Assessing Reliability in Energy Supply Systems

Ryan W. McCarthy*

Joan M. Ogden

Daniel Sperling

Institute of Transportation Studies

University of California, Davis

One Shields Avenue

Davis, CA 95616-8762

* Corresponding Author

Tel.: +1-530-754-4408

Fax: +1-530-752-6572

Email: rwmccarthy@ucdavis.edu

Abstract

Reliability has always been a concern in the energy sector, but concerns are escalating as energy demand increases and the political stability of many energy supply regions becomes more questionable. But how does one define and measure reliability? We introduce a method to assess reliability in energy supply systems in terms of adequacy and security. It derives from reliability assessment frameworks developed for the electricity sector, which are extended to include qualitative considerations and to be applicable to new energy systems by incorporating decision-making processes based on

expert opinion and multi-attribute utility theory. The method presented here is flexible and can be applied to any energy system. To illustrate its use, we apply the method to two hydrogen pathways: 1) centralized steam reforming of imported liquefied natural gas with pipeline distribution of hydrogen, and 2) on-site electrolysis of water using renewable electricity produced independently from the electricity grid.

Keywords: reliability, multi-attribute utility, hydrogen

1. Introduction

Several factors are heightening concern about energy reliability. Conventional oil supplies are widely believed to be approaching peak production (Zucchetto, 2006), and political tensions and high profile terrorist activity are increasing in energy-rich regions. While these factors constrain supplies and reduce excess capacity, economic globalization and the shift toward just-in-time logistics continue to make disruptions more costly (NPC, 2001).

Recent events illustrate vulnerabilities inherent in energy supply, and the costly impacts of disruptions. Massive blackouts, such as those that cut power to 50 million customers in the northeastern United States and Canada in August 2003 and most of the 57 million residents in Italy a month later (Lane, 2003) are prominent examples of potential fragility in the electricity sector. But massive outages such as those are not necessarily the most problematic. Each year, electricity outages in the U.S. cost an estimated $80 billion, most of which comes from small disturbances (LaCommare and Eto, 2004).

The spike in gasoline prices in the aftermath of Hurricanes Katrina and Rita illustrate the sensitivity of oil systems to disruption. With oil prices already approaching record highs, average gasoline prices in the U.S. leaped a record $0.46 per gallon (15%) over the course of a single week (EIA, 2005). Oil markets are expected to become even tighter in the future due to shrinking excess production capacity in Saudi Arabia and other supply regions and increasing demand worldwide (Kreil, 2004; McCarthy, 2004; Williams and Alhajji, 2003).

The global movement of oil creates the potential for additional threats from piracy, terrorism, and warfare in politically unstable regions and along trade routes.

With liquefied natural gas (LNG) trading expected to increase in coming decades, natural gas supply will increasingly face similar risks. And the potential formation of a natural gas cartel similar to the Organization of Petroleum Exporting Countries (OPEC) further increases supply uncertainty (EIA, 2001).

These concerns emphasize a need to develop a better understanding of reliability in the energy sector. Clearly, the reliability of an energy system depends upon numerous attributes, some of which can be measured quantitatively and others that must be assessed qualitatively. In order to accurately represent the overall reliability of an energy system, we must balance the diverse attributes and the considerations that affect them.

Several studies include qualitative considerations and assess reliability in terms of adequacy or security, but none combine diverse reliability concerns in an inclusive framework (e.g., Adams, 2003; Clark and Page, 1981; Farrell et al., 2004; Lovins and Lovins, 1982; U.S. DOE, 2001).

In this paper, we introduce a method that addresses reliability comprehensively. We base our methodology on the reliability assessment framework used in the electricity sector, which considers reliability quantitatively in terms of both adequacy and security, and we adapt it to include qualitative considerations using a decision-making process founded on expert opinion and multi-attribute utility theory. Being qualitative in nature, our method offers relative comparisons among alternate energy supply systems; it does not predict the performance of a single system in absolute terms.

To demonstrate its capabilities and limitations, we use the method to compare future hydrogen supply systems for transportation energy. We investigate two disparate pathways, one designed around renewable sources in a distributed system, and the other with imported fossil energy in a centralized system. The results from this case study are illustrative of the method and should not be taken as definitive, as they derive from an unrepresentative expert panel selected for convenience (hydrogen researchers at the Institute of Transportation Studies at the University of California, Davis).

While a transportation fuel application is presented in this paper, the proposed method can be applied to any energy system.

2. Framework for analysis

We developed the method by adapting the framework used in the electricity sector for assessing reliability to account for qualitative attributes using a multi-attribute decision making process. We provide background on the individual techniques here and describe their integration in Section 3.

2.1. Making decisions based on multiple attributes

Various methods have been proposed to sort the complex relationships between attributes to help guide decision making. They have been applied to a broad array of complex, multi-attribute problems, including siting nuclear facilities and handling nuclear waste (Dyer et al., 1997; Keeney and Raiffa, 1976), selecting energy feedstocks for electricity generation (Ahmed and Husseiny, 1978), judging the viability of investments (Alidi, 1996), and evaluating potential employees (Saaty, 1990). These methods each formulate a problem by organizing relevant attributes in a hierarchy that reflects the relationships among them and their relative magnitudes. They diverge in the techniques used to evaluate and aggregate the attributes. Some are based upon economic utility models, while others rely on pairwise comparisons of attributes using fuzzy integrals or matrix algebra (e.g., Hon et al., 1996; Keeney and Raiffa, 1976; Saaty, 1990).

