of diversification that accounts for the market concentration of a supplier. This approach can be used to calculate the average diversification of supply in a company or country basis.[2]

The Herfindahl Index may be expressed as:

$$H = \sum_{i} x_i^2$$

where x_i is the fraction of total fuel type supply from source "i."

If the concentration among the different suppliers is equal, the equation will equal 1/ the number of suppliers. The index value declines with increases in the number of suppliers; as the number of suppliers increases, this score will approach 0. The index increases with rising inequality of supply among any given number of suppliers.

Strategic Fuel Stocks

Maintaining commercial and noncommercial fuel stocks, such as the Strategic Petroleum Reserve, is another method to reduce the impact foreign sources has on the economy. This provides a somewhat broader measure. The greater the fuel stock, the better equipped we are to mitigate economic impact of a supply disruption. This attribute could be expressed in physical units (MMcf or barrels) relative to the consumption in physical units specified over a one-year time interval.

This attribute Strategic Fuel Stocks (SFS) will be quantified on a national level as **1 minus (total reserves (R) /total consumption (C)), or**

SFS = 1 - R/C

[1] Kendall, James (1998). *Measures of Oil Import Dependence.* Energy Information Administration, Issues in Midterm Analysis and Forecasting.

[2] Neff, Thomas (1997).

Based upon this equation, if total reserves in one year equaled total consumption for that year, the equation will approach 0.

Surge Capacity*

Excess surge capacity (storage) and production capacity can reduce the impact of price fluctuations due to periods of high process and declining periods of low prices (Kendall, 1998). This attribute attempts to measure the excess capacity of suppliers to compensate for supply disruptions that can be sustained for a specific number of days.

Quantification of this attribute SC will be measured as

$$\mathbf{SC = 1 - (actual\ output/rated\ output)}$$

This attribute may not be included in final calculation due to the extreme uncertainty in identifying this factor from foreign sources.

Quantification of Measure

The output of each attribute will be measured with values between 0 and 1.0. The final summation for this criterion will also use the Herfindahl approach. The output of each attribute will be squared, summed, then multiplied by 10 to reflect a score between 0 and 10.

Constraints

Developing a concise measure of energy dependence as an economic indicator of energy security requires a higher level of detail than what is incorporated into this criterion. The political stability of foreign sources and the strength of the dollar on the world market have a major impact on the US economy. Additionally, the development of supporting infrastructures, such as LNG terminals, which measures the capacity to support any increase in importation, requires further exploration. Further studies on measuring the economic vulnerability are necessary, and such studies can assist policy makers in gauging their progress towards insulating the nation from the harmful effects of sharp changes in the world market (Kendall, 1998)[3].

This criterion will be restricted to US imports of fuels for domestic consumption and total domestic consumption of the specified fuel.

[3] Kendall, James (1998). *Measures of Oil Import Dependence.* Energy Information Administration, Issues in Midterm Analysis and Forecasting.

APPENDIX G. Policy Needs Criterion

Definition

"In those instances where change is warranted, the reasons frequently seem technical. But it is the nature of politics that the technicians themselves often are not able to make the necessary changes. That requires the attention and persuasive powers of people at the highest levels of government." This quote from Richard D. Morgenstern and Paul R. Portney, writing in New Approaches on Energy and the Environment (Resources for the Future, Washington D.C., 2004 page 1), highlights the need to consider policy during the course of technology development. The authors go on to say that the problem of policy formation is especially acute in environmental science areas, because those on opposite sides of the environmental and industrial fence are particularly polarized and view the environmental debate as a zero sum game with winners and losers.

Importance

Policy considerations are often important during the introduction and further implementation of new technologies. As one of many examples, one might recall the introduction of the railway to the west. A generous incentive was required to attract investors, so land and exclusive rights were granted. During various phases of introducing electric power and telephone service, a wide variety of regulatory tools were used. Regulations that may serve well during introduction may become outmoded as conditions change. For example, if only a few motor vehicles are on the road, emission or performance standards are not important.

Impacts

The purpose of this metric is to call attention to policy considerations that might be necessary during the introduction and evolution of a new technology. Anticipating what is needed, and preparing the ground work with agency officials, law makers, the potential investment community, service providers, the public, and regulators could make the difference in setting the conditions between success and failure. It appears that technology developers do not often account for such considerations, and the aim of this metric is to assess the difficulty of implementing policies needed for a technology to capture a market share, and to assure that policy considerations remain in view during the technology development process and are researched as part of the R&D investment process.

Attribute Quantification

We will not attempt to provide a highly quantified metric, because the considerations form too large a parameter space, and differences from one technology to another make it advisable to make only qualitative comparisons. We recommend looking at the policy literature specific to each technology selected for study. We suggest summarizing key considerations as supporting material for the evaluation vector, which is proposed to span a range of 0-10 with 0 indicating no policy or market intervention while 10 represents substantial intervention; the components of this vector are described in the table presented in Appendix B.

Policy considerations include topics such as:

1. Price regulation.
2. Comfort level and familiarity with a technology; this will often determine whether policy makers or financial supporters will back an effort.
3. Consumption or use taxes.
4. Tax credits for building infrastructure, production credits, tax incentives for employing a technology, or requirements to use specified technologies; for example, government agencies may be mandated to purchase a specified fraction of renewable energy.
5. Regulation or user requirement of reliability or security, such as excess capacity requirements or other performance standards. International agreements like Kyoto, or expansions of such agreements that cause companies to deal only with those who conform.
6. Environmental regulations, including waste disposal. Regulations concerning decommissioning.
7. Regulations and policies on rights-of-way, land use leases.
8. Public perceptions. Regional concerns. Public trust in government or other institutions.
9. Social equity issues, perceived or real.
10. Power structure as reflected by business and lobby activity; for example, coal interests may effective in lobbying against nuclear, because they compete.
11. Economic needs, such as job preservation; for example, would a switch to renewables or nuclear using domestic equipment and supplies be superior, even if energy costs were more than from imported fuels, simply because more of the economic transactions stay at home?

A score of 0 will denote that no policy considerations or changes will be required for the introduction of a new technology or the continuation of a present technology.

A score of 10 indicates that implementation is completely dependent on policy changes and incentives, and that the technology is unlikely to succeed or continue in the absence of special policies or incentives.

A score of 5 would indicate that modest policy changes or incentives will be required to jump-start a technology, or that considerable red tape and delays are common for the technology.

Constraints

For purposes of an initial investigation for each technology, consideration will be given only to policy intervention that may be implemented in the United States. International agreements other than the ratification of existing agreements (e.g., the Kyoto protocol) will not be considered.

APPENDIX H. Service Limitations Criterion

Definition

The service provided by an energy technology often constrains the potential market share due to physical or economic reasons. While a detailed analysis of these issues is not needed when evaluating the merit of technology for continued R&D funding, it is useful to understand the approximate contribution that a technology might make towards meeting the service needs.

In the electricity markets, the ratio between peak and minimum demand can be 3:1 over a seasonal timeframe and 2:1 over a 24-hour period, so a portfolio of technologies is used for physical and economic reasons to address this load variability. For example, the intermittent nature of wind power without storage limits the practical market share it can serve.[1] Conversely, a nuclear power plant in some cases may take hours to days to restart once it is shut down; the lives of the fuel rods are shortened if subjected to wide fluctuations in activity; and a fairly steep energy penalty is extracted if a nuclear plant is not operated as a base-load facility. Distributed photovoltaics can eliminate the need for electrical transmission and distribution lines only if they reliably produce during peak load times, which is not possible without storage.

Also, the technology-related components of a technology's cost structure can impact its useful service when compared to other competing technologies. Technologies with high fixed costs (e.g., construction) and low variable costs (e.g., fuel) have much lower unit energy cost ($/kWh) when run as base-load facilities with high levels of annual utilization (capacity factor). In contrast, technologies with low fixed costs and high variable costs can be run at low capacity factor with much lower impact in unit energy cost—see Figure H-1. Pulverized coal plants are the least expensive at high capacity factor, but more expensive than the two natural gas technologies at low capacity factors. Recent increases in natural gas prices since 2000 have made gas less economical. Table H-1 lists the mix of US electricity generators in 2002. Capacity factors are listed both for the nameplate rating and for the net summer capacity rating. It should be noted that to be consistent, the capacity factor used in economic calculations should have the same basis (nameplate or net summer) used in the calculations of the cost criterion in Appendix C. Normally, costs are given on the basis of nameplate capacity.

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[1] This limit depends upon the local wind resource and the ability of other technologies to dispatch to meet load. Consequently, this limit will vary geographically, and it is also the subject of debate. Estimated limits typically range from 10-30% of capacity.

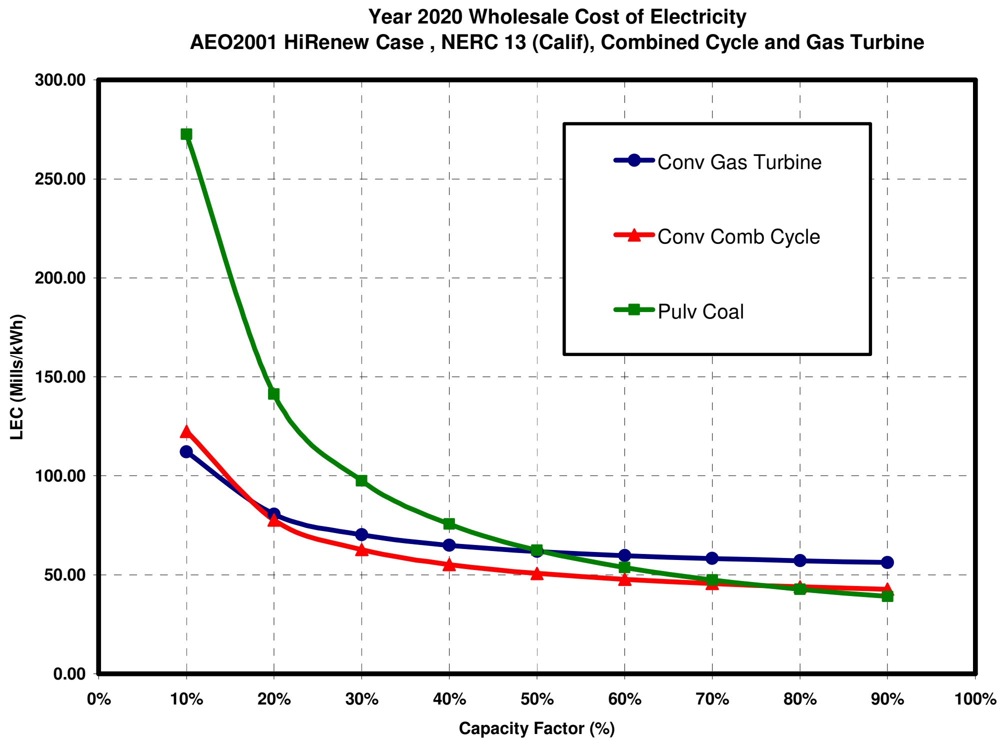

Figure H-1. Effects of capacity factor on unit cost (EIA Annual Energy Outlook, 2001).

Broad energy economic models often address these economic trade-offs between technologies and optimization of the system. Depending upon the model, limited or no consideration is given to physical constraints such as peak length and duration. However, physical constraints are often addressed in greater detail via load dispatching analyses done by utilities and regulatory agencies for short- and long-term planning, interconnection requests, and reliability studies. These analyses are often complex, time consuming, and are limited to only small subsets of the national grid. This criterion is intended to summarize the current state of knowledge, including some of the uncertainties, about the potential national market share a given technology could provide, and not to replace detailed local or regional analyses.

Table H-1. U.S. Electricity Sources in 2002

Energy Source	Nameplate Capacity (MW)[a]	Fraction Summer Capacity	Fraction Annual Generation	Capacity Factor (Nameplate)	Capacity Factor (Net Summer)
Coal[1]	338,199	34.8%	50.1%	65.3%	70.0%
Petroleum[2]	43,206	4.2%	2.5%	25.0%	28.3%
Natural Gas	194,968	19.0%	17.9%	21.0%	23.6%
Dual Fired[10]	180,174	17.9%			
Other Gases[3]	2,210	0.2%	0.3%	59.2%	65.2%
Nuclear	104,933	10.9%	20.2%	84.9%	90.3%
Hydroelectric[4]	96,343	11.0%	6.6%	30.3%	29.3%
Other Renewables[5]	18,797	1.9%	2.3%	52.8%	59.2%
Other[6]	756	0.1%	0.1%	86.3%	101.8%
Total / Average	979,585	100.0%	100.0%	45.0%	48.7%

Source: EIA 2002-Electric Power Annual

a p.16, Table 2.2

1 Anthracite, bituminous coal, subbituminous coal, lignite, waste coal, and synthetic coal.

2 Distillate fuel oil (all diesel and No. 1, No. 2, and No. 4 fuel oils), residual fuel oil (No. 5 and No. 6 fuel oils and bunker C fuel oil), jet fuel, kerosene, petroleum coke (converted to liquid petroleum, see Technical Notes for conversion methodology), and waste oil.

3 Blast furnace gas, propane gas, and other manufactured and waste gases derived from fossil fuels.

4 Conventional hydroelectric power and hydroelectric pumped storage facility production minus energy used for pumping.

5 Wood, black liquor, other wood waste, municipal solid waste, landfill gas, sludge waste, tires, agriculture by-products, other biomass, geothermal, solar thermal, photovoltaic energy, and wind.

6 Batteries, chemicals, hydrogen, pitch, purchased steam, sulfur, and miscellaneous technologies.

7 Electric utility CHP plants are included in Electricity Generators, Electric Utilities.

8 Small number of commercial electricity-only plants included.

9 Small number of Industrial electricity-only plants included.

10 Most “dual fired” generating plants consume natural gas most of the time and use oil as a backup source.

Note: Totals may not equal sum of components because of independent rounding.

Source: Energy Information Administration, Form EIA-906, "Power Plant Report," and predecessor forms.

Importance

The service traits of a technology are important to consider when evaluating a portfolio of technologies for R&D funding or for public policy measures. It is probably unwise to have a portfolio consisting of single technology (e.g., all electricity from natural gas combined cycles) because diversification reduces risks arising from such factors as fuel supply and price, projections of load and load-shape, and similar factors. Furthermore, it is unlikely that a single technology will be deemed most desirable in all markets, considering geographical, financial, regulatory, and resource variability. Nonetheless, the lower the potential unserved market share of a technology the better, in general, it may be for further development.

Impacts

Improvements that enable a technology to serve more of the market are desirable. Additionally, technologies that leave large portions of the market unserved may warrant less public policy or R&D support. In performing such evaluations on a portfolio of technologies, it is critical to consider not just the fraction of the market unserved, but also *which* fraction (e.g., base, intermediate, or peak load in the case of electricity) because of the potential for complementary portfolios. For example, assume nuclear and coal can each serve 50% of the market, but they both serve base load duty, so are not able to be combined to serve 100% of the market.

Attribute Quantification

The complex and interdependent calculations that would be needed to estimate market share of various technologies require quantiative economic and physical attributes as inputs. The attributes for the cost criteria are sufficient for economic considerations. Physical attributes needed include factors like ramp rate, planning horizon, and part-load efficiency.

However, because such calculations are beyond the scope of this project, and because a simple mathematical relationship between attributes and criteria is not possible, three *qualitative* attributes are used instead to aid in the estimation of criteria scoring and associated uncertainty: (1) economic duty limits, (2) load following limits, and (3) peak period capacity credit. Table H-2 lists attribute scoring for several technologies as well at the typical duty cycle. Lower scores are better except for peak period capacity credit where the opposite is true. An intermittent duty cycle means that the timing of power production cannot be well controlled, and typically applies to renewable energy technologies without any storage or backup capability.

Table H-2. Qualitative Service Limitations Attribute Scoring and Duty Cycle

Technology	Economic Duty Limits	Load Following Limits	Peak Period Capacity Credit	Typical Duty Cycle
Pulverized Coal	4	4	100[2]%	Base
Nuclear	5	5	100[2]%	Base
Photovoltaics w/o storage	5	3	37[2]%	*Intermittent*
CSP-molten salt tower	5	2	90-100%	Intermediate
CSP- trough hybrid	5	2	88[1]-100[3]%	Intermediate
Wind	5	5	26[1]-40[2]%	*Intermittent*
Natural gas combined cycle	2	1	100[2]%	Intermediate
Natural gas combustion turbine	1	0.5	100[2]%	Peak
Hydro	5	2	100[2]%	Intermediate

1 California Wind Energy Collaborative, California Energy Commission Consultant Report P500-04-054, "California Renewables Portfolio Standard Renewable Generation Integration Cost Analysis Phase III: Recommendations for Implementation", July 2004. Please note these estimate are for Effective Load Carrying Capability, which differs slightly in definition.

2 Energy Information Agency, Annual Energy Outlook 2004 data files: aeo2001.d101600a, hirenew.d101800a. These are national average estimates. Local or regional variations can be significant for renewable energy resources.

3 Price, H. and R. Cable (2001). "Parabolic trough power for the California competitive market." International Solar Energy Conference. 2001 International Solar Energy Conference, a Part of Forum 2001, Solar Energy: The Power to Choose; Apr 21-25 2001; Washington, DC, United States: 399-403.

Constraints

For purposes of the initial evaluation of electricity options, the scope is the aggregated US market. However, local variances are very important in this analysis, so regional analyses that are then aggregated into a national summary may reduce uncertainty.

Mathematical Model

For an example of a detailed model addressing the economics and some of the physical constraints, see the Energy Information Administration National Energy Modeling System (NEMS) documentation available on the web at www.eia.doe.gov:

- Electricity Market Module of the National Energy Modeling System, Model Documentation Report 2000. DOE/EIA-M068(2004).
- Renewable Fuels Module of the National Energy Modeling System 2004, Model Documentation. DOE/EIA-M069(2004).
- Load and Demand Side Management Submodule Vol. 1, Model Description, Model Documentation. DOE/EIA-M068-A1.
- Load and Demand Side Management Submodule Vol. 2, Model Code, Model Documentation.

The California Wind Energy Collaborative (2004) describes modeling related on this topic. Ivey, et al. (1999) and Hirst and Kirby (2001) also describe issues regarding higher fidelity analyses of physical constraints on generation and transmission.

Scoring

Table H-3 lists the estimated service limitations for several technologies. A lower score is better. The rationale describes how the estimates were reached and builds upon the attribute scoring. It should be noted that combinations of technologies also depend upon the duty cycle. For example, it would not be prudent to have a 50:50 mix of coal and nuclear because they are both baseload technologies and would be neither effective nor economic at meeting the highly time-variant and peak period loads. Conversely, natural gas based technologies might meet the entire load, but this would be more costly and could greatly increase imports of fuel. Also, having a diversity of generation technologies and fuels makes the system more resistant to disruptions.

Table H-3. Estimated Service Limitations

Technology	Low	Most Likely	High	Rationale
Pulverized Coal	20%	30%	40%	Baseload currently maximized because cheapest, use current
Nuclear	25%	35%	45%	less ameniable to cycling than coal
Photovoltaics w/o storage	70%	80%	90%	Higher capacity credit than wind
CSP-molten salt tower	60%	70%	85%	Transmission from West req'd
CSP-trough hybrid	60%	75%	85%	Storage more costly than towers, hybrids possible
Wind	70%	85%	90%	Intermittence requires regulation
Natural gas combined cycle	0%	15%	30%	Dispatchable
Natural gas combustion turbine	0%	5%	10%	Most dispatchable of all technologies
Hydro	90%	95%	98%	Mostly exploited already (6% total), operational constraints

APPENDIX I-1. Science and Technology Needs Criterion

Preface

Technology readiness or technology maturity are concepts that contain many elements that are qualitative. For example, some technologies are capable of performing at very small scales, and can enter the marketplace in easily attained steps. An excellent example is afforded by photo-voltaic cells that can find use in powering calculators from room light or providing electric power in relatively modest amounts at remote locations. By contrast, solar thermal power with molten salt heat storage can provide power in large quantities, including power during normal periods of darkness, but the installations must be large for practical application. In both cases, the technology is sufficiently developed for commercial use, although the case for solar thermal may be arguable, because a large plant with modern technology has yet to see a practical demonstration. One technology has been able to incrementally creep into the marketplace, and the other technology that has a built-in energy storage capability seems to be stagnating, although it is presently more economical, based on the maturity of available technology. Readiness obviously must include factors other than technology alone. Factors of familiarity and comfort for the investors or users of technology may supersede technical maturity in importance. Here we emphasize the technical aspects, but comfort and familiarity are essential elements featured in the vector concerning policy.