Attributes are organized in a hierarchy so that logic flows from specific to general: subordinate attributes describe the broader ideas above. This organization dissects general concepts into tangible metrics that can be more easily evaluated.

Figure 1 outlines the form of the hierarchy we use to assess reliability. At the top are the *general objectives* that pertain to the broad indices used to compare systems. The level below consists of wide-ranging *concepts* that the general objectives encompass. These, in turn, are described by a set of specific *metrics*.
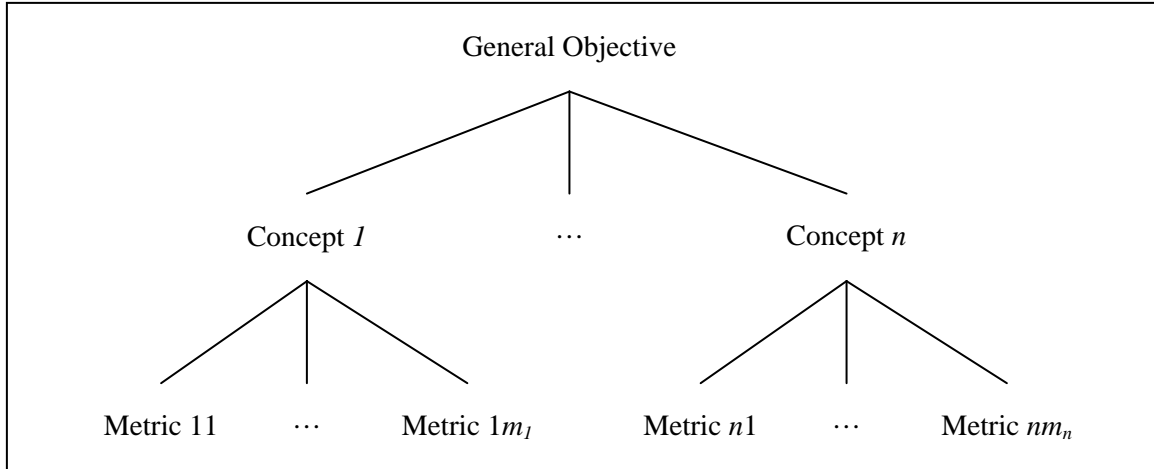
Figure 1. Outline of hierarchy used in this assessment. Logic flows from bottom up (from specific to general): from *metrics* to *concepts* to *general objectives*.

2.2. *Multi-attribute utility theory*

We use a multi-attribute utility theory (MAUT) model to calculate composite scores for the *general objectives* based upon evaluation of the lower-level attributes by an expert panel. We incorporate MAUT into the methodology because it provides an efficient method to capture the perceptions of an expert panel regarding the reliability and relative importance of a large number of attributes. Methods that use pairwise comparisons to evaluate each attribute, such as the Analytic Hierarchy Process (Saaty, 1990), would be impractical for our application because of the large number of attributes involved.

Multi-attribute utility models can take an additive or multiplicative form depending on the degree of independence among attributes.[1] In the preliminary application we present in this paper, we assume the attributes to be independent and

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[1] Refer to Keeney and Raiffa (1976) for details on independence conditions and the multiplicative form of MAUT.

apply the additive form of the model, which defines the overall utility of an alternative, U, as a function of attribute-specific utilities and weights:

$$U = \sum_{i=1}^{n} w_i u_i \qquad (1)$$

where w_i is the importance weight for attribute i and u_i is the utility of attribute i, scaled from 0 to 1. The importance weights reflect the degree to which attributes lower in the hierarchy contribute to the attribute above them, relative to each other. For a set of n lower-level importance weights, $\sum_{i=1}^{n} w_i = 1$.

2.3. Reliability assessment techniques from the electricity sector

In the electricity sector, a formal framework described by Billinton and Allan (e.g., 1984, 1996) is often used to assess reliability. We implement their overarching structure in our methodology. Their framework is broad enough to apply to any energy system if appropriate sector-specific considerations are used in selecting indices for evaluating reliability.

Reliability in the electricity sector is defined in terms of two components: adequacy and security. Adequacy refers to the ability of the system to supply customer requirements under normal operating conditions. It considers the system statically. Security includes the dynamic response of the system to unexpected interruptions, and relates its ability to endure them. Together, adequacy and security describe the overall

7

reliability of the system, which can be broadly described as the ability to supply the quantity and quality of energy desired by the customer when it is needed.

Due to the complexity of electricity systems, they are divided into three *functional zones*: generation, transmission, and distribution. The division allows appropriate measures to be developed for the different components of a supply system.

The zones can then be combined into *hierarchical levels* to convey performance for a greater portion of the system. Hierarchical level I (HLI) considers only generating facilities. Hierarchical level II adds transmission facilities, and HLIII includes all three functional zones. By combining the functional zones into hierarchical levels, a representation of the performance of the entire system emerges.

Reliability is evaluated at different hierarchical levels in terms of various indices. For example, adequacy indices at HLI include the expected loss of load (in hours or days) or energy (in MWh) per year, and can be extended to include their frequency and duration. A number of indices exist at HLII and HLIII, which relate to the probability of curtailments or interruptions (Billinton and Li, 1994). Security indices relate the probability that the system will be in a state the deviates from normal at a given time. In electricity systems, reserve margins, frequencies, and voltages that lie outside prescribed ranges might suggest a security breach (Alvarado and Oren, 2002).

Defining reliability in terms of adequacy and security and dividing an energy system into its functional zones is a helpful framework for evaluating the inherently complex problem. Other sectors have different reliability concerns, and appropriate indices must be developed for them. For example, while frequencies or voltages might be used to measure security in the electricity sector, a primary emphasis in natural gas

systems is protecting pipelines against third party damage (accidental or not) (U.S. DOE, 2002). Therefore, measures of pipeline capacity and pressure might be appropriate security indices for the natural gas sector. In the petroleum sector, where securing international oil supply is fundamental, indices that relate to disruptions on the global market are relevant.

3. Reliability assessment methodology

Reliability assessments in the electricity sector are probabilistic – they attempt to quantify the likelihood, frequency, duration, and severity of system inadequacy or security breaches (Billinton and Li, 1994). As such, they depend on historical data and focus on quantifiable measures. By incorporating expert opinion and MAUT into the framework used in the electricity sector, we extend it to include qualitative considerations and to apply to other energy sectors and to new energy systems that lack historical performance data.

The structure of our method is similar to that for the electricity sector. We define reliability in terms adequacy and security, and decompose an energy system into three functional zones: *primary energy supply*, *energy processing and conversion*, and *transport*.

Primary energy supply includes the systems and processes used to supply a primary energy resource to its point of conversion into the final energy product of interest, for example electricity or hydrogen. This includes the primary feedstock itself, its extraction and transport processes, and any intermediate conversion or processing required before conversion into the final energy product. For example, if assessing

electricity generation from natural gas, the *primary energy supply* functional zone would include considerations for all the functional zones of natural gas supply, such as reserves and extraction, processing, and pipeline delivery.

Energy processing and conversion relates to production of the final energy product. Examples include electricity generation, hydrogen production, or petroleum refining for gasoline pathways. The types of technologies used and the size and geographical reach of the processes are important considerations for this functional zone.

Transportation encompasses the transmission and distribution of the final energy product to its point of end use. Similar considerations apply to this zone as for *energy processing and conversion*.

We incorporate MAUT to evaluate adequacy and security for each of the functional zones, based on a hierarchy of important attributes. Adequacy and security constitute the *general objectives*, and the decision makers develop a set of *concepts* and *metrics* that encapsulates them for the energy systems under consideration.

The attributes are evaluated by a panel of experts, who rate their perception of utility (u_i) in terms of the *metrics*. The utility ratings are specific to an energy system and reflect the degree to which an expert feels that system is reliable in terms of a particular *metric*. Thus, an expert rates her perceived utility of each *metric* for each functional zone of each energy system under consideration.

The scope of the importance ratings (w_i) differs from that of the utility ratings. While the utility ratings are pathway-specific and only apply to the *metrics*, the importance ratings are pathway-independent and apply to both the *concepts* and the *metrics*. Although they are pathway-independent, they can vary between functional

zones. That is, the importance ratings for a given *concept* or *metric* can be different for the *energy conversion* and *transport* functional zones within a particular pathway, but when comparing pathways, the ratings for a specific attribute and functional zone remain the same.

The importance ratings express the degree to which the experts perceive attributes that are lower on the hierarchy to influence those above them in a given functional zone, and are used to weight the utility ratings according to the additive MAUT formulation. They allow attributes to be included in the hierarchy that may not apply to each functional zone, or that may have much less influence on reliability for one zone compared to another. For example, an attribute dealing with energy imports seemingly applies to *primary energy supply*, but not to the other two functional zones.

We use a variation of the well known five-point Likert scale to rate utility and importance. Likert assigned a value to each position in a qualitative rating scale to capture attitudes in a way that simplified statistical analyses (Likert, 1932). We assign values from *1* to *5* to qualitative positions regarding the reliability and importance of the attributes (Table 1). A rating of *1* corresponds to high reliability and low importance, and *5* represents poor reliability and high importance. Thus, when the utility scores are weighted and aggregated, high scores correspond to poor reliability and low scores correspond to good reliability.

Two additional ratings, *0* and *N/A,* are included to capture attitudes regarding seemingly non-applicable metrics. By not applying to a particular pathway component, an expert might perceive a metric to actually strengthen the reliability of the pathway, and would rate it *0.* If an expert felt that the metric had no bearing on the reliability of a

particular component, he would rate it *N/A*, and it would not be included in the assessment.

Table 1. Rating scale used to rate reliability and importance in terms of the attributes.

	N/A	0	1	2	3	4	5
Importance ratings	Unknown, or does not apply	None	Low	Moderately-low	Moderate	Moderately-high	High
Reliability ratings	Unknown, or does not apply	Perfect	High	Moderately-high	Moderate	Moderately-low	Low

A qualitative rating scale should be grounded by criteria from which the experts can base their evaluations. An example of the criteria we used in our application is described in Table 2 for the metric *intermittency* (McCarthy, 2004). The experts were left to interpolate the criteria for ratings of *2* and *4*.