We have split our technology readiness research in two directions. The first direction addresses a set of metrics adapted from a National Aeronautics and Space Administration (NASA) scoring method, referenced in the bibliography for this section, and the second approach is more theoretical. For the sake of this present report, the latter effort is a work in progress, and will use the simplified approach

Definition

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. The TRL approach has been used on and off in NASA space technology planning for many years, and we adapted to our purposes the maturity level structure originally intended to determine whether new technologies would be available for space application.

Importance

To be most useful, the NASA reference claims that the general model must include:

(a) “basic” research in new technologies and concepts (targeting identified goals, but not necessary specific systems),

(b) focused technology development addressing specific technologies for one or more potential identified applications,

(c) technology development and demonstration for each specific application before the beginning of full system development of that application,

(d) system development (through first unit fabrication), and

(e) system "launch" and operations.

Impacts

These steps are equally useful in looking at the history and projected future of energy systems, but in general, we will find it more useful to look at technologies that have largely advanced beyond the first steps. If we were to look at fusion energy for future power applications, then all the steps used by NASA would apply. We might also note that for space applications with unique requirements, the cost structure requirements would differ greatly from requirements for electric generation on earth. The NASA criteria do not include cost, except implicitly. Costs for the purpose of this study are considered only in the vector concerning that topic.

Attributes

Technology Maturity Levels Summary (Note that for display purposes, our levels run in inverse order in comparison with NASA TRLs, and we have added a level 10 that represents complete technology ignorance (might apply to cold fusion), and a level zero that reflects a maturity level so high that little or no improvement is expected. The 0 level might be representative of a hydro-power turbine, for example.

TML 10 – Nothing known about how to solve the problem
TML 9 – Basic principles observed and reported
TML 8 – Technology concept and/or application formulated
TML 7 – Analytical and experimental critical function and/or characteristic proof of concept
TML 6 – Component and/or breadboard validation in laboratory environment
TML 5 – Component and/or breadboard validation in relevant environment
TML 4 – System/subsystem model or prototype demonstration in a relevant environment—for example, in a power plant on a simulated power grid
TML 3 – System prototype demonstration in the power grid environment, but using a cadre of special experts
TML 2 – Actual system completed and qualified through test and demonstration and used on the grid in a commercial application
TML 1 – Actual system capable of turn-key operation by generally available operations personnel
TML 0 – The technology is so mature that substantial improvement seems unlikely

Note that for a system to be applied in a distributed power system, one merely would substitute homeowner or building supervisor, etc.

APPENDIX I-2. Alternative Approach to Science and Technology Needs

The following development concerning technology maturity is a work in progress, and has not yet developed to a degree that will allow actual use in a scoring process. It is included as a way to inspire comment and exchange. Please contact Jeffrey Tsao with comments and suggestions.

Definition

We explore here the possibility of developing a *useful* criterion for the "immaturity" of a technology. One interesting possibility is: a predicted length of time for the technology to evolve to a particular performance and price. Such a criterion has the advantage over some others in being both quantitative and easily understood: a technology that is 100 years away (from a particular performance and price) is less mature than one that is 10 years away, which in turn is less mature than one that is 1 year away.

Importance

Such a criterion would enable families of technologies to be compared using the same units. It would also serve as the foundation for additional useful criteria, such as what is the *uncertainty* in the time for the technology to evolve to a particular performance and price, and what is the possible influence of government policy and/or investment on both the time and the uncertainty in the time.

Impacts

Since time is a natural unit of economic analysis, this criterion would naturally lead to quantitative comparisons between present (discounted) values, based on anticipated future values, of various technologies. The future values of those technologies could be taken from the various other criteria proposed in this LDRD.

Attribute "Physics" or Quantification

The predicted length of time for a technology to evolve to a particular performance and price might fold together several attributes.

State of Technology. A first attribute is an appropriate technology metric. Ideally, the metric would be a relatively simple figure of merit such as $/kWh, or a number of simple figures of merit artfully combined to mimic market desirability. Such a metric would allow various states of technology to be compared quantitatively. Some of those states of technology might be: the current state (T), the best state allowed by current technology paradigms (T_∞), and the best state allowed by physics (T_p). The current state of technology $T(t)$ is time dependent, and evolves towards the best state allowed by current technology paradigms (T_∞). At the same time, the best state allowed by current technology paradigms ($T_\infty(t)$) is also time dependent, and evolves towards the best state allowed by physics (T_p). The rates at which the two states evolve are described by the next two attributes.

Strength of T&E Spiral. The second attribute is the predicted rate at which the current state of technology (T) will evolve towards the best state allowed by current technology paradigms (T_∞) in response to market forces. We might assume that this rate will depend on "how much room" there is for the technology to evolve (T_∞- T) within the current technology paradigm, as well as on a coefficient α_E that characterizes the strength of the intermediate goods and services markets that pull, as well as are pushed by, that technology paradigm.[1] These intermediate markets represent an "onramp" that enables the "learning-by-doing" extension of the current state of technology towards the best state allowed by the current technology paradigm. If such intermediate markets are absent, then government policy or investments would presumably be necessary to provide the necessary onramp.

Strength of S&T Spiral. A third attribute is the predicted rate at which the best state allowed by the current technology paradigm (T_∞) will evolve towards the best state allowed by physics (T_p), in response to increases in our understanding of the science that underlies the technology. We might assume that this rate will depend on "how much room" there is for the best state allowed by the current technology paradigm to evolve (T_p - T_∞), as well as on a coefficient α_S that characterizes the strength of the intermediate science "markets" that push, as well as are pulled by, the technology.[2]

Mathematical Model

As a crude initial ansatz at a mathematical model, we might write the following coupled set of rate equations:

$$\begin{aligned} \dot{T} &= \alpha_E\left(T_\infty - T\right) \\ \dot{T}_\infty &= \alpha_S\left(T_p - T_\infty\right) \end{aligned} \tag{I-1}$$

The basic idea here is to explore the simplest possible relationship that captures the above discussion of attributes: that the dependences of the rates of technology evolution on "how much room" and on the strengths of the various spirals is linear.

Note that in the unlikely but simplifying case where both α_E and α_S are constant in time, these coupled rate equations have the solution:[3]

[1] The justification here is loosely borrowed from Clayten Christensen's work, and the "onramp" ideas that Scott discussed at one of the team meetings. Somehow, we want to capture the idea that no matter how much potential a technology might for a desired application, if it is not participating in a virtuous spiral of technology and engineering (read goods and services), then it may take a long time to cross the required technology gap.

[2] The justification here for the importance of an S&T spiral is similar to that for the T&E spiral. However, science enters in differently. The idea is that science feeds the creation of new paradigms in technology, rather than the extending of existing paradigms.

[3] I think the solution is correct now, thanks to help from Jason.

$$T(t) = T_p - \frac{\alpha_E}{\alpha_E - \alpha_S}\left(T_p - T_{\infty o}\right)e^{-\alpha_S t} + \frac{\alpha_S}{\alpha_E - \alpha_S}\left|\left(T_p - T_o\right) - \frac{\alpha_E}{\alpha_S}\left(T_{\infty o} - T_o\right)\right| e^{-\alpha_E t}$$
$$T_\infty(t) = T_p - \left(T_{\infty o} - T_p\right) e^{-\alpha_S t} \quad \text{(I-2)}$$

where T_o and $T_{\infty o}$ are the initial $t=0$ values for the current state of technology and the best state allowed by the current technology paradigm, respectively. The solution is bi-exponential with two rates, α_E and α_S. If $\alpha_S >> \alpha_E$, then T_∞ evolves quickly to T_p and the subsequent and slower evolution is that of T to T_p. But if $\alpha_E >> \alpha_S$, then T evolves quickly to T_∞, and the subsequent and slower evolution is that of T_∞ to T_p.[4]

Challenges

The biggest challenge with this criterion for technology immaturity will be developing a way of thinking about the "physics" of the two rates α_E and α_S in terms of the two spirals of T&E and S&T.

Bibliography for Technology Needs

1. Office of Space Access and Technology, Advanced Concepts Office, NASA, "A White Paper," April 6, 1995, by John C. Mankins.

[4] It'd be nice to have an analytic expression for the time τ to reach the desired state of technology T_d. Jason, care to take another crack at it…?

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APPENDIX J. Sustainability Limitations Criterion (Exergy Sustainability)

Definition

The term sustainability is derived from the word sustain, meaning to continue or preserve. We as a society want to sustain, continue, or prolong our way of life while providing an equal or better future for our children and theirs. The decisions we make today will be felt by our offspring years to come. Historically, some Native American tribes understood that fact and made decisions that considered seven generations into the future. We are assuming a 200-year time horizon, in the belief that new knowledge will likely result in change in direction of sustainability plans that we might propose today. This period of time is somewhat similar to the Native American custom. Of course, we recognize that the 200-year time frame would not be appropriate for considerations of species preservation or cutting forests whose trees live even longer; for such matters, it would be inappropriate to assign time frames shorter than growing times or evolution time-scales.

Although several definitions exist that define the idea of sustainability, for the purpose of this project the definition proposed by the Brundtland Commission in 1983 will be used as the foundation for the development of exergy sustainability as a criterion for a multi-criteria analysis comparing different energy systems:

A form of sustainable development which meets the needs of the present without compromising the ability of future generations to meet their own needs (Barnaby, 1987).

Based upon the Brundtland definition, we define exergy sustainability as a system that maintains the exergy needs of our current population without compromising future exergy needs.

Technical Definition

The technical definition of exergy, which appears in modern thermodynamics texts, is derived partly from the second law of thermodynamics: *"A second law efficiency is the ratio of the minimum amount of available work required to do a particular job to the amount of work actually used to do the job" (Simpson and Kay, 1989).* A second law efficiency is used for this definition due to the fact that a first law analysis, a ratio of energy in versus energy out, does not take into account the quality of energy in its ability to perform useful work (Simpson and Kay, 1989). According to the second law, exergy defines the amount of energy from a given fuel or other energy source that is available to do work or other useful functions, such as water or space heating, given the environment. Exergy analysis includes all potential uses for the energy from its introduction into the system of interest through its rejection into the surrounding environment.

A related concept that deserves mention is entropy, a measure of the disorder that results as energy is used to produce work or other desired functions, such as warming our water and living environment. The sustainability literature mentions entropy because minimizing entropy production per unit of fuel or heat energy used is equivalent to maximizing efficiency and reducing fuel wastage. (Of course, a complete analysis must take into account the full energy cycle costs, including the energy used to extract fuel and the energy required to produce apparatus used in the energy cycle itself.) Entropy measures the amount of energy per degree of temperature that is unavailable or has ceased to be available to do work in any system, taking into account the temperature of the energy conversion processes. Entropy always increases as energy-related cycles are completed. There is no economic market for entropy production, but it finds use in the calculations that are necessary to achieve high efficiency standards, and is used in developing a physical understanding of our environment.

Based upon this reasoning, an alternate definition for exergy sustainability is defined as: *the continuous compensation of irreversible entropy production in an open system with an impedance and capacity-matched persistent exergy source*.[1] This definition implies that a sustainable system must utilize an energy source that is able to continuously meet our current and future energy needs with supplies that are greater than 200 years, and is used in manner that maximizes its work capability. However, the technical aspects of this definition will not be utilized in this criterion.

In context, we intend to examine the ability to satisfy energy needs now and well into the future; the ability to continuously provide those needs (including during times of darkness or no wind); and the ability to derive the maximum possible value of benefit from each unit of energy available. The last statement is equivalent to maximizing exergy use.

Importance

Most of our energy used today comes in the form of fossil fuels. There is significant concern among public officials, environmental groups, consumers, and industry regarding the longevity of fossil resources available and how long they will last. Fossil fuels are finite and time dependent and will eventually be depleted, so we need to find ways to maximize our available fossil fuel resources and further develop energy sources that will be more persistent. Eventually, we will have to make a transition to non-fossil persistent energy sources. When that transition occurs, we need to ensure that we have sufficient fossil resources or a sufficient installed capacity of more persistent energy sources to make that transition.

Impacts

Our current energy production facilities, including nuclear power, geothermal, solar, wind, and fossil fuel plants (coal or natural gas), depend on fossil fuels in some or all points of their life cycle. Fossil fuel is used in the mining of resources, processing, and transportation; construction of facilities; the operation and maintenance of the facilities; storage; and the reclamation of the facilities at the end of their productive lives. Furthermore, energy production impacts other resources, the environment, and investments into our energy infrastructure. Deciding investment directions for energy resource development significantly affects these other activities and our economic well-being. We suspect that the transition will take place gradually as increasing

[1] This definition is part of a working white paper entitled *Exergy Sustainability*. Please see this paper for further details.

scarcity causes the cost of fossil resources to increase, and more persistent sources (that are presently more costly than fossil fuels) take over the market. Of course, the transition may not be quite so simple, because the production costs of persistent technologies will certainly rise along with energy costs. Modeling of this transition would require an accurate forecast of future energy costs, and a reasonably accurate estimate of the costs of persistent energy technology; these factors are unknown, so an accurate prediction of the features of the transition to persistent energy sources will remain somewhat elusive, but it seems most likely that the changeover will be gradual, unless urgency arises from a climate emergency or some other sudden event.

Constraints

Sustainability is a broad topic that includes social, economic, environmental, and political, as well as physical factors. All of these factors must be addressed for a system to be sustainable. This criterion has been limited to the physical aspect of our energy resources as it relates to sustainability. Furthermore, exergy sustainability will only be assessed on a national level for domestic resources. Annual Energy Outlook (AEO) 2004 will be utilized to assess the mean value in quantifying exergy sustainability.

Attributes Quantification

Renewable and non-renewable resources have specific limitations that affect the sustainability of a system. Non-renewable resources are finite and can only provide our energy needs until depletion. Renewable resources are not finite but they are variable in that they do not provide continuous needs without the use of storage. In an attempt to develop a balanced method for rating the sustainability of renewable and non-renewable resources, the following two attributes are proposed: (A) persistence, which is time of supply of a resource; and (B) capacity matching, the ability to continuously meet exergy needs.

(A) Persistence (Time of Supply)

A sustainable energy system utilizes an energy resource that has a duration equal to or greater than 200 years. A time frame of 200 years seemed feasible because alternative energy resources should be developed within that time, and it seems unwise to speculate further than 200 years because unanticipated technologies are likely to emerge, and there is ample time to reassess and change direction of a given path. Coal, for example, is a resource has been used since the 13th century, and oil has been used as a fuel for at least a century (Grubler, 1998). Based upon Grubler's (1998) work regarding the effects of changes in technology in society, shorter time frames, such as 50 years, were considered. However, we note that technological changes affect the application or use of an energy resource, or the method of extraction, and such changes are factors when determining the duration of a resource.

For the ease of graphical representation, persistence is measured in years as the net supplies (current recoverable stocks and known reserves in physical units) of a specific resource divided by the current use. The net amount of currently recoverable supplies and known reserves is based upon current technology (extraction methods, efficiency of the plant or other parts of the

system), energy payback of the system, the current consumption rate, and the current expected population growth. Any changes in these factors will increase or decrease the longevity.
This attribute may be expressed as:

Net Supplies/Current Use = Years of Supply

Scoring:

Scoring of this attribute assumes that a resource with years of supply equal to 200 will count as a one (1). Longer time frames will approach zero (0). Shorter time frames such as 50 years will score a number greater than one (1). As this number increases, the less sustainable a system is.

Scoring will be calculated as:

Score = 200/Years of supply

(B) Capacity Matching

An energy system must continuously maintain our energy needs in order for the system to be sustainable. Thus, capacity matching compares the needs on a daily basis that are unmet (downtime) to the amount that is required within a year in decimal form, whereas $x \rightarrow 0$ is better.

$$\text{Capacity Matching} = \text{downtime/required} \qquad \text{(J-1)}$$

For example, if we require 365 days of continuous energy needs and coal provides 350 days, the downtime is 15 days. The capacity matching ratio for coal would be:

$$\text{Downtime/required} = 15/365 = 0.041.$$

Scoring for this attribute adjusts the raw score between 1 through 10. To accomplish this, the raw score is multiplied by 10. For example, a raw score of .5 will equate to 5 on a scale of 1 through 10.

Sustainability Function *F*(S)

The final sustainability score will be a summation of attributes (A) and (B).

$$F(S) = \text{Persistence} + \text{Capacity Matching} \qquad \text{(J-2)}$$

As F(S) approaches zero, the system is considered to be more sustainable. For simplification purposes, "Capacity Matching" will not be utilized in the final quantification of this criterion in the development of the computer model.

Selected References

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APPENDIX K. White Paper Summaries

The following excerpts were taken from white papers taken during the early months of work on this LDRD.

THE VALUE OF MODELING, PREDICTIONS, AND POLICY FORMULATION

Glenn Kuswa

Abstract

As a starting point in evaluating the merits of models, forecasts, and predictions, we first determine what basic types of models exist and how those models serve their sponsors. We then look at a few examples, including a model that is in current use, and what previous models or forecasts predicted and what actual results came about after several decades. The lessons learned should give some perspective to the value of modeling and can provide some guidance concerning what factors to emphasize in making models more faithful to reality. Some simple lessons emerge. If a forecast is correct or partially correct, one might presume it is good. However, if an accurate forecast becomes known to policy makers after other less accurate estimates become accepted, or if a forecast is overly complex and not credible at the time it is released, even a good report becomes a failure. A useful forecast is one that makes some difference in human events, but this difference may be very difficult to trace.

We also considered some fairly recent studies that use multi-attribute criteria in a formalized structure to determine optimal solutions from considerations that span a large space of variables. We did not find any examples of such studies having strongly influenced major funding decisions, because economic factors must dominate such decisions, unless there are regulations or incentives in place to force the economically favorable solution into alignment with the multi-attribute approach. It appears the multi-attribute approaches are good for influencing policy makers to seek more optimal solutions and to break away from using purely economic arguments or waiting until some effect of crisis proportions forces piecemeal solutions. With this thought in mind, the thrust of our LDRD was strongly influenced by the multi-attribute approach.

We used in particular two references for multi-attribute decision making. A general review of the subject is given in a paper by Lorna A. Greening and Steve Bernow, Design of coordinated energy and environmental policies: use of multi-criteria decision making, *Energy Policy*, Vol. 32, No. 6, pp. 721-735, April 2004. An interesting application that graphically demonstrates how one can choose attributes in a combined way to approach a theoretically determined boundary is given in a paper by Stephen R. Connors, Informing decision makers and identifying niche opportunities for windpower, *Energy Policy*, Vol. 24, No. 2, pp. 165-176, 1966.

We examine a model, Threshold 21, produced by the Millennium Institute, that seems to have been effectively utilized to exert influence and to change minds during its tailored use in a number of countries. Customers have included countries and the World Bank. In this case there seems to be little critical review of the actual outcomes, but the perspectives gained from looking at the descriptive material can give some useful perspectives on developing a clear sense of what is to be expected from a model. If such consideration is given at the outset of a study, the chances of timely success can increase.

In looking at the results of past studies, we observe that modeling tools in the late 1970s were less developed than is the case today. Would more detailed modeling have captured the future with more accuracy, or were there other dominant factors that would likely have been missed by modelers? Is the detailed data being collected for today's complex models worth the effort, in view of the many uncertainties that attend modeling? These questions are not answered here, but are worth continued discussion. I believe that the defects in the models applied many years ago would likely occur again today, if modeling were to be emphasized over an approach that seeks the widest diversity of opinions and knowledge, including more emphasis on considering changes in human behavior and anticipating important technological shifts. Lessons learned from looking at past and current modeling will apply to studies that may be part of Sandia's future.

We note that some easily used models have been developed by Arnold Baker's group (Organization 6010) at Sandia. They seem to have high potential for influencing decision makers, and might also find good application in heightening understanding and enthusiasm among energy practitioners at Sandia. We have not chosen to highlight specifics in this paper, but we want to acknowledge their potential importance. We also note that because of this recognized importance, we have opted to work intensively with the Sandia economists to make the results of the LDRD available in a computer modeling format.