Table 2. Criteria for reliability ratings of *0, 1, 3,* and *5* used to assess the metric *intermittency* in the preliminary application of the methodology described in Section 4.

0	1	3	5
Indicates that under no circumstances will the component operate intermittently	Indicates that, given sufficient inputs, the component will operate with low levels of predictable intermittency	Indicates that, given sufficient inputs, the component will operate with relatively high levels of predictable intermittency	Indicates that, given sufficient inputs, the component will operate with high levels of unpredictable intermittency

Qualitative rating scales and criteria invariably leave some interpretation to the experts, allowing them to apply their own perceptions of reliability and understanding of the systems. Although quantifiable criteria are often desirable, such flexibility is a meaningful and interesting aspect provided by expert opinion and can reveal qualitative wisdom that other assessments might overlook.

Using MAUT, we combine the utility and importance ratings to develop reliability indices in terms of the *concepts* and *general objectives* for each functional zone. These can then be combined to develop indices for an entire energy system, just as functional zones are combined into hierarchical levels in the electricity sector.

Before combining the ratings, they are normalized according to the additive MAUT formulation. Based on the scale we used, the reliability ratings are divided by five to transform them to a decimal scale from *0* to *1*. An importance rating is divided by the sum of the importance ratings for the set of subordinate attributes to which it belongs. This transforms the importance ratings into weights that relate the proportion of a higher-level attribute described by each of its subordinates, and maintains the requisite that $\sum_{i=1}^{n} w_i = 1$ for a set of *n* attributes.

The additive MAUT model yields aggregated utility scores (*U*) on a scale from *0* to *1*. The highest score, *1*, corresponds to poor reliability, and low scores represent good reliability.

An expert's ratings are aggregated three times using MAUT to develop various reliability indices. First, for a given functional zone, the utility ratings of the metrics are combined with the metric importance weights to develop utility scores at the *concept* level. These are aggregated with the concept importance weights to develop utility scores for the general objectives of *adequacy* and *security* for each functional zone. The utility scores for a general objective are then aggregated across the functional zones to develop an overall utility score for the entire energy pathway.

For example, consider the utility index calculations for *adequacy*. The utility of a concept, *i*, is determined from a set of *n* metrics for a particular functional zone, *j*, as follows:

$$U_{i,j} = w_{metric\_1,j}u_{metric\_1,j} + w_{metric\_2,j}u_{metric\_2,j} + ... + w_{metric\_n,j}u_{metric\_n,j}. \qquad (2)$$

The utility of the general objective (in this case *adequacy*) can be determined for functional zone *j* based on the utilities of its *m* subordinate concepts:

$$U_{adequacy,j} = w_{concept\_1,j}U_{concept\_1,j} + w_{concept\_2,j}U_{concept\_2,j} + ... + w_{concept\_m,j}U_{concept\_m,j}. \quad (3)$$

Finally, the utility of the general objective is determined for the overall pathway by combining the general objective utilities of each functional zone and the average functional zone importance weightings:

$$U_{adequacy} = \sum_{j=1}^{3} W_{adequacy,j}U_{adequacy,j}, \qquad (4)$$

where $W_{adequacy,j}$ is the weight of the functional zone, equal to the average of the concept importance ratings for functional zone *j* divided by the sum of the average concept importance ratings for all three functional zones. That is,

$$W_{adequacy,j} = \frac{ave\left(w_{concept\_1,j}, w_{concept\_2,j}, ..., w_{concept\_m,j}\right)}{\sum\limits_{j=1}^{3} ave\left(w_{concept\_1,j}, w_{concept\_2,j}, ..., w_{concept\_m,j}\right)} . \tag{5}$$

4. Sample application: Assessing the reliability of hydrogen energy systems

To illustrate the use of our method and discuss its capabilities and limitations, we apply it to compare two hydrogen pathways supplying a hypothetical network of refueling stations in the Sacramento (CA) area. Transportation fuels offer an interesting case study as petroleum can be replaced with a number of alternatives – including biofuels, hydrogen, plug-in hybrids and other electric vehicles, and synthetic petroleum fuels – each with unique reliability considerations. Of these alternatives, the transition to hydrogen is arguably the most complex. Hydrogen can be derived from several primary energy feedstocks and can be produced, stored, transported, and used in a number of ways.   The result is very different system configurations (i.e., pathways) with very different economic, energy consumption, environmental, and reliability attributes.

In the first pathway (Pathway #1), hydrogen is transported to the refueling stations via pipeline from a centralized steam reformation production facility using imported LNG. The LNG supplies come primarily from Trinidad and Tobago, but also from Alaska and other countries in the Pacific and Middle East. The second pathway (Pathway #2) produces hydrogen at its points of end use via electrolysis of water, so no hydrogen transport is needed. The electricity derives from locally-available renewable resources, and is distributed independently from the electric grid.

Twelve volunteer graduate and faculty researchers working in the Hydrogen Pathways Program at the Institute of Transportation Studies at the University of

15

California, Davis comprised the expert panel. We conducted the assessment as part of a three hour facilitated exercise, in which the panel was walked through the purpose and scope of the method, and the evaluation process. Details of this exercise can be found in McCarthy (2004).