There are some lessons learned here for Sandia studies on energy demand. Changing social habits and needs drive some changes, and studies should place some added emphasis in this area. Emerging technologies, such as those that led to the use of more natural gas for electric energy generation should be identified and possible dislocations should be thoroughly studied and emphasized. (Dislocations refer to brand new technology that can supplant old methods. Coal replacing peat as a fuel in England and the use of aircraft engine turbine variants for gas-generated electricity are examples.) If a similar study to the RFF or Ford efforts were to be conducted today, here are some examples of topics that might deserve attention:

1. *Examine the potential for harvesting methane-hydrates; call attention to the consequence of a breakthrough in this technology area.*
2. *Examine the impact of hybrid vehicles in the context of imports of fuel, and on other resources that might be needed in greater supply, such as lead or sulfuric acid.*
3. *Study social trends on energy usage, and in particular find out what the aging population will need/expect from the transportation sector.*
4. *Try to project how electronic conferencing will change transportation needs.*
5. *Integrate other resources, such as water, that are needed to produce energy.*
6. *Look more intensively at worldwide energy demand in making projections, because US prices and the relative ability of other nations to access cheap energy will do much to determine future pattern of prosperity and military power. Also, the practices of the rest of the world will dominate potential climate modifiers such as carbon dioxide and other emissions.*
7. *Energy security and scenario planning needs to play a stronger role in future studies.*
8. *Climate trends and the influence on water supplies and energy needs need to be factored in. For example, will a warming earth require more or less of various fuels under conditions of fixed living standards?*

9. *There seems to be a need for examination of energy use changes driven by a variety of changes in technology and business practices. For example, just-in-time deliveries cut down on space needs, but may increase fuel use in transportation. The increasing use of hub systems to handle air passenger and freight has some consequences for fuel use, but the magnitude may or may not be known. The increasing use and improvement of solid state devices saves energy per unit of benefit (increases efficiency), but can increase demand. For example, computers are more energy efficient than in the past, but there are now many more computers and the electricity usage of computers is significant. The quantification of changes in energy use brought about by these changes needs to be known.*
10. *Look very carefully at the entire life cycles for all technologies, and especially at the complex bio-renewable cycle. In the latter case, look at all requirements for growing energy crops—fertilizer, water, use of waste products, changes in fuel economy (especially important if methanol is blended with gasoline), changes in pollution from agricultural run-off to end use of product, cost of long-term soil depletion, alternative approaches and opportunity costs, and other factors.*

A COMBINED MEASURE OF ENERGY COMPARISON: SOME THOUGHTS ON THE ENVIRONMENTAL AND CLIMATE CHANGE EFFECTS FROM VARIOUS ENERGY SOURCES

Glenn Kuswa

Abstract and Added Summary Thoughts

Continued use of energy supplies, within the current constraints imposed by economics and regulations in the United States and in the rest of the world, may lead to climate changes that will cause economic dislocations and will disrupt the goal of providing a sustainable society for future generations. We sought some indicator that would serve to contrast and compare all energy sources. Climate change potential served as the metric for this comparison, on the premise that climate problems might soon eclipse other aspects such as cost and security. In the process of this study, we discovered surprises concerning biomass and climate change caused by population pressures, aside from more burning of fossil fuels, which are also noted in this summary.

There are significant differences in the climate change potential of various energy sources, ranging from nearly zero effect on the heat load imposed on the earth from fuel consumption itself, to 59 times more heat load than results from burning fuel alone. (The number 59 is based on very conservative estimates of residence times of carbon dioxide in the atmosphere, and could be ten times or more underestimated.) For each energy source there are opportunities to increase the efficiency of use and to thereby somewhat reduce climate changing effects, but the most effective way to reduce climate change is to reduce fossil fuel consumption or to sequester greenhouse gas from burning fossil fuel, where feasible. This would most easily and effectively be first accomplished in stationary power plants that do not require the convenience and high energy density of liquid hydrocarbon fuels. This paper considers the consequences of civilization's use of various energy sources, and defines the actions that may be required (or prohibited) to assure that energy will be available to present and future generations, with protection for the ecosystem.

Other human activities, aside from energy production that emit greenhouse gases, may also influence climate, and the aggregate effect of these activities is much less understood than the effect of greenhouse gases from energy production. The uncertainty imposed by a collection of climate-changing forces that could overshadow the well-advertised effects of energy-related climate factors—mostly associated with carbon dioxide—demonstrates the importance of conducting a more vigorous campaign to understand climate change.

Some "Executive Summary" Observations

(Details and references are discussed in more detail in the full text.)

Climate management will require wise application of regulation and subsidy, and the present allocation of resources is sometimes less driven by wisdom than by politics. Since most solutions that reduce risks for influencing climate add to the cost of doing business, and do not offer any economic benefits within the time horizons of businesses, workable solutions to reducing climate-changing emissions will usually require some government intervention. Conservation measures that save companies money and measures that result in positive public relations are beneficial exceptions that see frequent application by industry, even without regulation or subsidy. Some technologies enjoy large subsidies that are largely determined by political forces, rather that sound scientific investigation. A good example of heavily subsided activity that at first appears beneficial is the agricultural production and use of ethanol as a gasoline additive when crops are specifically grown for that purpose. We will discuss data that indicate that use of ethanol may actually increase greenhouse gas emissions; its use adds to soil depletion and takes considerable fossil energy for fertilization, cultivation, harvesting, and processing. Farming can result in more water vapor release into the atmospheres, and that is also a potent greenhouse gas and an influence on climate in other ways. The net result of purposely growing more biomass expressly for fuel production may, in balance, negatively effect public good, but it does help Midwestern farmers and some large corporations that produce alcohol from farm crops.

The enactment of incentives or subsidies that are small (on a per-unit of energy basis) in comparison with the ethanol subsidy could lead to an energy infrastructure that greatly reduces greenhouse gas emissions. Examples of technologies that reduce greenhouse gas on a permanent basis are wind, nuclear, and solar energy, and making existing processes more efficient. Growing forest or biomass can also be helpful in sequestering carbon, at least for the initial decades of new growth, but less is known about the time needed to reach equilibrium between carbon uptake, and decay processes that return carbon back to the atmosphere. In the initial stage or reforestation, carbon sequestration is positive, but after the forest reaches maturity, it appears that emissions of carbon may almost equal absorption. If this is true, the reforestation method to sequester carbon dioxide has only near-term implications, and other technologies will have to carry the major sequestration burden.

Carbon dioxide emissions may not be the premier climate problem. Changes in land use and introducing more water into the air could eclipse greenhouse gases in effecting climate change, especially on a local or regional scale. However, carbon dioxide is more studied, distributes its effects more uniformly in time and space over the entire globe, and is presently better understood than how land-use change, and particularly water emission, influence climate. Methods for carbon mitigation should be researched and might wisely be applied, at least in pilot programs, even before the entire climate change puzzle becomes understood in detail.

World stability depends upon a fairly steady climate, and depends upon preventing overpopulation. Continued supplies of energy will be useful only in a world that can support stable civilization, and any reasonable measure of energy sustainability must include provisions to keep society stable. Large climate changes would result in social instability, because of changes in areas where food is produced and people live, so we must assume that energy sustainability is attainable only if climate change is controlled. Even more important is the growth of world populations that increase demands for energy and food, and force more water vapor into the air. Technology can only delay ecological disasters if populations continue to expand without limit. The problem is one of social custom and religious/moral persuasion; science can provide facts but no solutions for this aspect of the environmental dilemma.

Greenhouse gas accumulation and the attendant solar warming is far more an important source of heat than the burning of carbon-containing fuel itself. We compared all energy sources from the vantage point of climate change. A new index, called the total equivalent heat generation (TEHG), describes the total environmental warming effects imposed by energy sources and end uses of the produced energy. This index gives a measure of the wasted heat deposited locally by each type of energy source, and also takes into account the side effects of emissions of other effects that result in bringing in or blocking radiated heat from the sun. In other words, taking the earth as an isolated system, the index provides a measure of the earth's total gain of heat from using energy supplied by various sources. This index is based upon carbon dioxide emissions, and using very conservative assumptions that the residence time of carbon dioxide is only ten years, one finds that the heat from a typical coal-fired plant is only $1/59^{th}$ of the extra heat trapped from the sun. If a less conservative and more accepted carbon residence time is assumed to be 100 years, the ratio changes to 1/590! In other words, the "amplification factor" posed by burning fossil fuels will likely result in hundreds of times more solar trapped energy than is released by the combustion alone. The equivalent warming from a renewable of nuclear source is much less—in the vicinity of five percent of the warming from a fossil plant—and derives primarily from carbon dioxide emitted as a consequence of building the physical plant; concrete and steel and the energy needed in mining, etc., all emit carbon dioxide, and these emissions are amortized over the expected plant lifetime.

"Traditional" greenhouse gas emissions may be less important in bringing about climate change than other factors introduced by civilization. The proposed TEHG index is not perfect or complete, because there are several other man-made contributors to climate change, including methane, ozone, sulfur dioxide, soot that settles on snow and changes its solar heat absorption, and aerosols. In addition, considerable uncertainties still exist in the understanding of all the pathways and rates of absorption and emission of CO_2 in the ecosystem. Some of the greenhouse chemicals arise from energy production, while others arise from methane leaks, cattle or rice farming, chemical manufacture and loss, irrigation and land fill decomposition, etc. TEHG does not take into account social concerns raised by air pollution or the risk of nuclear proliferation that could result from mismanaged nuclear energy expansion; these concerns may be more important in the near term, but climate change is viewed as being an overriding concern, for which correction of past miscalculation could prove beyond civilization's capability.

The TEHG principles could apply to all human activities, not solely energy production, but the complexity suggests this will not happen easily or soon. For example, irrigation to raise crops influences global warming, and a process resembling the following cycle would have to be explored in detail to determine the effect on climate. Consider solar energy that produces stored energy in caloric value of burnable mass or food. This measures biomass energy trapped from the sun, and the stored chemical energy may be as high as a few tenths of a percent, enough to demand inclusion in a complete energy balance, but a quantity that appears to be neglected in current climate models. (Of course, when the biomass is burned or rots, the energy and the trapped carbon are returned to the environment; how close the world is to such a balance appears to be unknown.) To calculate the TEHG, one would need to determine the change in solar balance caused by land-use change, including changes in the radiation balance as influenced by the leaf canopy, water vapor released (water is a strong greenhouse gas; water evaporation and transpiration carries latent and sensible heat, and resulting changes in clouds will also greatly influence solar energy balance), the release or absorption of greenhouse gases from the crops, changes in soil carbon content, and the emissions associated with energy to cultivate, fertilize, and irrigate the crops. If irrigation is from dammed reservoirs or other features that change the solar balance, that would need to be considered, including energy absorption and emission from water surfaces, the effect of water vapor as a greenhouse gas and as a cause of clouds, and the carbon balance of bodies of water created or reduced for agricultural purposes. Considering a complete model would include all aspects of human activity, and would give some measure of the carrying capacity of the planet based on climate stability. The complexity of making accurate estimates of the effects of these factors is enormous, because many of the effects are local or regional, and the history of change is largely unknown and may be unknowable with any certainty. By contrast, ordinary greenhouse gas effects are comparatively uniform and global, the energy transmission and radiation of the gases can be measured with high accuracy, and the history of concentration is quite well known. Developing more complex and complete models is an unmet challenge whose importance should not be diminished by seeking a simple one-parameter index that applies to energy. Even with this complexity, there are some data on which to estimate the global warming caused changes (see Pielke, 2002).

Simple assumptions and calculations of the errors likely in terrestrial energy balance studies indicate that the magnitude of temperature changes induced by civilization's other influences could easily be similar to changes attributed thus far to greenhouse gases; whether such factors balance out, or lead to warming or cooling appears to be beyond current understanding. The Kyoto protocol on climate change failed passage in the USA by unanimous vote, and has been the object of intense political debate over the past few years. Some proponents believe with a high degree of certainty that carbon emissions, left unchecked, will cause untenable climate changes, and others believe that taking action would lead to economic ruin. Both sides of the argument have much to learn from the science that is already understood, and both sides need to recognize that much more needs to learned before permanent solutions to the climate dilemma are implemented. At that same time, it may not be prudent to await precise answers before some actions are taken.

Biomass fuel production that is expressly for fuel, and not part of waste recovery, is a net emitter of greenhouse gas, and is far less efficient than other methods to harness solar energy. Biomass requires the use of considerable fossil fuel for fertilizer, and also for cultivation and processing, and may sometimes require irrigation. Because CO_2 is released from fossil energy sources in this production process, biomass is not neutral in its impact on the climate, as is often implied. Biomass has very small net useful energy gain from the sun, per unit area. Approximately less than .1% of the solar energy incident on a field typically ends up as energy content of the material produced, while about 10% of the energy falling on a solar collector field can be harvested and directly used. (A table of some typical solar conversion rates for growing plants can be found in some lecture viewgraphs by Laurens Mets of the University of Chicago at the following site: http://www.lbl.gov/LBL-Programs/pbd/energy/photosynthesis/338,29). On a land-use basis, using solar or wind generators would do far more—perhaps by a factor of 100—to lower greenhouse gases than growing biomass specifically for fuel. Biomass crop growth captures less carbon dioxide than a permanently growing (not periodically harvested to bare earth) environment. Biomass energy that results from purposefully growing crops to produce energy (i.e., not arising as waste from other crops) must be very heavily subsidized to be a market force. If subsidy investments for specifically growing biomass fuel were made elsewhere—such as for nuclear, wind, solar, or geothermal energy—the United States could more substantially lower CO_2 emissions. (This is not meant to imply that research should not go forth to more efficiently utilize biomass, as there are many areas for improving the treatment of materials that would otherwise be wasted.) Finally, the sustainability of biomass operations might be further questioned on the basis of topsoil depletion. Despite these problems, the public seems to favor biomass, because it is touted by many environment organizations that apparently fail to take a broadly based systems analysis approach.

References

Pielke, R. A., G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, Dev Dutta S. Niyogi, and S. Running. 2002. *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, 360, 1705-1719.

SELLING SUSTAINABILITY – HOW ENERGY AND ECOLOGY POLICY ARE INFLUENCED BY ORGANIZATIONS

Glenn Kuswa

Executive Summary

Sustainability is a theme underlying many energy and resource initiatives, ranging from conservation to increased use of renewable resources. A white paper, also summarized in this list, discusses metrics for sustainability; **here we assume that sustainability means that the present generation can satisfy its needs for the comforts of life, including ample energy supplies, without compromising the ability of future generations to enjoy similar benefits**. (This is the definition defined by the Brundtland Commission published in 1987 by the United Nations.) We examine how government, populations, religious organizations, and non-governmental organizations (NGOs) view sustainability, and how these groups influence environmental or energy-related decisions. Understanding some of these issues can help Sandia and its collaborators design better ways of assembling and marketing supportable energy programs. Considerable influence arises from faith-oriented organizations, as well as from various secular groups. There is a disciplined group of scholars who study religion and ecology, and some of their results are outlined. I searched with less success for similar materials that center on how non-religious organizations market ecology points of view, and that material constitutes a smaller section of the white paper. There are lessons to be learned about marketing and selling ecological stewardship from both faith-based and faith-neutral sectors, and we should not underestimate the importance of these groups in setting future directions for energy and sustainability issues. Unexplored areas not included in the white paper are the influence of the media, professional journals, lobbyists, the makeup of congressional and government staff offices, and educational institutions.

Another important element in ecology matters has emerged during the past three decades: the practice of environmental conflict resolution by government bodies, often through contracts to other organizations. A description of this increasingly practiced, hyper-democratic approach to solving environmental conflict is a third section of the draft paper. This is increasingly part of the ecology policy landscape, and technologists should be prepared to understand its workings, because new technology introduction may increasingly be regulated by such "grass roots" approaches. We also note a variant of this practice. When central governments are viewed by sub-populations as not responding to problems, for example, greenhouse gas constraints, the sub-groups can start independent actions. For example, groups of states are undertaking some initiatives to restrict carbon emissions, and some industrial groups and some European governments are applying pressures by refusing to do business with entities that are not regulating carbon. Some of these initiatives are doubtless driven or strongly influenced by the non-profit community.

One of the references encountered in this mini-study gave a list of attributes that serves as a good way to understand how groups form opinions. Although it was aimed at religious groups, it also applies to other interest groups, and is reproduced below.

1. To identify and evaluate the *distinctive ecological attitudes*, values, and practices of diverse religious traditions, making clear their links to intellectual, political, and other resources associated with these distinctive traditions.
2. To describe and analyze the *commonalities* that exist within and among religious traditions with respect to ecology.
3. To identify the *minimum common ground* on which to base constructive understanding, motivating discussion, and concerted action in diverse locations across the globe; and to highlight the specific religious resources that comprise such fertile ecological ground: within scripture, ritual, myth, symbol, cosmology, sacrament, and so on.
4. To articulate in clear and moving terms a *desirable mode of human presence with the earth*; in short, to highlight means of respecting and valuing nature, to note what has already been actualized, and to indicate how best to achieve what is desirable beyond these examples.
5. To outline the most significant areas, with regard to religion and ecology, in need of *further study*; to enumerate questions of highest priority within those areas and propose possible approaches to use in addressing them.

The lessons learned from this study are:

1. There are significant differences in the ways various religions view nature and sustainability. The Christian view is less well aligned with the stewardship of nature than some other world religions, but there is considerable difference between denominations, and there is some change in attitude for the better.
2. Many non-governmental groups hold views that seem to be as embedded as views based on faith.
3. Finding common ground and working with these groups is likely to be influential in the long run.

Some Features of Non-Governmental Groups and Their Methods of Promoting Their Viewpoints

As an example, we see how the Worldwatch Institute sells its point of view. Browsing the web sites that contain energy- or sustainability-related information shows that some organized and substantial efforts exist to sway the readership to their viewpoint. For an example, I visited a site that, by reputation, might be considered as one of the more reliable. The Worldwatch site for nuclear energy turned up an article that took some delight in explaining how expensive and impractical nuclear power had become, with plant costs around 4000 dollars per kWh, and that by contrast wind power was in the 1000 dollar per kW range. I do not know the exact present figures for these energy sources, but seems that the referenced numbers were quite far from being accurate. There was no discussion of the need for base and peak loads, the advantages of encouraging a balanced mix of energy sources, and the fact that nuclear energy is not a large greenhouse gas producer. No references were given. There are many similar examples on the Worldwatch site alone.

Incomplete information abounds in energy and sustainability reporting. It is easy to dismiss a decision to forgo nuclear power by stating that the reasons are lack of public trust, the inability of

Congress to finalize a waste disposal program, and a cost high in comparison with gas-fired plants. These statements, which reflect the main reasons given in the first ten articles I pulled from a Google search on "nuclear power," correctly describe the reasons for decisions made. Much of the public would expect to hear these reasons, or could cite those reasons without much prompting. But very few of the public could discuss the underlying reasons behind disposal problems and plant costs escalated by cumbersome licensing and decision processes, and very few understand any of the issues associated with plant efficiency. The public is frozen in time with a view of how issues have developed, with little cognizance of what progress could be made. They are largely unaware of trade-off issues. For example, Belgium and Japan have cut back on nuclear power plans, and will be producing significantly more CO_2 than had been expected. The news items that reported the CO_2 outcome were, in my opinion, not sufficiently clear in laying out the risks and consequences associated with the alternative options. Conversely, the public often receives excessively high expectations for other energy alternatives such as hydrogen, fusion, and renewables, based again on incomplete reporting.

How Can We Make Technical Communications More Effective?

Whose fault is the incomplete information that is mentioned above? Sometimes that fault lies with optimistic technologists who may either intentionally or inadvertently ignore problems with their technologies. Reporters are seldom equipped to probe highly technical issues. A public that is more analytic and questioning may ignore poor reporting and essentially drive it out of business, but it seems unlikely that the education system can be brought to a high standard. A direct although only partial solution is for research laboratories and industry to place more emphasis on accurate and well-planned communications. A more direct approach may be to seek more in-depth contacts between national laboratories and technical staffs within the NGO community. Some contacts made during the conduct of this LDRD indicate that such contacts would be welcomed, and this seems to be a faster-track approach to promoting mutual understanding that could eventually lead to more financial support for laboratory energy initiatives, better legislative and regulatory decisions, and enhanced effectiveness for many NGOs in promoting their goals.