The composition of our panel inevitably limits the impact of the assessment, but it suffices to demonstrate the methodology. If we were aiming to affect policy decisions through our assessment, the expert panel would represent expertise from all relevant stakeholders, including the energy industry (the natural gas, electricity, and petroleum sectors), academia, government, non-governmental organizations, and the public.

This application was designed to demonstrate and further develop the method, and provide a transparent framework for investigating energy sector reliability. The intention is not to identify a winner between the two pathways, which in any case is not possible due to our limited expert sample.

4.1. Hierarchy of attributes

We developed a set of attributes that embodied reliability in the two hydrogen pathways. The selection and ordering of the attributes was based on our knowledge of hydrogen systems and a review of literature pertaining to reliability in the electricity, natural gas, and petroleum sectors. An inclusive review of relevant energy sectors is especially important for analyzing hydrogen systems, which may resemble the electricity sector in some regards, and natural gas and petroleum systems in others.

We do not purport to have perfectly characterized reliability for hydrogen systems or to have identified all relevant attributes. We simply selected and organized a set of

attributes based on our knowledge of hydrogen and other energy systems that we felt efficiently described our perception of reliability in the time allotted and allowed for aggregation into broad indices using additive MAUT.

The hierarchy we used in this assessment is shown in Figure 2, which shows the attributes and their relation to one another. We identified five *concepts* to describe the ideas captured in the *general objectives* and selected 20 *metrics* to value them. *Adequacy* is described by two concepts – *capacity* and *flexibility* – which we evaluate in terms of two and three metrics, respectively. Three concepts describe *security* – *infrastructure vulnerability*, *consequences of an infrastructure disruption,* and *energy security* – valued by a total of 15 metrics.
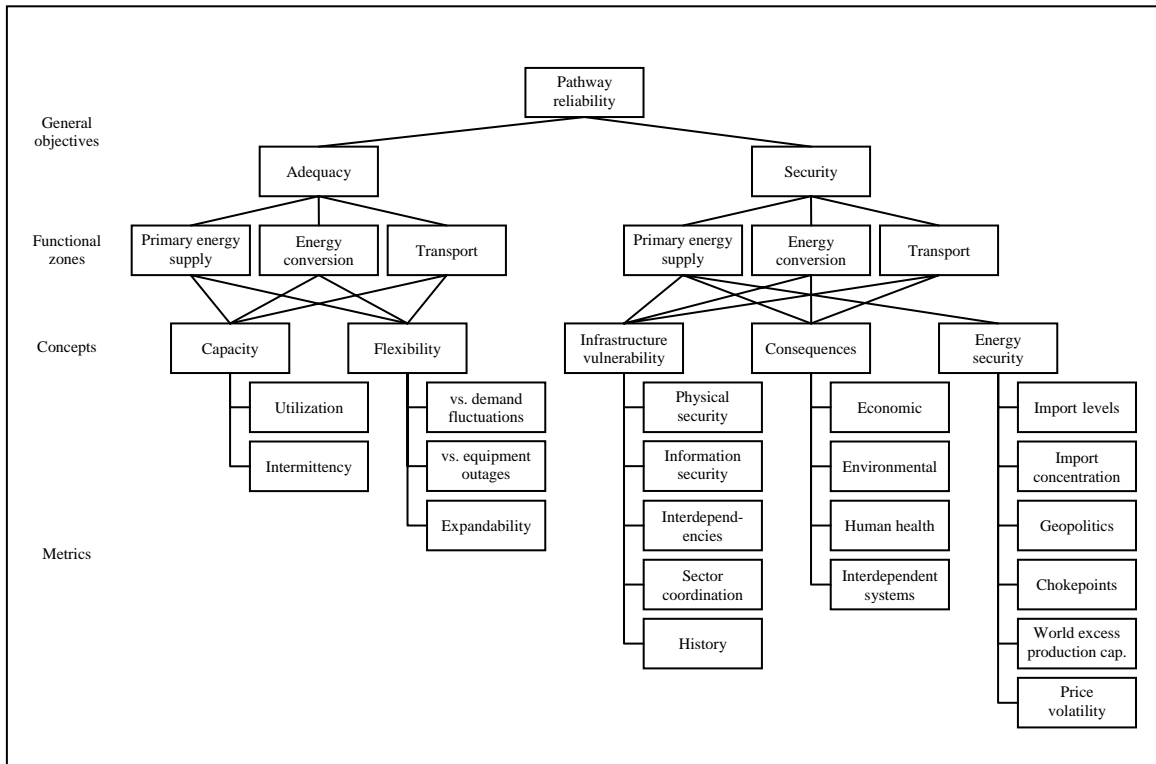
Figure 2. Hierarchy of attributes used to value reliability in hydrogen pathways. For three functional zones of two alternative hydrogen pathways, 20 *metrics* are used to value five *concepts* which describe the *general objectives* of maintaining *adequacy* and *security* in an energy supply.

We intend the metrics to be independent from one another, as required for additive MAUT, but we recognize that there may be some relation. For example, many of the qualities that lead to geopolitical concerns in some regions of the world can lead to vulnerable shipping *chokepoints* in the same regions. We instructed the expert panel to consider the attributes independently to the extent possible, but some correlation may persist. A more rigorous assessment would test the assumption of independence and the appropriateness of using MAUT in its additive form. For simplicity in our demonstrative application of the methodology, however, we assume independence.