HYRDOGEN ASSESSMENT OBSERVATIONS

Glenn Kuswa, August 2004

The hydrogen initiative of President Bush and interest in the subject in previous years have given rise to some reviews. This set of notes attempts to summarize some of those reviews, seeks common features and differences, and comments on some aspects of the reviews. Some comments from hydrogen economy protagonists and antagonists are included. Areas for possible Sandia study are suggested. An effort will also be made to determine the political forces that are fostering the Hydrogen Initiative.

We note that much of the hydrogen movement is based upon misinformation, wishful thinking, and social engineering. For example, we observed in the process of reading reports and discussing some of our conclusions with friends and acquaintances that many people view hydrogen as a natural resource, much like natural gas, rather than an energy conversion and transfer mechanism. We have even heard anecdotes that even some members of Congress are similarly misinformed. Some of the papers that describe how a hydrogen economy would work assume the need for higher efficiency in fuel cells will be met, and also assume super-light vehicles will evolve in order to keep energy usage under control. The assumption is made that this will satisfy the consumer. These papers do not make the same assumptions about what might be done to change the performance of conventionally fueled vehicles. These views at least border on social engineering, rather than working on satisfying market needs as they now exist.

It became obvious early on in this author's reading that creating a brand new infrastructure for hydrogen based upon compressed or liquid hydrogen or on likely hydride storage schemes all failed the total energy efficiency comparison with fossil fuels. The reasons include energy loss in producing hydrogen, and in compressing or cooling or otherwise containing hydrogen to make transport possible. The weight and volume of tanks and the driving range of vehicles carrying a reasonable fuel load presented some problems. The infrastructure to deliver fuel to motorists seemed destined to be based on natural gas as the most likely energy source, and when all factors are considered, it appeared that sequestering carbon would not be easily accomplished with a natural gas backbone with many substations where hydrogen would be produced. Using larger central hydrogen plants would present an opportunity to sequester carbon dioxide, but the subsequent transport of hydrogen to filling stations would become more complex and costly.

From these observations, and from recognition of the hazards potentially posed by rising atmospheric carbon, we started to consider using hydrogen to convert atmospheric carbon dioxide back into liquid hydrocarbon fuels that could fit in with the existing infrastructure. The energy to do this would have to come from renewable or nuclear sources in order to be attractive. It appears that the total cycle efficiency may compare favorably with the cycle efficiency attainable from hydrogen, all things considered, and the current fuel infrastructure investment would remain in use, making it easier to introduce synthetic fuel. This synthetic fuel scenario would also pose virtually no climate change problems because an equal amount of carbon dioxide emitted from combustion would be reclaimed and "recharged" (hydrogenated) to make synthetic liquid fuels almost identical to gasoline. This was the genesis of efforts at Sandia to more thoroughly explore this concept, and work on such a project is beginning as we strive to complete the report on this LDRD.

There are many different viewpoints expressed in reports on hydrogen, and we will not attempt to reproduce all views in this summary, but we will list some observations from the American Physical Society (APS) study on the topic. Note that some of the protagonists complained that the assumptions in that study were too pessimistic. In this summary, the author quotes what he believes to be reasonable and accurate, rather that trying to devote equal time to each point of view; the raw notes contain more critical and comparative comments.

Summary from March 2004—American Physical Society, Panel on Public Affairs: The Hydrogen Initiative. Contact Francis Slakey, (202) 662-8700.

This review starts by noting the gap between promise and reality:

- Hydrogen engines require 10-100 factor of improvement in cost or performance.
- Current production is four times as expensive as gasoline.
- Handling technology, such as storage vessels, will not allow convenient or economical handling.
- If the intended goal of having the technology ready by 2020 is not met, there are no provisions for using bridge technologies.
- The authors noted that a balance has to be maintained between developing the science and fostering demonstrations, and suggests that was not the case for the Synfuels project of the Ford Administration, and is certainly not the case for the Hydrogen Initiative.
- A balanced approach might use renewable energy to produce hydrogen, but coal or other fossil energy might also be used.
- A statement is made that the Hydrogen Initiative might reduce our dependence of foreign oil (about 2/3 of the oil goes into the transportation sector).
- The commercial use of fuel cells in transportation, portable power, and stationary and distributed applications by 2012. (This is a quote from the national energy roadmap http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/bk28424.pdf.)
- The APS report has a table that lists the attributes for the so-called FreedomCAR. This chart shows a 4- to 10-fold advantage required in production costs for hydrogen to make it competitive with gasoline, a 2- to 3-fold advantage in storage technology to gain a 300-mile range on a tank load of fuel, and a 10- to 100-fold improvement in fuel cell technology to make the motive power similarly attractive in price and performance of a gasoline engine.
- The report notes that the United States annually produces 9,000,000 tons of hydrogen, mostly using steam reforming, a process already perfected to give close to theoretical yields, but costing several times more than gasoline per energy unit. Natural gas is its source. Coal gasification has lower cost potential, but the added costs to sequester carbon dioxide and to get the required purity for fuel cell operation are unknown.
- The science issues include: storage, whether cryogenic, high pressure, or bound systems such as hydrides; catalysts to improve electrolysis; better membranes and catalysts in fuel cells.

The report goes on to make parallels with the Synfuels initiative of the Ford Administration in 1975, which had costs in a similar range, although roughly twice as great in inflated dollars. The Synfuels initiative was based on the high cost of oil, and when prices fell and stabilized, the initiative foundered. The demo projects were not well matched to the current state of the technology. Interest faded, and by 1983, the program essentially vanished. *What the report does not say is that the Synfuels product was compatible with all current distribution and end-use systems, so that production was the only concern of the program. Also, the program was not driven by the environmental concern of greenhouse gas. (Depending upon the audience, hydrogen is billed as climate friendly or as route to energy independence.) In other words, the Synfuels program was on a much stronger footing than today's Hydrogen Initiative, and it was more generously funded. Also, to some observers, the Synfuels program put OPEC on notice that there were other alternatives to their oil, and it put a cap on oil prices; whether this was truly intentional, and how strongly this affected world oil prices can be argued, of course. Hydrogen initiatives could have a similar effect on OPEC decision makers, but unexpectedly convincing success would be necessary.*

Recommendations from the APS report include:

- Couple more basic science into the program, avoiding earmarking, using peer-reviewed research with some promise of continuity, and using some research centers along with academic involvement.
- Pursue energy efficiency.
- Pursue better renewable energy supplies to produce hydrogen—presumably including nuclear.
- Consider bridge technologies—such as more fuel-efficient hybrid vehicles—and the use of hydrogen in the non-transportation sector.
- Early on, the APS realizes that hydrogen will most likely be supplied from sources that emit greenhouse gases, so the report urges emphasis on conservation and efficiency as well as carbon sequestration. *Why not do this anyway, whether or not hydrogen is in the future?*

My impression overall is that the APS is being political and making excuses at every turn to make the program appear reasonable. The suggested associated programs all seem reasonable and desirable, and do not require an emphasis on hydrogen as "glue" to hold the pieces together. There is no mention of using alternative fuel synthesis, say from using renewable or nuclear energy to convert carbon dioxide from the air (or from industrial processes) into hydrocarbons that could go into the current infrastructure, thus bypassing the storage issue and the need to build an entirely new fleet. Hydrogen would come from water. Such a cycle would eventually aim at being neutral in terms of dumping carbon into the atmosphere.

LINKS BETWEEN ENERGY SUPPLIES AND WATER NEEDS

Glenn Kuswa, March 2004

It became apparent that water and energy are closely linked, because most power plants and many industrial processes require a supply of water to carry away heat. There is also competition for agricultural water and this sometimes competes with water for hydro-electric generation, and in some cases commercial or recreational navigation and ecological effects become issues. As population grows, individual wells and municipal requirements grow, creating more pressures on a finite resource. We summarize a few of our observations here.

There are trades involved in the water-power nexus. A power plant can operate dry, but this requires more fuel and adds to the cost of power and to competition for dwindling fuel supplies. Some power plants fueled by natural gas use turbines that discharge the hot exhaust into the air, and no cooling water is needed, but more efficient combined-cycle plants tap the otherwise wasted heat, and cooling water then becomes desirable. While there may be more developable gas supplies in the world, the distribution of supply and the convenience of use for this fuel have driven costs up, so it seems unlikely that that its expanded use will have much effect on water needs. Power plant location depends upon a host of factors, including proximity to markets, costs and availability of transmission lines and fuels, the availability of cooling water, competing electric sources, and a host of licensing and taxation constraints. At some level of willingness to pay more for electricity, it will probably always be possible to add more generating capacity, but such a glib statement would dismiss the desire to work toward a sustainable society. Vastly higher power costs violate the Brundtland Commission definition of sustainability that we have adopted for the LDRD, because much higher costs would make it difficult to satisfy current needs without some adjustment in the quality of life.

Less pure water supplies, which are plentiful in some parts of the United States, can be used to make up some the shortfall, but the impurities cannot be discharged in ways that pollute, and there is a penalty in processing costs. Fossil-fueled power plants emit various pollutants that enter the water and cause various ecological problems, a common one being high mercury levels that concentrate in fish. A separate initiative on water not directly related to this LDRD is in progress, so we will not treat water great detail here, but we have had to pay attention to water matters throughout the work. Early in the LDRD we developed the following set of questions concerning water issues, and we have kept these in mind during the course of our work:

- What is the current use of water in power generation by category (none, pass-through, evaporative, dry, hybrid wet/dry) and efficiency (gal/kWh) by generator type both in terms of installed capacity (GW) and annual generation (GWh/yr)?

- What is the cooling water "resource" and how much are we currently using? This could be broken down into pass-through and evaporative resources and should be compared to other uses, such as domestic and agriculture.

- If there appears to be a potential shortage looming in the future based on projected electricity demand growth (seems to be likely), what are the options to address it? For example, increase agricultural water efficiency or reduce production, use low water usage generation sources, transmit electricity over long distances from areas rich in cooling water resources, etc.

- What are the trade-offs in terms of water use, electricity cost, and environmental impacts?

- What are the costs associated with these trade-offs and how does that compare to the current and potential future cost/value of water?

- What creative options exist for addressing water use or environmental trade-offs? What are their cost and efficiency?

- For which problems can Sandia technology or other skills solve problems?

- Which issues may be influenced by technology, but might be settled by market forces or by regulatory action? One example of this sort of thinking would be to use agricultural water for cooling, and return what is left after evaporation in the power plant to agricultural use at a temperature that may be too high for river discharge, but not so high as to preclude agricultural use.

Finally, we note that water is a greenhouse gas that offers much greater difficulty in assessment than carbon dioxide. Water use (and land-use changes that, in turn, influence water balance, in addition to directly changing solar radiation and re-radiation balance) will rise in response to increasing population and increasing energy use. The magnitude of climate change induced by changes in water emission and land use may easily outstrip problems caused by carbon dioxide, but the political and public awareness of this is presently limited. Further understanding the relationship between water, land use, and climate and finding technical solutions may offer a rich set of opportunities for Sandia and its sister laboratories to serve humanity.

Since water studies are being pursued separately at Sandia, we did not further pursue this topic within the context of this LDRD, but the perspectives gained were used in the conduct of the LDRD work, especially with regard to electric generation.

ENVIRONMENTAL CONSEQUENCES OF TECHNOLOGIES

Juergen Ortner, visiting scientist

We tabulated information on energy usage and environmental consequences, and included projections to the year 2025, and in some cases to year 2050. These data have references included, and can be used for subsequent studies. The results are in Excel spreadsheets that can be obtained from Glenn W. Kuswa or Scott A. Jones. Examples of key indicators collected for the transportation sector appear in the chart below. Using key indicators for the amount of travel and shipping projected to take place in the next 20 years, together with information on energy efficiency projections, Excel calculates carbon dioxide emissions for each category. The effect on net carbon dioxide emission if substitution of each of the fuels by hydrogen were to be made is calculated, using the assumption that hydrogen is produced from natural gas via water gas shift reaction. *The result is that, with the exception of coal, more carbon dioxide would be emitted by replacing other fuels with hydrogen, unless the carbon dioxide from the natural gas to hydrogen production process were to be sequestered.* We also produced estimates of carbon dioxide emissions from residential, commercial, and industrial sectors from the burning of coal, petroleum, and natural gas, and from electricity use. (Electricity has large nuclear and hydro contributions.)

KEY INDICATORS

Level of Travel (billions)

Light-Duty Vehicles <8500 lb (VMT)
Commercial Light Trucks (VMT) 1/
Freight Trucks >10000 lb (VMT)
Air (seat miles available)
Rail (ton miles traveled)
Domestic Shipping (ton miles traveled)

Energy Efficiency

New Light-Duty Vehicle (MPG) 2/
  New Car (MPG) 2/
  New Light Truck (MPG) 2/
Light-Duty Fleet (MPG) 3/
New Commercial Light Truck (MPG) 1/
Stock Commercial Light Truck (MPG) 1/
Aircraft (seat miles per gallon)
Freight Truck (MPG)
Rail (ton miles/thousand Btu)
Domestic Shipping (ton miles per thousand Btu)

Energy Use by Mode

quadrillion Btu
  Light-Duty Vehicles

Commercial Light Trucks 1/
Bus Transportation
Freight Trucks
Rail, Passenger
Rail, Freight
Shipping, Domestic
Shipping, International
Recreational Boats
Air
Military Use
Lubricants
Pipeline Fuel
Total

Million Barrels Per Day Oil Equivalent
Light-Duty Vehicles
Commercial Light Trucks 1/
Bus Transportation
Freight Trucks
Rail, Passenger
Rail, Freight
Shipping, Domestic
Shipping, International
Recreational Boats
Air
Military Use
Lubricants
Pipeline Fuel
Total

Other environmental data concerning such factors as greenhouse gases other than carbon dioxide and water, particulate emissions, mercury, etc., were tabulated using methods specified in ISO 14042 (year 2002) procedures. The categories and indicators are listed below. These data can be applied when assessing the consequences of various mixes of energy sources. The materials needed to construct and maintain energy-producing facilities were included in these data.

CATEGORIES	INDICATORS	
green house effect	green house potential	as CO_2-equivalent
eutrophication of soils and water	eutrophication potential	as SO_2-equivalent
acidification of soils and water	acidification potential	as PO_4-equivalent
impact on human health	lost life span life time with affected health	as years of life lost
damage of environment made by man	cost generated by damages on materials and plants	as $
consumption of primer energy carriers	cumulated energy effort	as GJ
consumption of non-energy feedstock	consumption of minerals	as kg

Finally, we made some estimates, also available on Excel spreadsheets, of emissions that show pollution consequences of electric power generation today and in the year 2050, taking into account expected population growth, and estimated those same emissions if hydrogen from natural gas were to be substituted. Again, carbon dioxide sequestration was not assumed to be in use. When hydrogen is substituted for other electric generation fuels, greenhouse gases actually increase, except in the case of burning coal, for which there is a substantial reduction. This is not entirely surprising, because coal is carbon rich and the efficiency of the conversion process is rather low today. It becomes quite clear from the data gathered that the most effective way to initially reduce carbon dioxide emissions, as well as other emissions such as SO_x and mercury, is to sequester these substances at the power plant, or to replace coal with other fuels. This approach to reducing carbon emissions would be easier and more cost-effective than striving to eliminate carbon from transportation fuels, because there are many technical options available for reducing emissions from central stationary energy plants.

MODELERS AND POLICYMAKERS: IMPROVING THE RELATIONSHIPS

Thomas H. Karas

A report on this sub-topic is available in a Sandia National Laboratories Report, SAND 2004-2888, Unlimited Release, June 2004

Early in this LDRD study, the need became evident to understand how policymakers interact with modelers. By examining this need in detail, it should be possible to make such interactions more productive. The Advanced Concepts Group at Sandia undertook this study by inviting 14 policymakers, analysts, and scholars to participate in a workshop. The meeting resulted in 20 guidelines for modelers and 10 guidelines for policymakers. If these were to be followed, the interactions would be more productive.

Modelers need to be particularly cognizant of communications. They must understand the context of what they are modeling, take special care to provide clear explanations, and must accept the burden of the communications effort and establish continuing dialogues. Throwing results over the fence or waiting for the world to recognize the modeler's wisdom will not be productive. The modeler must be relevant by identifying the target audience, addressing the purpose, and concentrating on the salient questions. Modelers need to place the most emphasis on the problem, and not on the model itself. The modeler must always be credible, and cannot assume impossible scenarios. The modeler must tell a story that makes sense to the audience. Perhaps most importantly, modelers have to be timely in getting their results to the target audience. Modelers need to establish and maintain credibility by paying close attention to their reputations and by not overly extrapolating or overreaching their sphere of understanding. Modelers often are hampered by insufficient data. Credibility is aided if a modeler can point to a good previous track record. Simple models that are highly transparent are generally best. Modelers should look closely at human wants and desires. To assure quality, conducting reviews by peers and stakeholders and comparing and collaborating are very important.

Policymakers likewise need to focus on communications by meeting frequently with modelers, thoroughly explaining their needs and purpose, and they must provide as much accurate data as required by the modelers. Policymakers need to engage modelers early, and they should make certain there are peer reviews and make comparisons of the results for competing models.

THE INFRASTRUCTURE THAT WOULD BE REQUIRED FOR TRANSPORTATION HYDROGEN FUELS

Max Valdez

During the last several years, the United States has placed considerable emphasis on replacing liquid motor fuels with hydrogen. Currently, natural gas is the least costly route for producing hydrogen. Hydrogen is a chemical feed stock for making ammonia fertililizer and enriching refined petroleum products, and today, US industry synthesizes from natural gas approximately ten percent of the amount of hydrogen that would be required to replace all motor fuel consumed in the United States. This process releases carbon dioxide. If the transition to hydrogen is mandated by the need to reduce greenhouse gas emissions, there would be a need to trap these emissions. Carbon reduction might most reasonably be accomplished by first trapping carbon dioxide from current sources, including fixed plants that produce hydrogen, and coal-fired power plants. Of course, carbon sequestration processes require added energy, so the time to deplete fuel supplies would be lessened, and the costs would rise. Carbon sequestration would only become reality under a strict regulatory program; without regulations, we would assume that the lowest cost hydrogen source would win most of the business. Even though the prices of natural gas are rising, we believe that its ease of distribution and overall lower cost for producing hydrogen would make natural gas the raw material of choice to produce hydrogen.

Hydrogen can also be produced by electrolyzing water with about 85% efficiency, and this could rise with further development. This hydrogen would have to be compressed or liquefied before distribution, and those processes consume considerable energy that cannot reasonably be reclaimed with current technology. If fossil or nuclear power are used to produce electricity that, in turn, produces hydrogen, the thermodynamic losses incurred in making the conversion from heat to electricity take an efficiency toll, because power plants are typically only 35 to 60% efficient. In terms of using energy as efficiently as possible to produce hydrogen, the chemical conversion of natural gas appears to have the advantage. Of course, if wind or photovoltaic energy is the primary source of energy, electrolysis may be most attractive. We note, however, that thermo-chemical processes may be developable to directly use solar heat to generate hydrogen at lower cost than through electrolysis.

We did not study the alternative approaches to hydrogen in detail during the conduct of our LDRD work. Rather, we made the assumption that the lowest cost hydrogen production methods currently being used would be the methods of choice during early infrastructure development. Therefore, we examined how the natural gas system would have to grow, as part of a new infrastructure to produce hydrogen for transportation.

Developing a Pipeline Network for Hydrogen Production Via Natural Gas Reformation

Producing hydrogen via natural gas reformation has been currently identified as the least expensive method and the first choice in transitioning to a hydrogen economy. Several studies such as the National Academies of Science (NAS) 2004 report on hydrogen suggest that developing a hydrogen economy may require huge investments in our energy infrastructure.[1] Although this report mentions that identifying and defining a hydrogen infrastructure on the national level in detail may be impossible at this time, it is possible to develop an understanding of the magnitude of investments that may be required, and the impacts a hydrogen economy could have on other infrastructures.

Regional studies have been conducted to assess the technical feasibility and economics of a hydrogen infrastructure. In 1999 Joan Ogden from UC Davis wrote a report on a hydrogen infrastructure using the Los Angeles Basin as a case study. In her findings, she concluded that the initial development of a hydrogen infrastructure within California is feasible due to the excess hydrogen production capacity currently available from industrial gas companies. However, Ogden (1999) claims that hydrogen reformers will have to be constructed when demand begins to outstrip current production capacity.[2] Another hydrogen infrastructure report, Mintz et al. (2002), states that additional investments in the natural gas infrastructure will be required if hydrogen becomes a significant source for vehicle fuel.[3] Spath and Mann (2001) conducted a life cycle assessment of a natural gas steam methane reformation plant to assess the environmental consequences.[4] They reported that the production of hydrogen via natural gas will require large investments in the natural gas pipeline network. With the exception of Spath and Mann (2001), these fore-mentioned studies discuss the need for natural gas infrastructure development, but they do not address the impact a hydrogen economy could have on the natural gas infrastructure.

Two scenarios have been widely accepted for the development of a hydrogen infrastructure: centralized and distributed. In the centralized case, natural gas is piped to large centralized reformers, where it is then converted to hydrogen and shipped to the end user via pipeline or truck. The distributed case assumes natural gas will be piped to small end-use hydrogen reformers where the hydrogen will be consumed on site. Identifying the difference between the two hydrogen scenarios is very important because each scenario will determine the development of the natural gas infrastructure. Furthermore, understanding the current status of natural gas infrastructure is necessary in order to assess how and possibly where the natural gas system might develop. As of yet, only the centralized case is included in this draft of the white paper.

Current Natural Gas Infrastructure

The US natural gas pipeline network is primarily composed of transmission lines, distribution lines, field and service lines, storage, and compressors. The Interstate Natural Gas Association of America (INGAA) defines transmission lines as pipelines with a diameter greater than 24 inches, and defines smaller pipes as distribution lines. Transmission lines move the bulk of the natural gas across the country, while distribution lines tie the end users to the transmission

1 National Academies (2004). The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D.

2 Joan Ogden (1999). Prospects for Building a Hydrogen Infrastructure. Center for Energy & Environmental Studies. Princeton, New Jersey, Princeton.

3 Marianne Mintz*, John Molburg, Stephen Folga, Jerry Gillette (2002). Hydrogen Distribution Infrastructure. Argonne National Laboratory, Center for Transportation Research* and Decision and Information Sciences Division, Argonne, IL 60439, USA.

4 Pamela L. Spath and Margaret K. Mann (2001). Life Cycle Assessment of a Natural Gas Combined-Cycle Power Generation System. National Renewable Energy Technology.

network. Field and service lines are generally between 3 to 6 inches in diameter and connect the natural gas field to the transmission network. Storage is primarily underground in caverns or abandoned mines, which are used to provide natural gas to the end users during peak demand periods and reserve capacity during production shortfalls. Natural gas can also be stored in liquefied form, but this technique now accounts for only 2% of the total storage capacity. Compressors maintain the pressure in the pipeline network that enables the system to operate and move the natural gas from the source to the end user.

Since 1960, natural gas consumption has increased from 12 trillion cubic feet (Tcf) to about 22 Tcf in 2003. Although consumption reached a high of 23 Tcf in 2002, demand for natural gas has remained relatively stable since 1996. Historical trends in natural gas transmission lines have been relatively flat over the past four decades, averaging about 0.2 million miles, or about five feet per capita. (This comparison is useful, because a 5-foot section of pipe 24 inches in diameter, with a ½ inch wall, contains an amount of steel that compares with that used in a small automobile.) However, growth in the natural gas infrastructure has been dominated by the growth in distribution lines from 0.39 million miles in 1960 to just over 1.1 million miles in 2000. Currently, the EIA reports that 1,033 miles of pipeline has been added in 2004, while future projections out to 2020 estimate 45,000 miles of new pipeline will be required to meet the future needs of the natural gas industry in the US.[5] Based upon those needs, the INGAA estimates that 66% (30,000 miles) will be for distribution lines less than 24 inches in diameter, and 34% (15,000 miles) of the total projection will be for regional and interstate transmission lines with a diameter greater than 24 inches.

Capacity utilization is a significant factor when attempting to identify when the natural gas system will require expansion if hydrogen consumption increases. Obviously, when developing centralized natural gas reformers, new pipelines will need to be constructed to service those reformers. The same is true for distributed facilities when many are placed in service, but initial impacts of low volume facilities may not greatly perturb supporting infrastructures. The main question, however, is how much will be needed? Spath and Mann (2001) estimated in their study that a centralized reformer will require 2,486 miles of natural gas pipeline in order to deliver the natural gas to the plant. Spath and Mann (2001) provide little justification for their assumption except that a centralized reformation plant will require large amounts of natural gas, and they refer to Ecobalance Inc., a consultation firm that provides life cycle assessments, as their source. The Ogden (1999) case study focuses on a hydrogen refueling infrastructure and provides cost estimates for hydrogen pipelines. The Simbeck and Chang (2002) hydrogen report provides cost estimates for various hydrogen pathways; it assumes that the hydrogen infrastructure will use the existing natural gas infrastructure and mentions that more investments may be required. Except for Spath and Mann (2001), current research has not identified how a hydrogen economy will affect the natural gas infrastructure.

The natural gas pipeline network is segregated into nine regions; each region operates at different capacity levels, which can lead to a misleading figure when attempting to ascertain a system-wide utilization rate. "Capacity utilization is defined as the annual throughput volume divided by the design capacity," and in 1996, the EIA reported that the United States was utilizing 75%

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[5] INGAA (2001). *An Update Assessment of Pipeline and Storage Infrastructure for the North American Gas Market.*

of the natural gas pipeline design capacity.[6] Currently, the average utilization rate reported in the Annual Energy Outlook (AEO) 2004 supplemental table #108 is 57%.[7] However, the EIA contends that utilization rates below 100% do not imply that additional capacity is available because pipeline companies prefer to operate as close to capacity as possible.[8] Furthermore, capacity can be increased and utilization can exceed 100% when storage, line packing, and secondary compressors are added to the system (EIA, 1998). In fact, we do not have sufficient data to understand the 18% drop in capacity during the eight years following 1996. Understanding such factors can provide insights into which areas could more easily support a hydrogen economy and which areas will require expansion.

Case Studies for Natural Gas Infrastructure—Centralized and Distributed Plants

The Energy Systems Analysis Group at Sandia National Laboratories conducted a preliminary analysis of the hydrogen infrastructure to assess the requirements necessary to bring into realization a full conversion of the light duty vehicle fleet to hydrogen by the year 2050, and the related impacts to the environment, economic security, health and safety, and the supporting infrastructure. For this paper, only the natural gas portion of supporting infrastructure is addressed. Due to the degree of variation described previously between a centralized vs. distributed case, both scenarios were utilized for this study based upon vehicle projections in the NAS 2004 hydrogen report. Hydrogen demand and natural gas projections were calculated using a modified version of the Hydrogen Futures Simulation model (H2Sim) developed at Sandia National Laboratories.[9] Other hydrogen and natural gas projections were calculated using a Markal energy model developed by Lorna Greening, a private energy economics consultant. All other projections and estimates were derived using Excel spreadsheets. The scope of this study was limited specifically to steam methane reforming utilizing natural gas as the feed stock.

Centralized Case

The amount of natural gas pipelines needed to support a hydrogen economy will depend upon the number of centralized hydrogen reformers and distance to source. The size of the reformers is primarily dependent on the output of hydrogen required and the cost of production. Simbeck and Chang (2002) looked at a variety of plant sizes ranging from 20,000 kg/day to 200,000 kg/day, and used a 150,000 kg/day for the purpose of their report.[10] The Spath and Mann (2001) Life Cycle Assessment of a hydrogen reformation plant assumes a 133,000 kg/day reformation plant based upon data obtained from the Stanford Research Institute (SRI). The Ogden (1999) study refers to hydrogen reformers as large as 1mil scf/day ~ 236,239 kg/day. Although Simbeck and Chang (2002) and Ogden (1999) provide complete analyses regarding the costs of developing and delivering hydrogen, they do not discuss how it could impact the natural gas

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6 URL:http://www.eia.doe.gov/neic/press/press95.html.

7 http://www.eia.doe.gov/oiaf/aeo/supplement/supref.html#pet.

8 EIA (1998). Deliverability on the Interstate Natural Gas Pipeline System.

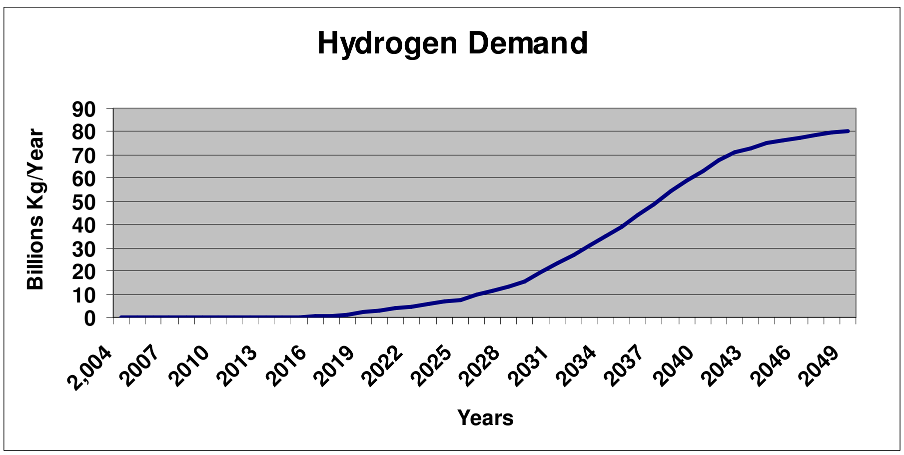
9 Drennon, Thomas et al., (2004). The Hydrogen Futures Simulation Model (H_2Sim) Technical Description. SAND2004-4937.

10 Simbeck, D. and Chang (2002). Hydrogen Supply: Cost Estimate for Hydrogen Pathways: Scoping Analysis. SFA Pacific Inc, National Renewable Energy Laboratory.

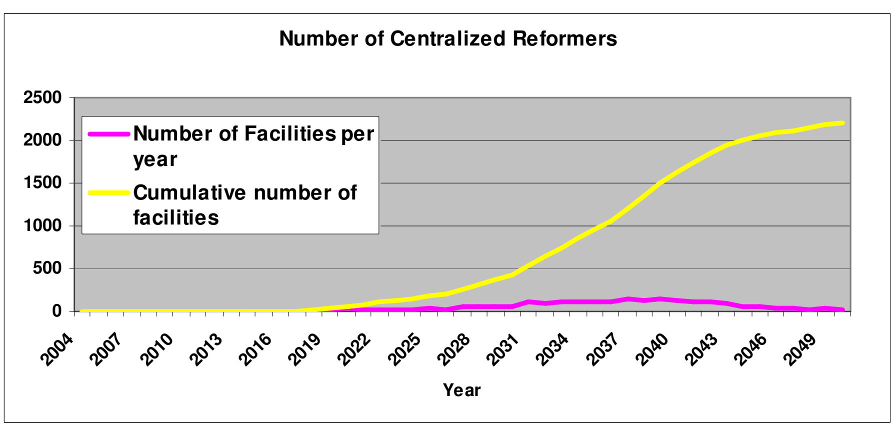
infrastructure, which is the primary mechanism for delivering natural gas to the reformers. For this paper, a 100,000 kg/day reformer is chosen to coincide with the assumptions used in the H2Sim model.

Based upon discussions with David Borns, manager of the Geotechnology & Engineering Department (06113) at Sandia National Laboratories, and consulting energy economist Lorna Greening, a hydrogen reformation plant was assumed to be located to the nearest natural gas source that was economically feasible. A natural gas source could be a large transmission line, natural gas field, or a liquefied natural gas facility. A maximum distance of 200 miles with an average of 100 miles and 25 miles minimum was chosen for this study. The size of pipe used to connect this facility to the source is 24 inches in diameter and ½-inch thick based upon the Spath and Mann (2001) study and American National Standards Institute (ANSI) specifications.

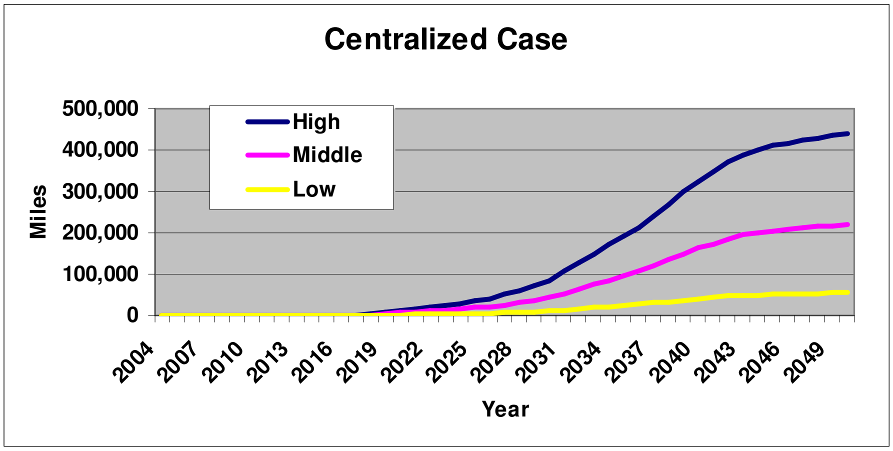
Hydrogen demand was forecasted out to 2050 using H2Sim based upon hydrogen light duty vehicle projections developed by the NAS. Based upon the NAS projections, H2Sim calculated that hydrogen demand could reach 80 billion kg/year by 2050.



The number of 100,000 kg/day reformers required to supply the amount of hydrogen forecasted was calculated by multiplying the 100,000 by 365, then dividing the forecasted demand by that number.



Based upon these projections, the number of centralized reformers required could exceed 2000 plants by the year 2050 and the natural gas system may need to be expanded by 200,000 miles in terms of larger pipes than presently used. This is more than twice the size of our current infrastructure.



Distributed Case

The use of distributed generation has been considered a more enticing method for the delivery of hydrogen. Economically, Ogden (1999) claims that distributed hydrogen production is more attractive because no hydrogen distribution system is required, and it will continue to do so until geographically concentrated demand increases. However, Simbeck and Chang (2002) contend that the costs for delivering natural gas to small distributed reformation plants would be higher than centralized generation because commercial feedstock rates for small scale reformers is 50% to 70% higher than industrial rates, delivery rates are 70% greater, and power cost is 55% higher. The distributed case has not been addressed in this paper. However, it is interesting to note that some researchers suggest that a distributed case is not feasible due to the difficulty associated with carbon sequestration.

NUCLEAR ENERGY FOR ELECTRICITY GENERATION: CURRENT CONDITIONS AND FUTURE DIRECTIONS

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Keywords: nuclear energy, nuclear fuel cycle, electricity generation

This document summarizes key portions of the content of a SAND report being written in support of the Multi-attribute Criteria Applied to Electric Generation Energy Systems Analysis LDRD. The title of the SAND report will be *Nuclear Energy for Electricity Generation: Current Conditions and Future Directions*. The SAND report will be completed by the end of October 2005, although it is hoped to have the document completed by September 2005.

Nuclear power has proven to be a safe, reliable, and efficient method of generating electricity in the United States and many other countries. Nuclear power reactors do not emit greenhouse gasses, are not affected by the vast majority of potential weather conditions, require relatively small amounts of fuel by volume, and exhibit fuel supply stability. Of course, reactors also depend upon fissile materials that present unique hazards to people and the environment if a fission product release should occur either by accident or due to malicious intent. Long-term storage of radioactive spent fuel is also an issue that has not been resolved (i.e., conducted on an industry-wide scale) in any country—although the United States is one leader in this process. Several dramatic accidents involving nuclear power around the world (i.e., Three-Mile Island (TMI), Chernobyl, and a few less-well known events[1]) have generated concern and fear regarding this energy source; some have skillfully argued that concerns are excessive given the actual risks to the public. Unfortunately, recent surges in terrorist activities that have caused many fatalities, injuries, and financial burdens have also heightened concerns among the general public of an intentional diversion of reactor fuel for nuclear weapons or dirty bombs. In contrast, the threat of terrorism has also raised concern regarding the stability of fossil fuel supplies. This paper presents an overview of nuclear power along with the opportunities and obstacles that are being discussed by those who will influence the path ahead for nuclear power both in the United States and throughout the world.

Due to the discussion of certain critical issues in the SAND report, it is anticipated that the document will only be authorized for limited distribution.

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[1] Several accidents in addition to TMI and Chernobyl are discussed later in this paper. It is also important to note that the TMI accident did not cause any negative health effects among the general public.

RISK PERCEPTION AND STRATEGIC DECISION MAKING: GENERAL INSIGHTS, A NEW FRAMEWORK, AND SPECIFIC APPLICATION TO ELECTRICITY GENERATION USING NUCLEAR ENERGY

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Keywords: decision-making biases, decision-making, risk perception, human biases, nuclear energy

This document summarizes key portions of the content of a SAND report being written in support of the Multi-attribute Criteria Applied to Electric Generation Energy Systems Analysis LDRD. The title of the SAND report will be *Risk Perception and Strategic Decision Making: General Insights, A New Framework, and Specific Application to Electricity Generation Using Nuclear Energy*. Although many examples are tailored to nuclear power, the insights, framework, and decision making approach presented are applicable to any high-consequence, technologically advanced domain. The SAND report is to be completed by the end of September 2005.

It is suggested that all decision makers, whether ordinary citizens, academics, or political leaders, ought to cultivate their abilities to separate the wheat from the chaff in particular decision making instances. The wheat includes proper data sources and helpful human decision making heuristics; these should be sought. The chaff includes "unhelpful biases" that hinder proper interpretation of available data and lead people unwittingly toward inappropriate decision making "strategies"; obviously, these should be avoided. It is further proposed that successfully accomplishing the wheat vs. chaff separation is very difficult, yet tenable. This report does not support an Orwellian-type of decision making "wisdom" that enables manipulation by an elite group with a specific agenda, but hopes to expose and facilitate navigation away from decision-making traps that often ensnare the unwary. Furthermore, it is emphasized that one's personal decision making biases can be examined and tools can be provided that provide better means to generate, evaluate, and select among decision options.

Understanding the factors that influence risk perception and strategic decision making is especially important when decisions regarding high-consequence, highly sophisticated technological systems are required. This report brings together insights regarding risk perception and decision making across domains ranging from nuclear power technology safety, cognitive psychology, economics, science education, public policy, and neural science (to name a few) and form them into a unique, coherent, concise framework and list of strategies to aid in decision making. Early drafts of this report focused exclusively on decision making in the "energy domain" as the laboratory directed research and development (LDRD) project supporting this work specifically dealt with energy and infrastructure systems analysis. Significant portions of this report are still tailored to that topic as it is believed that risk perception and decision making tendencies cannot be adequately presented outside the specific milieu of a particular subject. Fortunately, the decision making framework and approach presented here are applicable to any high-consequence, highly sophisticated technological system. This report is intended to promote increased understanding of decision making processes and hopefully to enable improved decision making.

The order of exposition of this complex topic is as follows: first, a unique framework for understanding decision making is briefly presented along with several illustrative examples; second, critical thinking processes are defined and described which are considered foundational to proper decision making; third, the nature of a "technologically advanced" society is briefly discussed; fourth, a detailed discussion (including examples) of the foundations for the framework is presented; fifth, a concise description of a recommended decision making approach is presented; sixth, a discussion of perceived risks and analyzed risks related to nuclear power is presented along with pointers to the proposed framework and decision making approach. Finally, a summary restates the essential components of the framework and approach along with an appeal for using this type of structured approach for decisions involving high-consequence, highly sophisticated technological systems where time is available for thoughtful reflection.

Several key elements included in the report are included below.

1. Modeling uncertainties

When approaching any decision, especially one that involves complex, high-consequence systems, an important consideration is to consciously review what is known and suspected about the domain of interest and to probe areas where unknown factors may lurk. Several months after the terrorist attacks on the United States on September 11, 2001, Secretary of Defense Donald H. Rumsfeld provided an entertaining description of imperfect knowledge while responding to a question about what the United States knew about weapons of mass destruction and terrorist support activities in the country of Iraq (Rumsfeld, 2002):

> **The Unknown**
> As we know,
> There are known knowns.
> There are things we know we know.
> We also know
> There are known unknowns.
> That is to say
> We know there are some things
> We do not know.
> But there are also unknown unknowns,
> The ones we don't know
> We don't know.