The metric *intermittency* and those associated with *energy security* apply only to *primary energy supply*. We included these attributes in the hierarchy because we felt they were relevant to the reliability of hydrogen supply. The experts might disagree, however, which is an important and interesting capability of the method. For instance, *intermittency* is an important problem for electricity systems, but is presumably less important for hydrogen systems, which can more readily store energy. But for systems that resemble Pathway #2, which relies on intermittent electricity, the metric may be thought to influence *adequacy*. The experts can convey the extent to which they perceive the attribute to affect reliability, and may feel that it is irrelevant for one or more functional zones (we did, and only apply it to *primary energy supply*). If the experts indicate that an attribute has little influence on the reliability of hydrogen supply, it should be incorporated into future assessments by removing the attribute from the hierarchy.

4.1.1. Description of adequacy attributes

We describe *adequacy* in terms of the following *concepts* and *metrics*:

Capacity: The ability of the system to provide sufficient throughput to supply final demand.

- *Utilization:* The degree to which the system is being utilized.

- *Intermittency:*   The degree to which the system lacks constant levels of productivity.

Flexibility: The degree to which the system can adapt to changing conditions.

- *Response to demand fluctuations:* The extent to which the system is able to adapt to changes in quantity of energy demanded or location of demand.

- *Response to equipment outages:* The degree to which the system is able to continue reliable operation in the event of equipment downtime.

- *Ability to expand facilities:* The degree to which the system can be easily and cost-effectively expanded.

Adequacy fundamentally derives from demand and *capacity*. Although we do not consider demand explicitly in our assessment, it drives supply and dictates the *capacity* required for a given level of *adequacy*. *Capacity* must offer sufficient throughput to

supply peak demands temporally and spatially, while accounting for reasonably expected demand fluctuations and equipment outages. Generally, *capacity* is assessed separately for the three functional zones. Planners project future demand and supply for each zone, and the probability that *capacity* will be sufficient to operate reliably (e.g., Billinton and Allan, 1984; NERC, 2002).

Demand and *capacity* devolve into *utilization*, which is commonly used to assess adequacy in the production and transmission components of an energy supply chain. *Utilization* is measured at production facilities (power plants, refineries, and natural gas processing plants) and in pipelines in terms of capacity factors. Depending on the scope of an assessment, a capacity factor may relate average, low, or peak throughput over the course of a day, week, month, or year. In pipelines, *utilization* may be measured on a system-wide basis or at state borders (EIA, 1998). *Utilization* is more difficult to measure for electricity transmission, as system throughput may be limited by operational, thermal, or voltage constraints (EIA, 2002).

Intermittency also influences *capacity*, and is especially important when assessing capacity in the primary energy supply system. Whereas *capacity* assessments are somewhat straightforward for generation/production and transmission/distribution facilities (usually based on proposed facility additions and retirements), a primary energy supply system may be subject to levels of often unpredictable *intermittency*. Uncertain factors such as environmental regulations, geopolitics, technological advancement, and weather patterns may affect *capacity* in those systems intermittently.

Aside from having sufficient *capacity,* an adequate system has the *flexibility* to adapt to spatial and temporal variations in demand. Flexible systems can withstand

expected equipment downtime and expand or contract with demand. Marginal economics and operating characteristics are thus important to *flexibility*, as well as centralization, diversity, redundancy, and storage. The latter concepts are also critical to infrastructure security, and are commonly associated with that category in the literature (e.g., Farrell et al., 2004; Lovins and Lovins, 1982). But to the extent they contribute to the reliable supply of an energy product under normal operating conditions, they apply to *adequacy* as well.

4.1.2. Description of security attributes

Based on a review of other energy sectors and our knowledge of hydrogen systems, we selected the following *concepts* and *metrics* to describe *security*, defined below:

Infrastructure vulnerability: The degree to which the system is susceptible to disruption.

- *Physical security:* The degree to which physical assets in the system are secure against threats.

- *Information security:* The degree to which information assets in the system are secure against threats.

- *Interdependencies:* The degree to which the system relies on other infrastructure for its reliable operation, and is vulnerable to their disruption.

- *Sector coordination:* The degree to which coordination between stakeholders within the sector results in an effective exchange of information alerting stakeholders of emerging threats and mitigation strategies.

- *History:* The degree to which the system has been prone to disruption in the past.

Consequences of infrastructure disruption: The degree to which a disruption in the system could cause harm.

- *Economic impacts:* The degree to which a disruption in the system might feasibly cause economic damage to industry stakeholders, the government, or the public.

- *Environmental impacts:* The degree to which a disruption in the system might feasibly cause environmental damage.

- *Human health impacts:* The degree to which a disruption in the system might feasibly harm the health of employees and/or the public.

- *Impacts on interdependent systems:* The degree to which a disruption in the system might feasibly cause damage to interdependent systems.

Energy security: The degree to which the primary energy system is secure against threats to global supply infrastructure.

- *Import levels:* The degree to which *primary energy supply* relies on resources originating outside of the country.

- *Import concentration:* The degree to which imports are concentrated among a small group of supplying countries.

- *Geopolitics:* The degree to which political and social conditions in primary energy-exporting countries threaten the supply of their exported energy resources.

- *Chokepoints:* The degree to which imported primary energy resources are vulnerable to disruptions in narrow shipping lanes.

- *World excess production capacity:* The degree to which excess production capacity exists in the global market and provides flexibility against demand fluctuations and supply outages.

- *Price volatility:* The degree of fluctuation in the average price of primary energy.

Infrastructure vulnerability has long been a general concern in the energy sector, as well as for national security. While the focus has evolved from cold war concerns of nuclear warfare to today's emphasis on cyber security and localized attacks (e.g., Adams, 2003; Clark and Page, 1981; Lovins and Lovins, 1982; NPC, 2001; White House, 2003), similar concepts appear. Farrell et al. (2004) summarize several general infrastructure security concerns, including attack modes, stress, routine security, cyber security, diversity, storage, redundancy, survivability, *interdependency*, and centralization. Attack modes and stress are fundamental here, as they encompass real and perceived

vulnerabilities facing an infrastructure (e.g., natural disaster, human error, malicious attack). Routine security involves hardening physical assets to secure against the identified vulnerabilities (monitoring and limiting access to facilities, for example). Similarly, cyber security hardens cyber and information assets against vulnerabilities posed by hackers, viruses, or other disruptions. Current thinking in the industry is that the most effective way to secure against cyber attacks is by coordinating efforts and sharing intelligence throughout industry, the government, and law enforcement (NPC, 2001). Diversity, redundancy, storage, and survivability describe the inherent flexibility of a particular infrastructure, and its resilience under stress conditions. *Interdependency* and centralization present their own vulnerabilities, but are also important in assessing potential impacts of an infrastructure disruption. *History* plays an important role as well, warning against vulnerabilities and demonstrating past performance (NPC, 2001). Altogether, these attributes elucidate vulnerabilities faced by an infrastructure, potential impacts of an infrastructure disruption, and mitigation measures.

The *consequences of an infrastructure disruption* are also important to *security* – indeed, the reason for our concern with the general objective at all. Typical system risk assessments define risk in terms of the likelihood and associated consequence of a failure. We develop the latter component in our assessment in terms of economic, environmental, and human health effects, and consequences on interdependent systems.

Our final concept, *energy security*, extends from *infrastructure vulnerability*. The same attributes that expound vulnerabilities, consequences, and mitigation for the infrastructure do so for *primary energy supply* as well. But *energy security* takes on added elements, particularly when acquiring resources extends the infrastructure to the

24

global scale. These are most apparent in the petroleum sector, but increasing LNG imports worldwide add relevance to the natural gas sector as well. Considerations such as *import levels*, the geographical concentration of imports, political and social conditions in energy-exporting nations, storage (such as the Strategic Petroleum Reserve in the U.S.), and the shipping routes through which imports travel relate to regional vulnerabilities associated with imported energy supplies (Adams, 2003; Alhajji and Williams, 2003; CSIS, 2000; EIA, 2004a; Williams and Alhajji, 2003). Global markets extend regional vulnerabilities worldwide, so the level of *world excess production capacity*, price stability,[2] and the associated economic implications pertaining to balance-of-trade are important as well (Copulos, 2003; EIA, 2004b; Greene and Tishchishyna, 2000).

4.2. Sample results

The average of the aggregated utility scores was taken across all experts to determine reliability indices for the panel. The average ratings and aggregated utility scores are given for both pathways in Table 3 (for the objective *adequacy*), and Table 4 (for *security*). Although the results and conclusions we draw from them cannot be taken as definitive for the two systems considered in this preliminary assessment, they indicate the capabilities and limitations of the methodology.

Our model indicates that the experts perceived Pathway #2 (the renewable-based decentralized pathway) to be more reliable in terms of both *adequacy* and *security*. Pathway #1 received average scores of 0.56 and 0.57 for *adequacy* and *security*,

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[2] *Price volatility* is seemingly an outcome of a pathway, rather than a feature. But we only apply the *energy security* metrics to *primary energy supply*, and we define the metric as the level of fluctuation in the price of primary energy, and its subsequent effect on the reliability of hydrogen supply.

respectively, while Pathway #2 received scores of 0.39 and 0.23 (recall that the utility scores are on a scale from *0* to *1*, and higher scores represent poor reliability).

Table 3. Average utility and importance ratings and aggregated concept and general objective reliability indices for *adequacy*. Scores of *1* represent the worst reliability rating (*u*) and the highest important rating (*w*), while *0* corresponds to high reliability or low importance.