The above quotation, criticized by some as a bit wordy and repetitive, is quite correct. That is, the accumulation of knowledge about any complex topic is a challenging endeavor that involves an indirect journey out of ignorance. Along that journey one makes observations and proposes inferences in the face of many uncertainties. Some of these uncertainties can eventually be categorized into "known unknown"–areas of uncertainty that are known to exist, but there is no clear way or no practical way to increase knowledge in those areas. Always lurking are the "unknown unknowns"–gaps in knowledge that are critical to understanding the complex topic, but have not been identified at all. Figure 1 provides possible visualizations of one's state of knowledge regarding a system with conceptual boundaries established by defined system goals.

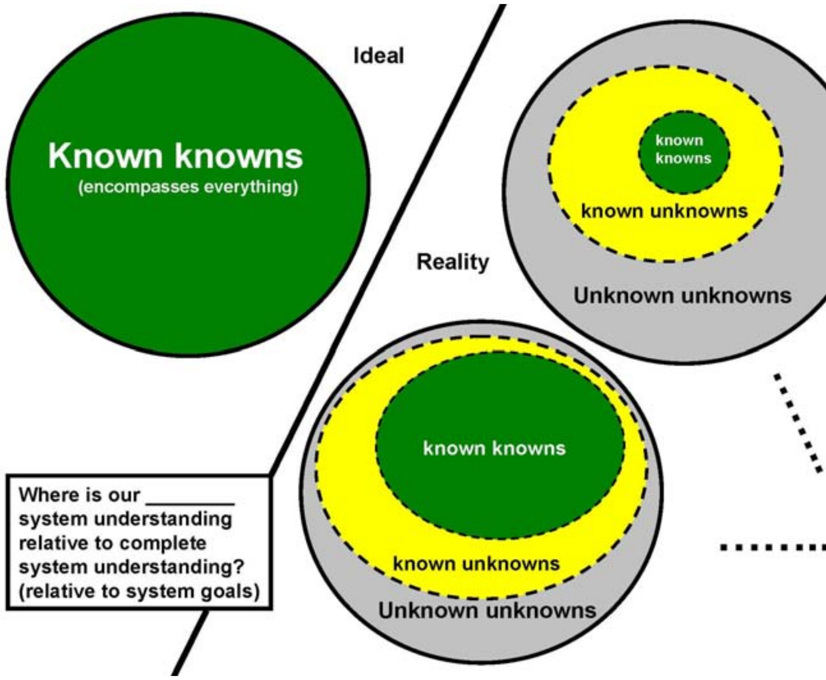

Figure 1. One's state of knowledge regarding a system.

In the community of risk and reliability professionals, two words are increasingly used to dichotomize uncertainties as being either *aleatory* or *epistemic* in nature (Hora, 1996; Parry, 1996; Zio and Apostolakis, 1996). Aleatory uncertainty involves events or phenomena that occur in a random or stochastic fashion. A simple example of aleatory uncertainty would be random variations introduced when a rubber ball is dropped twice from the same location. Newtonian laws of motion and laws of energy conservation are very effective for enabling predictions of general trajectories the ball may follow and heights of intermediate bounces before the rubber ball comes to rest on the floor. But subtle, random variations will occur in how the ball is released, the specific portion of the ball that hits the floor first, imperfections in the spherical shape of the ball, etc. These are aleatory uncertainties in the rubber ball drop system. Another example of aleatory uncertainty would be anticipating the type of weather conditions present in the vicinity of a chemical plant at the time a pressure vessel explodes and releases chlorine gas.

Epistemic uncertainty involves one's confidence in the correctness of their observations and inferences concerning a system, and confidence in derived models or representations of that system. Both known unknowns and unknown unknowns fall into the epistemic category. A "known unknown" example of epistemic uncertainty using the rubber ball drop system could be the general shape of trajectories taken by the ball on successive bounces when all that is needed is the average time taken for the ball to come to rest on the floor. Detailed analysis could be performed to turn this known unknown into a known item if desired. Epistemic "known unknown" uncertainties include modeling structure and specific model parameters. An example of an "unknown unknown," never conceived by the person analyzing the system, might be the occurrence of a rubber ball splitting into two pieces upon contact with the floor due to defects caused during the rubber ball manufacturing process. Epistemic “unknown unknown” uncertainties include modeling structure and modeling completeness mistakes and omissions.

2. Critical thinking processes

> The simple but difficult arts of paying attention, copying accurately, following an argument, detecting an ambiguity or a false inference, testing guesses by summoning up contrary instances, organizing one’s time and one’s thought for study—all these arts…cannot be taught in the air but only through the difficulties of a defined subject; they cannot be taught in one course in one year, but must be acquired gradually in dozens of connections.
>
> Attributed to Jacques Barzun, cited in Arons (Arons, 1990)

This section presents ten critical thinking processes or skills that are deemed essential to enable one to properly understand their interactions with their environment, and with other people; therefore they are foundational for decision making activities. The list is not intended to be complete or exhaustive, yet it is intended to define key concepts which are often thrown out casually (i.e., rarely defined) by educators and other commentators lamenting the decline of “thinking-reasoning capacities,” “critical thinking skills,” “higher order thinking skills,” or “critical thought.” The material for this section borrows very heavily from *A Guide to Introductory Physics Teaching*, published in 1990 by the late Arnold B. Arons.

Arons spent decades studying the teaching and learning of science and math by grade school children, science and non-science majors in college; he even included university professors in his research. Much of the research of Arons and his colleagues is quite astonishing, as it uncovered many misconceptions regarding “good teaching,” found systematic causes for deficiencies in teaching, and provided the discovery that a significant number of advanced students, and even physics professors, manage to achieve an impressive academic record without mastering relatively elementary mathematical, and physical science concepts. Arons pioneered new ways to teach math and science concepts based on this extensive research.

Here then is a summary of the ten critical thinking process deemed foundational for decision making activities. Extensive discussion and examples are provided in the full SAND report to elucidate the meaning of each process summarized in Figure 2 below:

Critical thinking processes

1. Raising the **questions**: "What do we know…? How do we know…? Why do we accept or believe…? What is the evidence for…?
2. Clear and explicit awareness of **information gaps** (i.e., recognizing when one is taking something on faith).
3. Discriminating between **observation and inference**, between established fact and subsequent conjecture.
4. Recognizing that **words are symbols for ideas** and not the ideas themselves. Recognizing the necessity of using only words of prior definition, rooted in shared experience, in forming a new definition and in avoiding being misled by technical jargon.
5. **Probing for assumptions** behind a line of reasoning.
6. **Drawing inferences** from data, observations, or other evidence and recognizing when firm inferences cannot be drawn (i.e., **inference adequacy check**).
7. **Hypothetico-deductive reasoning**; apply relevant knowledge of principles and constraints, and abstract visualization of plausible outcomes from imagined changes imposed on the system.
8. Discriminating between **inductive and deductive reasoning**; that is being aware of when an argument is made from the particular to the general or from the general to the particular.
9. Test one's own line of reasoning and conclusions for **internal consistency**.
10. Develop **self-consciousness** concerning one's own thinking and reasoning processes.

Figure 2. Summary of critical thinking processes appropriate for supporting decision making in high-consequence domains.

3. The technologically advanced society and assembling the team of decision makers

The achievements of science and technology have been important, impressive, and have helped to provide unprecedented physical safety and material wealth. Yet they have done so at the cost of substantially increasing an individual's vulnerability to risks associated with interdependence (Freudenburg, 2001). This section summarizes reflections by Freudenburg (2001) regarding risk-related decision making and, in particular, how the nature of a technologically advanced society as opposed to an agrarian/simple craft-based society amplifies the need for trust between technology experts, high-level decision makers (e.g., politicians), and members of the general public. This section ties strongly to the critical thinking processes introduced in the previous section. Furthermore, this section suggests who ought to be included in high-consequence, technologically advanced decisions and when technology experts or the general citizenry deserve the strongest vote on aspects of those critical decisions.

Freudenburg begins his discussion by reflecting upon public sentiments he heard while being on a US National Academy of Sciences National Research Committee reviewing the analyses conducted for a nuclear waste storage site. Comments from the citizens included the classic, "Scientists have lied to us before, and scientists will lie to us again" (Freudenburg, 2001, p. 125). This reflected a sentiment widely held by fellow citizens in attendance that scientists habitually put their organizational interests ahead of even-handed analysis. Freudenburg quickly learned that he was not dealing with a group of extremists who irrationally opposed the nuclear waste dump. What he found were people who had initially supported the idea of a "scientific process" for analyzing proposed sites, but who had become, over the course of the site selection process, convinced that the process was neither fair nor scientific.

> Although many of us initially believed that the citizens were simply being sore losers, we ultimately learned something else: in fact, the process had included not just technical errors, but many cases in which arbitrary decisions had been characterized as scientific ones. Understandably—at least from the point of view of the proponents—whenever the arbitrariness was questioned, the critics were accused of being "anti-science." The proponents' intent of course, had been to improve the credibility of the siting process by wrapping it in a flag of science. The result, however, had been virtually the opposite; what actually took place was instead a serious drop in the credibility of science. The net unintended effect, in other words, had been the creation of a self-fulfilling prophecy—accusing a wide range of people of being anti-science, and then ultimately creating just that result (Freudenburg, 2001, p. 125).

Once the technical experts and the general citizenry descend into this polarized relationship, a phenomenon called the "spiral of stereotypes" may emerge in which people on opposing sides of an issue stop talking to one another, but not about one another. That is, rumors and a priori beliefs that are already accepted in each camp take on more credibility than dialogue intended to promote mutual understandings between the camps. The us/them thinking takes over and "rationality" is assumed to characterize the "us" members of the debate, and anyone who shows the poor judgment to disagree with "us" must therefore be exhibiting irrationality (Freudenburg, 2001).

Before proposing a solution for avoiding a polarized decision making environment, it may be helpful to explore some of the subtleties that encourage such a polarization. It is proposed that many arguments about the proper roles of experts and citizens in high-consequence, technologically complex decision making emerge due to a fundamental misunderstanding of what it means to live in a "technologically advanced" society. For instance, there have been some broad indications of declining public confidence in science and technology and the experts who defend them. How can this sentiment prevail when dramatic reductions in risk can be attributed to advancing technology? The prime example being the dramatically reduced risk of death, measured by life expectancy data (i.e., more defenses against and treatments for disease and physical injury, improved shelters with heating and cooling, better plumbing and general hygiene practices, improved quantity and quality of food, safer means of transportation, safer means to produce food and durable goods, etc.). To many, such improvements make them feel justified in denouncing many or all public concerns toward science and technology as being ignorant, ill-informed, and/or irrational. At least three key problems with this type of thinking have been identified (Freudenburg, 2001).

The first problem is the personal affront caused by telling someone they must be ignorant, ill-informed, and/or irrational. This affront may be indirectly expressed by expending considerable effort to exclude the public from a decision. Either form of insult tends not to engender receptivity of anything else that follows. The second problem is one of adaptation; scientific and technological achievements rapidly become part of people's baseline expectations. There is likely to be very little persuasive power to the argument that all should be happy to live as long as did our great-great-grandparents—especially when this implies that anyone over 40 years of age ought to be very happy about not being dead (Freudenburg, 2001).

The third problem is the most serious, most often overlooked, and has been termed the "fundamental misunderstanding" about what it means to live in a technologically advanced society. We begin with a question: Do people living today (i.e., in a technologically advanced society) actually "know more" than their great-great-grandparents did? Collectively, the answer is a resounding "yes." Individually, however, we know much less today than did our great-great-grandparents about the tools and technologies on which we depend (Freudenburg, 2001).

> In the early 1800s, roughly 80% of the US population lived on farms, and for the most part, those farm residents were capable of repairing, or even of building from scratch, virtually all of the tools and technologies upon which they depended. By contrast, today's world is so specialized that even a Nobel laureate is likely to have little more than a rudimentary understanding of the tools and technologies that surround us all, from airliners to ignition systems, and from computers to corporate structures (Freudenburg, 2001, p. 128).

Therefore, people living in a technologically advanced society tend not so much to be in control of technology as dependent upon technology. Our increases in *technical control* have led in a sense to a decrease in *social control*. Stated simply, the problem is that people now must depend on whole armies of specialists and specialized organizations, most of whom we will never meet, let alone be in a position to control.

The failure of an expert, or specialized organization to accomplish the job required has referred to by some as *recreancy* (Clark and Short, 1993; Freudenburg, 1993). Recreancy, and its close neighbor trustworthiness, have been shown by systematic research to be key factors in the increasingly acrimonious chemistry between technical experts and members of the general public. For example, an analysis of attitudes regarding a proposed low-level nuclear waste facility found that sociodemographic variables were weak predictors of attitudes whereas measures of recreancy were found to be very strong predictors of attitude (Freudenburg, 2001).

Thus we have the three problems with dismissing people who express concerns regarding decisions involving high-consequence, advanced technologies: personal affront; increasing expectations for technological advancements; and increasing dependency upon advanced technology (i.e., increasing need for trust). These three problems, combined with the folly of experts who try to pass off arbitrary decisions as scientific decisions, provide a proven recipe for creating a polarized decision-making environment. A polarized decision-making environment will severely frustrate application of the bias mitigation insights, critical thinking processes, and decision-making approach proposed in this report. So how does one avoid this very large decision-making trap? General suggestions are described below and summarized in Figure 3:

1. Do not automatically brand members of the public who raise concerns over decisions involving high-consequence, advanced technologies as ignorant, ill-informed, or irrational.
2. Apply the ten critical thinking processes in the previous section to ensure that technical experts are focused upon **factual or technical questions**. Poor command of the critical thinking processes will prevent proper identification of authentically *factual* or *technical* questions.
3. Identify when aspects of a decision (model assumptions, metrics, etc.) involve answers to questions that are value judgments. Examples of such questions include, is that safe enough? Is that level of uncertainty in the safety estimate acceptable? When it comes to questions of **values**, another word for "scientist" is "voter." Ordinary citizens have just as much legitimacy in deciding questions of values as do scientists and engineers (Freudenburg, 2001).
4. Apply the ten critical thinking processes in the previous to aid in identifying **blind spots**. That is, items that have been overlooked. Additional terms for blind spots include *epistemic uncertainties* and unknown unknowns, which were discussed earlier in this report. Ordinary citizens are also very helpful for contributing to the discussion of blind spots as their thinking tends to be bounded much differently than those of a particular community of "experts." One should keep in mind Perrow's memorable definition of an *expert* as one who can solve a question much more quickly and efficiently than most, but who runs a higher risk than do other citizens of asking the wrong questions altogether (Perrow, 1984).

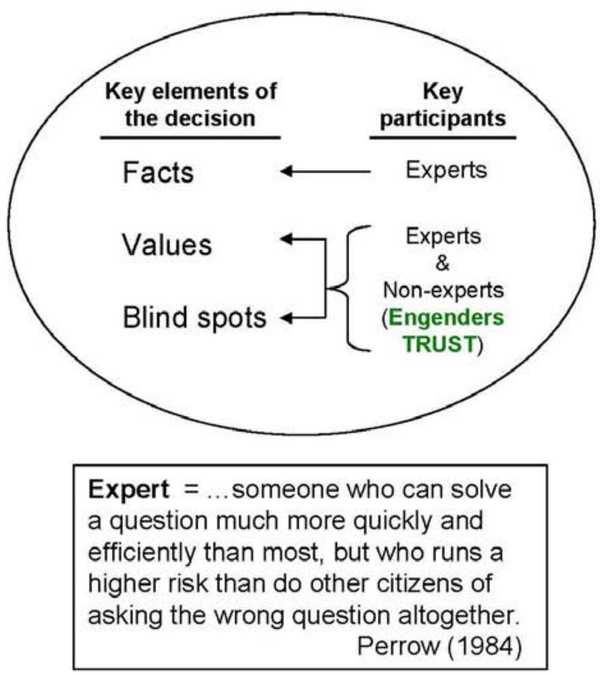

Figure 3. Building an appropriate decision-making team.

4. The proposed framework of biases and tendencies

Understanding the general types of uncertainties involving complex, high-consequence domains is helpful. But, how exactly does someone move along the path from a state of ignorance or impoverished knowledge to a state of adequate or extensive knowledge? In this case, adequate or extensive refers to the amount and quality of knowledge required to make an appropriate decision regarding high-consequence, advanced technology. To answer this important question, we begin with summarizing a unique framework.

This report proposes a unique framework for understanding key aspects of risk perception and decision making. The proposed taxonomy of biases (see Figure 4) contains the headings of **normative knowledge**, **availability**, and **individual specific** biases. **Normative knowledge** involves a person's skills in combinatorics, probability theory, and statistics. Research has shown that training and experience in these quantitative fields can improve one's ability to accurately determine event likelihoods. Those trained in statistics tend to seek appropriate data sources when assessing the frequency and severity of an event. The **availability** category of biases includes those which result from the structure of human cognitive machinery. Two examples of biases in the availability category include the anchoring bias and the retrievability bias. The anchoring bias causes a decision maker to bias subsequent values or items toward the first value or item presented to them. The retrievability bias refers to the bias that drives people to believe those values or items which are easier to retrieve from memory are more likely to occur. **Individual specific** biases include a particular person's values, personality, interests, group identity, and substantive knowledge (i.e., specific domain knowledge related to the decision to be made). **Critical thinking skills** are also offered as foundational for competent risk perception and decision making as they can mute the impact of undesirable biases, regulate the application of one's knowledge to a decision, and guide information-gathering activities. In addition to borrowing insights from the literature domains mentioned in the introduction, the formal decision making approach supported in this report incorporates methods used in multi-attribute utility theory.

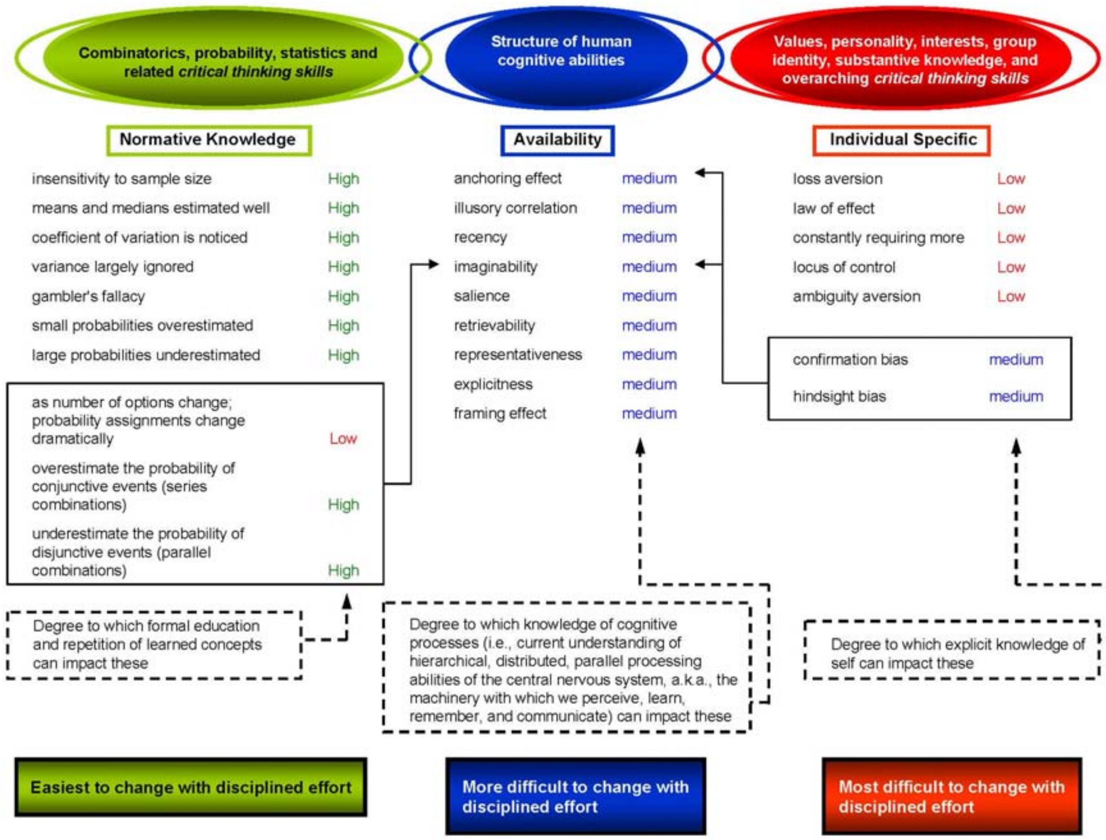

Figure 4. This figure attempts to provide assistance in exploring the types of biases/tendencies that researchers have identified, the ways in which these may be related and the ease with which one may become a better decision maker. The unique aspects introduced by the author, following a review of relevant data, include (1) the three primary categories into which previously investigated biases are ordered, (2) strong interdependencies hypothesized between biases as indicated by solid lines with arrows, (3) degrees to which these biases may be mitigated via focused efforts by a specific decision maker indicated by dashed lines with arrows; high, medium, and low ratings; and the green, blue, and red boxed items. This report is intended to present strong arguments supporting the face validity of the unique framework above and the associated decision-making improvement strategies.

A powerful example illustrating a number of biases in the framework includes the following hypothetical scenario: a respected energy expert who specialized in electricity production using fossil fuels was confronted with risk data showing the outstanding safety record and cost competitiveness of nuclear energy relative to electricity from fossil fuels (i.e., dramatically higher safety and comparable or even lower costs—without the emission of airborne pollutants or greenhouse gases). Instead of acknowledging the data and allowing himself to be open to the possibility that nuclear power might be as viable an energy source as fossil fuel, he recalled watching the TMI accident unfold on television in 1979 and expressed how dangerous the situation was and how close to disaster we had come. He could recall salient images of people racing to leave the nearby communities and the recommendation that all pregnant women be evacuated within a five-mile radius. He could also recall contradictory information being presented by “experts” regarding the severity of the event. Following this comment about TMI he was presented with data showing how there was essentially no danger to the public from that accident and also with data showing how slight the dangers would likely have been from even a severe “reactor core meltdown.” In response, the fossil fuel expert stated, “Yes, but nuclear energy was supposed to be the energy panacea–it was supposed to be too cheap even to meter—free electricity for all.”

In addition to the above-mentioned topic areas, the SAND report contains a step-by-step decision-making approach and an extensive application example based on the review of the topic areas.

CONCEPTS FOR DETERMINING AN OVERALL TECHNOLOGY SCORE AND PORTFOLIO MIX

Jason V. Zuffranieri

Among the many benefits made possible through the Energy Systems LDRD is the ability to compare technologies on the basis of their scores in each of the nine individual criteria categories. As a general rule, the methods for determining the criteria scores are varied, with some more quantitative than others, usually depending on how well-defined the data are. Still, it would be valuable to combine these scores into an overall technology score, especially when one considers the difficulty in determining which technology is preferred over another; consider the case where one technology scores better in five categories while scoring worse in four. It is vital for a user to have the ability to give additional weight to the categories which he feels are more important than others, and similarly to lessen the importance of those which he feels are less important.

However, even if one were able to cogently weight the categories to his liking, there is no telling whether the scales of numbers are even comparable. The criteria have been formulated to return scores from 0 to 10, but there is no inherent benchmarking. Even if it were true that a score of 5 were deemed to be an "average" score, the concept of "average" cannot be very clearly defined.

What follows is a possible method that allows for user-defined weights and has built-in benchmarks; a similar but simplified version of this method was utilized in the quantification of the Environmental and Natural Resource criterion. The effect of the benchmarks is to always give the user a conceptualization of what certain scores truly mean. Portfolio optimization will be examined in a later section, and a summary concludes the paper.

Before going much further, it is important to emphasize that what is described below is a remapping of the scores; this process can take any numerical value and transform it to a value from 0-10. Each technology has nine values associated with it, based on how well it performs in the nine criteria defined earlier in this report. For clarity's sake, let the criteria values before they enter this process be known as *intermediate values*, which will then be transformed into *criterion scores* by the process.

This method is similar to those illustrated in [1] and [2], although different enough to warrant a separate explanation.

Finding a Criterion Score

It has been decided that criterion scores should always range in the single digits, so as to put everything on a similar scale. Since there is value in standardizing scores across criteria, it is useful to give meaning to certain scores (0-10), so that a criterion score of 2 will mean roughly the same thing regardless of which criterion it was. To this end, the following is proposed:

Criterion scores will run from 0 to 10,[1] inclusive, and will be determined by where a technology's intermediate value falls along the following piecewise linear function.

10 – The upper-limit intermediate value determined by legislation; e.g., if the government has set a daily/yearly limit for a certain amount of pollutant. In those instances where the government has not set a bound, this will instead be a value which, if surpassed, would thereby disqualify a technology on account of its extreme nature. Such a value would be determined from expert opinion, and should be a limit generally accepted by the community at large. For many of the more qualitative criteria, this value should be whatever maximum was chosen by the criterion's creator, and will often be exactly 10. Note: the selection of 10 as the score corresponding to the "upper-limit" value is fixed, since it is indeed the largest possible score for a criterion.

6 – The highest intermediate value for any top-five electricity-producing technology *currently* employed at the regional or national level. These five categories are coal, nuclear, natural gas, hydropower, and oil, which comprise 99% of today's electricity portfolio. Note: the selection of 6 (as opposed to 5 or 7) as the score corresponding to the "high" value is variable – this choice is up to the user. Furthermore, this may not correspond directly to an intermediate value of 6.

3 – The weighted-average intermediate value for the top-five energy-producing technologies *currently* employed at the regional or national level. This will require taking the intermediate value for each of the five technologies and weighting them by their share of the overall portfolio; these weights are found in the following table. Note: the selection of 3 (as opposed to 2 or 4) as the score corresponding to the "median" value is variable – this choice is up to the user. Furthermore, this may not correspond directly to an intermediate value of 3.

Table 1. Proportion of current electricity portfolio devoted to five largest sources.

Coal	Nuclear	Natural Gas	Hydropower	Oil
53%	21%	15%	7%	3%

1 – The lowest category value for any top-five energy-producing technology *currently* employed at the regional or national level. Note: the selection of 1 (as opposed to 0.5 or 1.5) as the score corresponding to the "low" value is variable – this choice is up to the user. Furthermore, this may not correspond directly to an intermediate value of 1.

0 – A value of zero for the category. This is the ideal. For many of the more qualitative criteria, this value should be whatever minimum was chosen by the criterion's creator, and will often be exactly 0. Note: the selection of 0 as the score corresponding to the "lower-limit" value is fixed, since it is indeed the smallest possible score for a criterion.

The 0-10 normalization described above seeks to do several things. First off, it will keep all criterion scores within the single-digit range, which has already been decided. Secondly, the extremes are clearly true extremes, while the intermediate values are sensible and will keep all

[1] It is possible, due to special and possibly unlikely circumstances (e.g., grandfather clauses), that a technology may surpass the legal limiting value for a category. In these instances, the category score should be determined by using a linear extrapolation on the 6 and 10 basis values.

scores within a logical range among the single digits. Furthermore, it allows for constant updating; as the electricity portfolio changes, the percentage weights (and perhaps the five technologies themselves) will be adjusted appropriately. In this manner, the criteria scores will always have a basis in reality.

A spreadsheet illustrating the determining of criteria scores is included at the end of this paper.

Combining Into One Overall Score

Now that the criteria scores have all been put onto similar scales, combining them into one overall score can be performed. For this, the user will choose weights (totaling 100%) and assign them to each of the different categories. These will strictly be up to the user, as there is no scientific reason to restrict a weighting. The technology's overall score will be determined by summing all of the results from multiplying each criterion score with its associated, user-defined weight.

This may appear to be propagating uncertainty too much – so-called "weightings of weightings" – since value judgments may have been used to find the initial, unadjusted intermediate values. However, the reality of the situation dictates that a user simply *must* be allowed to participate in the weighting of the criteria; without this ability, all efforts would have proven to be fruitless, since they would not be adaptable to each user and his situation. Also, a distinction can be found between the two types of weightings. The user-defined weights reflect a preference on the part of the user, whereas the weightings that may have gone into finding an intermediate value were based on scientific dependencies and relationships. As an illustrative example – while it is difficult to combine deaths and illnesses into one cohesive number, it is certainly true that the former are of greater import than the latter. Such an absolute statement cannot be made regarding the importance of environmental concerns vis-à-vis cost. It is the distinction between the two types of weightings that prevents any biases from affecting the outcome of this method adversely.

A spreadsheet illustrating the combining of criteria scores into one overall score is included at the end of this paper.

Portfolio Optimization

With the relationships within a criterion being strictly defined and scientifically justified, and with the relationships between criteria being up to the user's discretion, the output of the above methods is an overall score for each technology. These scores can certainly be compared to one another, and relationships can be quickly determined. However, since the technology-related issues have been effectively reduced to a single value, and since multiple technologies are used to generate electricity, it is possible to do a numerical optimization on these overall scores to find a split of technologies that delivers the lowest weighted-average portfolio score. Furthermore, this optimization can take into account the restrictions on what percentage of national production a certain technology could deliver (both minimum and maximum values).

The optimization itself can be quite easily implemented using a software package such as Microsoft Excel; the solver function performs optimizations with east. The advantage with undertaking such a process is that service limitations can be taken into effect. For example, it may appear that a certain technology (e.g., wind) has an advantage over longtime stalwart energy technologies like coal or nuclear. However, wind cannot account for more than a small fraction of the overall portfolio. Similarly, some technologies only achieve such low costs by running at full power for long periods of time, thereby delivering only large shares of the portfolio. By using these optimization techniques, the true impact of a technology can be felt by looking at it in a national context.

Admittedly, there is significantly more to the national energy portfolio than just a simple optimization exercise. Even if some real insights were determined through its utilization, the realities of today's portfolio, plus the sheer amount of current infrastructure that would need to be replaced or renovated, make any optimizations more of a theoretical exercise. As such, these results would perhaps best be something for which to aim, or could give true guidance in developing markets where the infrastructure is waiting to be determined.

A spreadsheet illustrating portfolio optimization is included at the end of this paper.

Conclusion

There are many ways to combine several criteria scores into one overall score. The method described here does so in a consistent manner well suited for an interactive program, since it leaves important decisions in the hands of the user. Moreover, the decisions are made based on a thoroughly analytical outlook of the criteria. With this capability, as well as a quick method for optimization, the techniques described in this paper will satisfy users who wish to combine several categories from several candidates into one overall mix.

References

[1] Azapagic, A. 2004. "Developing a Framework for Sustainable Development Indicators for the Mining and Minerals Industry." *Journal of Cleaner Production*, 12: 639-662.

[2] Mavrotas, G. et al. 2003. "Combined MCDA-IP Approach for Project Selection in the Electricity Market." *Annals of Operations Research*, 120: 159-170.

Determining Criteria Scores

	Cost	Env.	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm..
				Intermediate Values				
Coal	0.035	5.5	4.2	10	0	0	0	0
Nuclear	0.029	1.8	1.4	20	20	15	10	5
Nat. Gas	0.04	2	2.3	30	5	60	50	10
Hydro	0.03	1.3	2	25	5	0	0	20
Oil	0.06	3.2	2.6	30	5	60	20	10
Wind	0.05	0.5	1.1	5	10	0	0	30
Solar-PV	0.3	0.3	0.3	0	0	0	0	45
Biomass	0.06	1.4	0.8	0	10	0	0	25

These hypothetical intermediate values are for currently employed technologies in the energy portfolio, and come from the different criteria definitions. Some are continuous, unbounded variables, while some run from 0-100 and some from 0-10.

The benchmarks are determined by taking absolute maxima (10) and minima (0) for the different criteria, finding a weighted-average (3), and taking the best (1) and worst (6) intermediate values for the top-five technologies. In the cases where the best top-five intermediate value is exactly 0, the benchmark value at 1 is exactly 0.

				Benchmark Values				
Ranking	Cost	Env.	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm..
0	0.000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	0.029	1.3	1.4	10.0	0.0	0.0	0.0	0.0
3	0.035	3.8	3.1	16.8	5.5	14.1	10.3	4.3
6	0.060	5.5	4.2	30.0	20.0	60.0	50.0	20.0
10	0.300	10.0	10.0	100.0	100.0	100.0	100.0	100.0

				Criterion Scores				
	Cost	Env.	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm..
Coal	3.01	6.00	6.00	1.00	0.00	0.00	0.00	0.00
Nuclear	1.00	1.40	1.00	3.72	6.00	3.06	2.94	3.14
Nat. Gas	3.61	1.56	2.05	6.00	2.82	6.00	6.00	4.09
Hydro	1.34	1.00	1.70	4.86	2.82	0.00	0.00	6.00
Oil	6.00	2.51	2.40	6.00	2.82	6.00	3.73	4.09
Wind	4.81	0.38	0.79	0.50	3.93	0.00	0.00	6.50
Solar	10.00	0.23	0.21	0.00	0.00	0.00	0.00	7.25
Biomass	6.00	1.08	0.57	0.00	3.93	0.00	0.00	6.25

The intermediate values have been transformed into criteria scores (all 0-10) based upon where they fall compared to the benchmark values. Note that each highest score in the top five rows of the intermediate values table shown at the top of the page corresponds to a value of 6 in the criteria scores table.

Combining Into One Overall Score

	Criterion Scores							
	Cost	**Env.**	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm..
Coal	3.01	6.00	6.00	1.00	0.00	0.00	0.00	0.00
Nuclear	1.00	1.40	1.00	3.72	6.00	3.06	2.94	3.14
Nat. Gas	3.61	1.56	2.05	6.00	2.82	6.00	6.00	4.09
Hydro	1.34	1.00	1.70	4.86	2.82	0.00	0.00	6.00
Oil	6.00	2.51	2.40	6.00	2.82	6.00	3.73	4.09
Wind	4.81	0.38	0.79	0.50	3.93	0.00	0.00	6.50
Solar	10.00	0.23	0.21	0.00	0.00	0.00	0.00	7.25
Biomass	6.00	1.08	0.57	0.00	3.93	0.00	0.00	6.25

These scores come from the previous slide, and are to be weighted on this slide, based on the weights (in the possible weightings table) determined using the motivations listed below. To determine a weighted result, each column of criteria scores was multiplied by each row of weightings, with the sum of these products being the overall score.

*

	Possible Weightings								
	Cost	**Env.**	**S**	**IV**	**P**	**D**	**U**	**TI**	**Total**
Green	5%	50%	15%	0%	0%	10%	20%	0%	100%
USLC	50%	0%	10%	10%	10%	15%	0%	5%	100%
Future	25%	25%	25%	15%	0%	0%	10%	0%	100%
User1	30%	15%	0%	25%	0%	20%	0%	10%	100%
User2	5%	30%	0%	20%	0%	15%	30%	0%	100%

Green: Concerned with the environment and emphasizing renewables; less concerned with cost
USLC (US Low Cost): Concerned more with keeping prices low in the near future
Future: Optimistic about the future, with strong belief in public's acceptance of promising technologies
User1: This researcher's opinion of what's important for the next ten years
User2: Where this researcher feels R&D money should go, thinking towards the future

=

	Overall Scores							
	Coal	Nuclear	Nat. Gas	Hydro	Oil	Wind	Solar	Biomass
Green	4.05	1.79	3.07	0.82	3.26	**0.55**	0.65	0.93
USLC	2.21	2.19	4.00	**1.91**	5.23	3.25	5.38	3.76
Future	3.90	1.70	3.30	1.74	4.00	**1.57**	2.61	1.91
User1	**2.05**	2.37	4.43	2.37	5.29	2.27	3.76	2.59
User2	2.15	2.56	4.55	1.34	4.27	**0.46**	0.57	0.62

Overall scores are seen here. Lower numbers are better, and preferred technologies for each motivation are listed in **bold**.

Portfolio Optimization

				Criterion Scores				
	Cost	**Env.**	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm..
Coal	3.01	6.00	6.00	1.00	0.00	0.00	0.00	0.00
Nuclear	1.00	1.40	1.00	3.72	6.00	3.06	2.94	3.14
Nat. Gas	3.61	1.56	2.05	6.00	2.82	6.00	6.00	4.09
Hydro	1.34	1.00	1.70	4.86	2.82	0.00	0.00	6.00
Oil	6.00	2.51	2.40	6.00	2.82	6.00	3.73	4.09
Wind	4.81	0.38	0.79	0.50	3.93	0.00	0.00	6.50
Solar	10.00	0.23	0.21	0.00	0.00	0.00	0.00	7.25
Biomass	6.00	1.08	0.57	0.00	3.93	0.00	0.00	6.25

These criteria scores come from the previous slides, based on this researcher's opinion of where R&D money should go. These numbers will be used to find an optimal portfolio based on this user's preferences and on service limitations.

		User2's Criterion Scores for the Studied Technologies							
	Cost	Env.	Safety	Inf. Vuln.	Policy	Dpndence	Unsustain.	Tech. Imm.	Totals
Coal	0.90	1.80	0.00	0.20	0.00	0.00	0.00	0.00	2.90
Nuclear	0.30	0.42	0.00	0.74	0.00	0.46	0.00	0.16	2.08
Nat. Gas	1.08	0.47	0.00	1.20	0.00	0.90	0.00	0.20	3.85
Hydro	0.40	0.30	0.00	0.97	0.00	0.00	0.00	0.30	1.97
Oil	1.80	0.75	0.00	1.20	0.00	0.90	0.00	0.20	4.86
Wind	1.44	0.12	0.00	0.10	0.00	0.00	0.00	0.33	1.98
Solar	3.00	0.07	0.00	0.00	0.00	0.00	0.00	0.36	3.43
Biomass	1.80	0.32	0.00	0.00	0.00	0.00	0.00	0.31	2.44
Weights	0.3	0.3	0	0.2	0	0.15	0	0.05	1

This table shows the individual scores in each criterion for each technology based on this researcher's opinion of which criteria are important. To get these numbers, the above raw criterion scores were multiplied by the weights listed in the Weights row. Of note is that three criteria were deemed unimportant, and contribute nothing to the next step.

	Percentages	Score
Coal	0.5	1.451991
Nuclear	0.21	0.436721
Nat. Gas	0.19	0.73235
Hydro	0.09	0.177687
Oil	0.01	0.048572
Wind	0	0
Solar	0	0
Biomass	0	0
	Overall	2.847322

	Percentages	Score
Coal	0.3	0.871195
Nuclear	0.43	0.894239
Nat. Gas	0.1	0.385447
Hydro	0.12	0.236916
Oil	0	0
Wind	0.05	0.099099
Solar	0	0
Biomass	0	0
	Overall	2.486896

The leftmost table shows the approximate current portfolio. Based upon certain service limitations regarding how high and how low a share of the portfolio a technology can handle, these percentages were adjusted. On the right is the breakdown that returns the lowest score, and therefore the most-preferred portfolio, based on this researcher's opinions of what criteria are important. This optimization was performed in Microsoft Excel using the Solver function.

ENERGY SECURITY: DEFINITIONS AND ISSUES

Orman Paananen

1. Definition and Scope

Establishing a definition and scope of issues surrounding energy and national security is not simple, because of the large number of factors that determine the connection between energy and security. For example, in the short term, an act of terrorism or a natural disaster might disrupt supplies, but in the long term, maintaining sufficient supply at affordable cost might be of great concern. Threats to the climate stability from burning fossil fuels, or the threat of nuclear weapons proliferation might cause great international tension. A recent energy fest workshop at Sandia National Laboratories [7], which included members of Sandia staff and management, explored three broad energy security topics:

- Global and US economic oil dependence (and natural gas)
- Potential security implications of global climate change
- Vulnerabilities of US domestic energy infrastructure

Workshop members found that these three broad energy security topics tended to share several challenging characteristics:

- They are worldwide in scope
- They involve public goods and market externalities
- Their solutions (or neglect) involve intergenerational transfers of costs and consequences
- They involve multiple decision makers
- Different parties contribute to them and suffer their consequences in different ways
- Policies to address them will interact significantly with other policies
- There are pervasive uncertainties in assessing them and their solutions
- Their inertia is such that they can be turned around only in decades

Workshop participants noted the importance of understanding the psychological, social, and economic dimensions of these characteristics.

A somewhat less wide-ranging scope of energy security has been suggested by Ahearne [1], which also contains three elements:

- The United States has adequate energy supplies to support a healthy economy
- Our allies also have adequate supplies
- We and our allies in concert have the capability to protect our vital energy supplies if they are threatened

This white paper focuses on the first two elements of Ahearne's definition in an initial attempt to establish potential overall quantitative measures of energy security. However, in these times of terrorism and uncertain military futures, we recognize that scenarios that include disruptions of supplies should be developed to provide a complete picture of energy security. Barnett [3] argues that oil supply disruptions may be more damaging to developing nations since they lack resources to mitigate oil shortages with other energy sources. This view suggests that energy security has a specific link to national security because major disruptions may result in instability in developing nations, which in turn may require military intervention. This issue is beyond the scope of this paper; however, it is important to note this wider national security issue with its international implications.

Given the narrower definition of energy security used in this white paper, indicators of national economic well-being become the important measures of economic security related to energy demand and supply scenarios. Gross domestic product (GDP) and employment are the most common indicators used. This relates generally to the first energy security topic explored during the energy fest workshop, while putting aside the global climate change and infrastructure topics. In fact, in the context of the framework used for this study, climate change enters into our evaluation in other "vectors."

Energy supply issues have largely centered on world oil supplies, and, more recently, world natural gas supplies. The citations discussed here deal with energy security at the national, or macroeconomic, level. Different measures of energy security may be required when considering infrastructure aspects of energy security, or energy security issues at the regional of local levels, e.g., potential vulnerability of the electric power grid in a specific community.

The following is a sample of discussions and analyses of energy security, reflecting different viewpoints on the issue.

2. Oil and Energy Supply Security

Most of the writings over the last 10 to 15 years have focused primarily on imported oil as the main element affecting US energy security. Three types of oil-related energy security challenges are considered:

- Major supply disruption – oil shortages similar to those in the 1970s
- Supply disruptions that result in price spike but not actual physical shortages
- Volatile oil prices

In the last few years natural gas supply has increasingly been viewed as facing similar challenges. Increasingly, natural gas is becoming a commodity comparable with petroleum, because the increasing use of liquid natural gas tankers makes it possible to establish a world gas market, whereas in the past delivery was tied to pipelines connecting specific sources to fixed markets. The citations summarized here, while not a complete listing of references on energy security associated with oil and natural gas import dependence, give a sense of the scope of issues.

> **U.S. Department of Commerce, Bureau of Export Administration,** *The Effect on National Security of Imports of Crude Oil and Refined Petroleum Products*

The energy security issue addressed: vulnerability to an oil supply disruption.

Vulnerabilities:

- Capability of the United States and Office for Economic Cooperation and Development (OECD) countries to offset a major supply disruption has not improved in the last decade. In fact, the production margin and the availability of refineries to deliver specific products is probably less robust today.
- Most of the world spare production capacity is in the politically unstable Persian Gulf region.
- Government oil stocks (Strategic Petroleum Reserve, SPR) provide less protection from interruption than in the 1990s because of continued growth in domestic demand.
- No viable substitute for oil in transportation will be available for at least a decade, and, if introduced, technology under development is likely to result in actual increase in demand for fossil fuels.
- We can achieve enhanced energy security by promoting increases in non-OPEC oil production. This statement was true during the oil crisis of the early 1970s, and there has since been considerable diversification of supply, but this principle can be further extended.
- Lower oil prices may benefit economic activity but not reduce vulnerability from imported oil dependence, and in fact may increase vulnerability, because reduced prices will increase the tendency to use a resource.

An example of enhancing energy security – Article 605 of NAFTA – provides reciprocal provisions for energy security between the United States and Canada:

- No cross-border restrictions on energy delivery during a supply disruption
- Shortfalls are shared equally based on historical percentages
- No disruption of the prevailing proportion of energy goods supplied
- Will not charge prices higher than prevailing domestic prices

Alan Larson, *The Role of Energy in U.S. Foreign and Security Policy*

Energy affects national security to the extent that our dependence on foreign energy sources limits flexibility in directing economic and foreign policy agendas. The United States and its allies remain vulnerable to a major oil supply disruption because of two factors:

- Where the oil is, and
- Where the domestic oil is increasingly going. The current trend in the United States and its allies is toward increasing concentration of oil demand in the transportation sector. Promoting diversification of oil supplies and use of other energy types is an important energy security and foreign policy issue. Of course, the convenience of oil for transportation makes substitutes unlikely.

Baker Institute, *The Importance of Diverse Supply*

A similar view to Larson's comes from the Baker Institute (Rice University). The stakes for developing diverse sources of oil are high since lasting price increases can have a dampening effect on economic prosperity. Further, prolonged oil price volatility poses risks to the national economy by diverting real resources toward activities that deal with risks arising from supply/price uncertainties.

Forum for International Policy, *Energy and National Security*

Domestic and international vulnerability to oil supply disruptions is real and increasing. Possible answers/responses:

- Increase energy efficiency in the transportation sector
- Maintain contingency planning – grow the SPR
- Promote a strong competitive US oil industry abroad. Promote an even business playing field in terms of tax structures, and international support for continued non-OPEC oil supply development

Woolsey et al., *Energy Security: It Takes More Than Drilling*

Oil energy security requires an oil delivery system that makes large-scale failures impossible or at least extremely unlikely, and makes local failures benign. Energy efficiency starts with using less energy far more efficiently to complete the same tasks. The next step is to obtain more energy from sources that are inherently less vulnerable because they are dispersed, diverse, and increasingly renewable. At minimum, the U.S. must not increase reliance on existing vulnerable systems. Moving away from reliance on Middle East oil and a vulnerable domestic infrastructure, such as the Trans-Alaska pipeline system (TAPS), will reduce the oil security dangers for the United States and its allies.

3. Energy Security Beyond Oil

Some recent articles have started to address energy security in a wider context that includes consideration of more energy resources than oil. These papers point out that the United States will become more dependent on natural gas imports, as well as having continued (and growing) dependence on imported oil. In addition, all of the current US nuclear fuel supplies are imported. In this view, considerations of energy security need to address issues around all of these fuel types simultaneously. In addition, some authors include environmental aspects of energy use as part of energy security.

Zweifel and Bonomo, *Energy Security: Coping With Multiple Supply Risks*

The United States and other developed nations are exposed to multiple risks for energy supplies – oil, natural gas, and nuclear fuel. Energy security policy is more effective if supply risks to all energy sources are considered simultaneously. For example, the risks of an oil supply disruption may be positively correlated with natural gas supply disruption, particularly if both energy supplies come from the same geographic region.

A more complete energy security focus:

- Fuel-specific rules (e.g., 90 days of oil reserves) neglect the fact that modern economies rely on a multitude of energy sources to operate effectively.
- Decision rules that focus on a single risky energy supply type tend to yield suboptimal results, and may induce improper policy adjustments.
- As a result, energy security policy should focus on an approach capable of dealing with multiple energy supply risks and their specific risks, including different energy types.

The overall energy security goal is to minimize the expected costs of maintaining multiple energy supplies, which means minimizing the expected losses (e.g., decreased GDP) resulting from disruptions from more than one energy source. This requires understanding the impacts of disruptions of different risky energy supplies and the trade-offs in use between the energy types, including time lags to achieve trade-offs. If energy security policies do not evaluate all potential energy source disruptions simultaneously, minimizing the expected cost of energy security will in general not be achieved.

Stern, *A Multivariate Cointegration Analysis of the Role of Energy in the U.S. Macroeconomy*

Stern also shows that different energy sources are cointegrated into the structure of the United States macroeconomy. Energy security policies directed toward one energy source exclusively are likely to invoke changes in the use, and potentially the security conditions, of other energy sources. This is particularly true where energy users have the ability to use different energy sources to satisfy their energy needs (e.g., cogeneration capability). Optimized energy security policy needs to consider the risks and associated costs for all energy sources. Diversification of energy types and diversification of supply sources for any type of energy both play a role in optimizing energy policy.

Lidsky and Miller, *Nuclear Power and Energy Security*

These authors, in addition to energy security issues around oil and natural gas supplies, add potential disruptions to uranium supplies as an energy security issue. As such, their focus on energy security is both near term and medium term, rather than the near-term rapid responses to oil or natural gas supply disruptions. They suggest that establishment of a strategic uranium stockpile, similar to the SPR, for oil would enhance energy security in two ways. First, in the near term, such a strategic stockpile of natural or low-level enriched uranium would ensure a domestic supply of uranium for electric power production, since currently there is no mining and production of uranium in the United States. Second, in the medium term, guaranteeing a continued source of uranium would encourage development of new nuclear power facilities and support movement away from the current “monocultural” dependence on the light water reactor (LWR) fleet now deployed in the United States. In turn, this would decrease the risk of the loss of all nuclear power if a major fault or disruption occurs for the current LWR technology.

Thomas Neff, *Diversification and Risk Reduction for Fossil and Nuclear Fuels*

Neff argues that the best measure of energy security is couched in terms of energy dependency, based on a combination of physical and economic conditions. The focus must be on a combination of factors and policy responses. For example, an industrial policy that encourages knowledge-based industries over energy-intensive industries is also a form of energy policy, and may have as much consequence on energy security as an energy supply policy. Of course, this change in policy might make sense for economic security, but might not serve the interests of military defense, at least in protracted conflict that could demand a strong and diverse domestic production capability. As part of the energy supply measures, Neff focuses on diversification of energy supplies and energy technologies, using portfolio theory to obtain risk diversification, and quantifies energy supply diversification through use of the Herfindahl Index:

$$H = \sum_i x_i^2$$

Where x_i is the fraction of one type of energy supply from source *i.* A lower value of the index means greater diversity, and greater opportunities to avoid a major disruption in the energy type. Thus energy security would be enhanced by policies that lead to diversification and result in lower Herfindahl index values.

Hossein Razavi, *Economic Security and Environmental Aspects of Energy Supply*

Razavi presents a methodology for analyzing a national energy strategy in relation to energy security and environmental impacts of energy supply and consumption. He concentrates on two policy decisions: (1) the appropriate mix of fossil fuels, and (2) the desirable level of petroleum inventories. Four exogenous factors or attributes are considered:

- Growth in energy demand
- International price of crude oil
- Possibilities of oil supply disruption
- Availability of natural gas supplies

Razavi defines energy security as security of energy availability and the economic cost of energy supplies. Given the multiple attributes, use of optimization methods is difficult, and, where objectives conflict, may not be solvable. The author's approach is to use trade-off analysis.

Figure 1 summarizes the trade-off approach.

Box 1: Introduction to Trade-Off Analysis

Trade-off analysis is used to investigate the impacts of policy and exogenous factors on multiple, and often conflictive objectives. The multi-objectives approach is necessary when we need to ensure that we do not equate apples and oranges of various objectives. Instead each attribute is measured by an appropriate yardstick -- dollars, tons of SO_2, etc.

Trade-off analysis is an organized way of considering all possible plans and eliminating those which are inferior in to others. Trade-off analysis involves the following steps:

1) identify the objective attributes, e.g., cost of energy in dollars, SO_2 emissions in tons, etc.

2) identify policy decisions, e.g., mix of fuels, strategic petroleum reserves, and exogenous factors, e.g., energy demand, international price of oil, etc.

3) determine plausible values for each policy and exogenous variable. For example, one may choose ten fuel mix options, five various growth rates for energy demand, three oil price scenarios, etc.

4) form a database of all possible combinations of policy and exogenous variables. Each combination is referred to as a "plan". The number of these plans increases exponentially as we add to the number of variables or the optional magnitudes for each variable.

5) measure the impact of each plan on all attributes. For example, we may measure the economic cost, and SO_2 emissions of each plan.

6) considering the corresponding attributes, eliminate many plans which are inferior to other plans. Prepare a short list of plans for presentation to policy makers.

As a simple example of trade-off analysis, we consider a case where there are only two objective attributes, e.g., cost of energy and SO_2 emissions, one policy variable, e.g., the mix of fossil fuels, and two exogenous factors, e.g., energy demand and international price of oil. We further simplify the example by assuming three plausible magnitudes for each policy and exogenous variable.

The combination of magnitudes of policy and exogenous factors results in --- plans. The cost and SO_2 emission of each plan is calculated and depicted on the following figure. Some plans are considered inferior and eliminated because they are worse than the others in both areas of concern (cost and SO_2 emission). What is left is a relatively small number of plans on the trade off curve of which the ones in the knee set are of particular interest.

Alternative Assumptions about Policy and Exogenous Variables

	Mix of Fossil Fuels (%) coal/oil/gas	Energy Demand Growth (%)	Price of oil in 2010 ($/bl)
1	30/60/10	1.5% p.a.	20 $/bl
2	35/55/10	3.0 % p.a.	25 $/bl
3	40/50/10	4.0% p.a.	30 $/bl

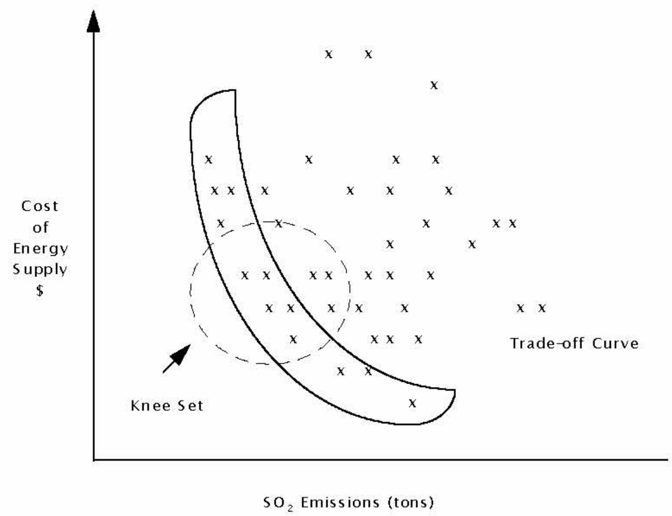

Figure 1. Energy Supply Trade-off Analysis Framework

Institute for National Strategic Studies, *Energy and National Security*

This report summarizes different measures and opinions about energy security:

- House Energy Subcommittee: the enduring security question is the concentration of oil reserves, production, and surge capacity in the Middle East. Energy security will be improved through diversification.

- Amoco: energy security is best maintained by ensuring the United States is fully supportive of free trade and market forces worldwide. Opposes a buffer stock (SPR) in the event of a supply disruption, which is likely to be felt as a price spike, which would force the economy to adjust to the disruption.[1]

- Resources for the Future: energy security is an empty concept – the 1981 decision to end price controls led to spot and futures markets which disrupt the ability of any country to control oil prices. Implicit in this is that there is a continuation of a free market, and the influence of a war or natural disaster seems not to be considered.

- US DOE: dependence on energy imports can reduce foreign policy options. In general, there is a need for a military component to energy security – specifically, the growing dependence of China as a large-scale oil importer may lead to future confrontations between the United States and China over oil supplies. There is a need for a clearer policy view on the role of the SPR. Increased use of nuclear fuel affects both energy security and larger national security issues because of proliferation concerns.

4. Key Issues and Questions

Some generally common themes emerge from this sample of the literature on the challenges to energy security:

- Major oil and/or natural gas disruptions – anywhere in the world, and for any reason – have the potential to cause damage worldwide as well as domestically.

- Oil and/or natural gas price volatility also has the potential to cause economic damage by diverting resources toward activities and institutions that can manage price risks.

- Disruption in uranium supplies, while not a short-term challenge to energy security, is still an important element.

- US dependence on foreign energy sources limits flexibility in directing economic and foreign policy options to address energy security issues.

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[1] It should be noted that this position by petroleum producers may be directed by their well-being rather than the well-being of the nation as a whole.

- Lack of diversity of energy types and sources, and increasing dependence on an energy source in sectors of the economy, tend to make it more difficult to achieve energy supply security. Diversification of sources for each energy type, as well as diversification across energy types, will contribute to energy security.

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ASPECTS OF WASTE PRODUCTS AND PUBLIC ACCEPTANCE

Jason Zuffraneiri

There are certain facets of electricity production that are important enough to mention but perhaps not widespread enough to be included as a separate metric. This section delves into two of them.

An issue unique to electricity production by nuclear means is the potential risk associated with the by-products of the energy-generating reactions. These reactions produce radioisotope waste that could theoretically be used to create a weapon of mass destruction. Furthermore, due to the radioactive decay that is produced, there are issues with nuclear waste even if it all were to be securely stored. No other source of electricity has by-products that provide such a significant cause for concern; the emissions and thermal waste from non-nuclear technologies are much more benign, and the public has come to understand and accept such waste. This section serves as an examination of radioactive waste, which deserves mention despite not fitting neatly into one of the aforementioned metrics.

Fuel rods are not rechargeable and do not last forever. Every 12 to 18 months, plants shut down and the fuel rods are replaced, with the spent rods put into a spent fuel pool before being bolted shut inside of steel containers. The Government Accountability Office (GAO) estimates that 2,000 metric tons of fuel are consumed and then subsequently warehoused each year.

However, recently federal regulators have been charged by the GAO with being lax with security measures, resulting in the loss of spent radioactive rods. Plants in California, Vermont, and Connecticut have temporarily lost track of spent rods. In each case, there has been no evidence to show that the material left the plant location, but the initial confusion is troubling enough.

The Nuclear Regulatory Commission (NRC) sees things differently, and notes that none of the missing fuel has ever fallen into the wrong hands. Furthermore, the NRC feels that since security has generally increased since the September 11th attacks, spent nuclear reactor fuel is at even less of a risk of theft than before, especially since sophisticated on-site protection measures are now in place. [1]

Part of the problem with maintaining a secure on-site storage of spent fuel is that the proposed national spent fuel repository has not been opened yet. Yucca Mountain, a permanent underground storage facility in Nevada that has been in the works since being commissioned in 1982, has seen its construction delayed while various political factions express vehement disagreements. The site, now scheduled to open in 2010, is anticipated to hold 70,000 tons of nuclear waste, which would lessen (but not eliminate) the burden of on-site storage at each of the active reactors.

A possible solution to the issue of spent fuel is twofold, and requires the same kind of ingenuity that went into the push for recycling aluminum, paper, and other household goods. Researchers with the Fuel Cycle Initiative have determined that separating out the highly radioactive materials from spent fuel, while adding an initial cost, could have extremely beneficial effects. Additional nuclear fuel could be made from some of these products, and the amount of high-level waste that would require storage in a repository would be only a tiny fraction of the original total. With such a practice in place, the need for further Yucca Mountain-like facilities would be reduced, and today's finite uranium reserves would be extended greatly. Without such a strategy, on the other hand, the need for further repositories may become too great for nuclear technologies to take a larger role of the nation's energy portfolio, especially considering all the difficulties that have been encountered with Yucca Mountain, a site which is believed to be as remote and secure as there is to be found in this country.

While the radioactive material from nuclear power plants is generally contained, the same cannot be said for another somewhat unlikely radioactive source of concern: coal. Scientists estimate that a coal-fired power plant gives off more radiation than a nuclear-fired power plant. On average, coal has 1.3 ppm of uranium and 3.2 ppm of thorium, both of which are radioactive. Radon-222, a radioactive gas, goes straight up the chimney when coal is burned. Adding everything up, one sees that coal plants dump much more radioactivity (up to 100 times) into the biosphere than a nuclear-fired power plant.

In all, a total of 73 different elements have been identified in coal. A single 1000-megawatt plant annually emits 5.2 tons of uranium, 12.8 tons of radioactive thorium, and 0.22 tons of radioactive potassium-40. This includes enough uranium-235 to make a World War II-style bomb each year; ironically, the radioactive metals in coal contain 50% more energy than the carbon. These isotopes are contained in fly ash, the airborne ash that escapes from coal power plants utilizing older technologies; today's clean coal plants, such as the US FutureGen plant, do not have such pollutant issues.

Despite the radioactivity inherent in much of the coal waste, there are some who feel that the cost to society is negligible. Studies have shown that the maximum radiation dose to an individual living within 1 km of a modern power plant is equivalent to, at worst, a 5 percent increase above the radiation level from the natural environment; this number is even lower for the average citizen. Changes to drinking water purity on account of fly ash are similarly benign. While it is true that coal technologies may be larger emitters of radiation than nuclear ones, it seems these additional emissions are not hazardous to human health at their current levels.

The results presented here offer both worries as well as possible hope for the future of electricity production in the United States. By taking a more strict approach towards radioactive waste, both with regards to nuclear and coal technologies, the country could improve its efficiency, lessen its need for repositories, and extend its fuel supply. Those possibilities make for a winning blueprint, regardless of how much concern there should be for the waste products mentioned above.

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