			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone electricity	Distributed electrolysis	No transport
Capacity	Utilization	u	0.67	0.51	0.53	0.65	0.37	0.07
		w	0.60	1.00	1.00	0.60	1.00	1.00
	Intermittency	u	0.40	N/A	N/A	0.82	N/A	N/A
		w	0.40	N/A	N/A	0.40	N/A	N/A
	Capacity	U	0.54	0.51	0.53	0.72	0.37	0.07
		w	0.56	0.55	0.54	0.56	0.55	0.54
Flexibility	vs. demand fluctuations	u	0.65	0.47	0.43	0.88	0.43	0.10
		w	0.36	0.35	0.40	0.36	0.35	0.40
	vs. equipment outages	u	0.63	0.73	0.80	0.48	0.47	0.15
		w	0.32	0.33	0.32	0.32	0.33	0.32
	Ability to expand facilities	u	0.55	0.55	0.70	0.57	0.43	0.07
		w	0.32	0.32	0.28	0.32	0.32	0.28
	Flexibility	U	0.61	0.58	0.62	0.66	0.45	0.10
		w	0.44	0.45	0.46	0.44	0.45	0.46
Adequacy		U	0.56	0.54	0.58	0.70	0.41	0.08
		W	0.32	0.36	0.32	0.32	0.36	0.32
Pathway adequacy		U		0.56			0.39	

Table 4. Average utility and importance ratings and aggregated concept and general objective reliability indices for *security*. Scores of *1* represent the worst reliability rating (*u*) and the highest important rating (*w*), while *0* corresponds to high reliability or low importance.

			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone electricity	Distributed electrolysis	No transport
Infrastructure vulnerability	Physical security	u	0.70	0.60	0.83	0.33	0.28	0.13
		w	0.23	0.21	0.21	0.23	0.21	0.21
	Information security	u	0.43	0.47	0.47	0.43	0.30	0.05
		w	0.22	0.26	0.25	0.22	0.26	0.25
	Interdependencies	u	0.65	0.67	0.43	0.28	0.28	0.03
		w	0.20	0.24	0.24	0.20	0.24	0.24
	Sector coordination	u	0.58	0.33	0.33	0.25	0.25	0.10
		w	0.18	0.17	0.16	0.18	0.17	0.16
	History	u	0.40	0.18	0.38	0.30	0.30	0.08
		w	0.18	0.13	0.13	0.18	0.13	0.13
	Infrastructure vulnerability	U	0.57	0.48	0.50	0.35	0.29	0.09
		w	0.30	0.46	0.47	0.30	0.46	0.47
Consequences	Economic impacts	u	0.77	0.75	0.73	0.45	0.45	0.13
		w	0.27	0.26	0.23	0.27	0.26	0.23
	Environmental impacts	u	0.52	0.47	0.47	0.23	0.23	0.07
		w	0.22	0.23	0.24	0.22	0.23	0.24
	Human health impacts	u	0.43	0.50	0.50	0.17	0.23	0.08
		w	0.27	0.27	0.29	0.27	0.27	0.29
	Interdependent systems	u	0.75	0.63	0.65	0.45	0.33	0.08
		w	0.24	0.24	0.24	0.24	0.24	0.24
	Consequences of disruption	U	0.63	0.61	0.58	0.33	0.32	0.10
		w	0.37	0.54	0.53	0.37	0.54	0.53
y se	Import levels	u	0.73	N/A	N/A	0.07	N/A	N/A

	w	0.17	N/A	N/A	0.17	N/A	N/A
Import concentration	u	0.72	N/A	N/A	0.12	N/A	N/A
	w	0.19	N/A	N/A	0.19	N/A	N/A
Geopolitics	u	0.53	N/A	N/A	0.10	N/A	N/A
	w	0.17	N/A	N/A	0.17	N/A	N/A
Chokepoints	u	0.68	N/A	N/A	0.22	N/A	N/A
	w	0.15	N/A	N/A	0.15	N/A	N/A
World excess production capacity	u	0.53	N/A	N/A	0.13	N/A	N/A
	w	0.16	N/A	N/A	0.16	N/A	N/A
Price volatility	u	0.53	N/A	N/A	0.38	N/A	N/A
	w	0.16	N/A	N/A	0.16	N/A	N/A
Energy security	U	0.63	N/A	N/A	0.16	N/A	N/A
	w	0.34	N/A	N/A	0.34	N/A	N/A
Security	U	0.61	0.55	0.55	0.28	0.31	0.09
	W	0.35	0.33	0.33	0.35	0.33	0.33
Pathway security	U	0.57			0.23		

The utility scores can be compared at various levels to reveal relative strengths and weaknesses of each pathway.

From this application, we see that the panel perceives that distributed production and limiting hydrogen transport may improve reliability in hydrogen supply pathways. On average, the experts rated these two functional zones as more reliable than the same two in Pathway #1 (centralized production and pipeline transport) in terms of every metric except *history*. The experts felt that distributed production and onsite utilization of hydrogen at refueling stations offers added adequacy by providing flexibility to adapt to volume and geographical fluctuations in demand. They also felt that the small scale of the process and its utilization of stable energy feedstocks added to *security* in Pathway #2. The isolated processes can be easily monitored against threats, and the onsite facilities can be more easily hardened against accidental or intentional third party damage. The small scale of the process and the lack of volatile or toxic ingredients also minimize the attractiveness of such facilities as targets of a malicious attack, and the consequences that might stem from a disruption. In the case of a disruption, human health and environmental consequences would be minimal due to the small scale and benignity of the compounds involved. Economic effects would be small, likely isolated

to the owner of the facilities. Some level of inconvenience might be experienced by the customers of the refueling station.

It is more difficult to discern which of the two primary energy supply systems offer better reliability. The panel felt that the established, global LNG infrastructure provided a more adequate primary energy resource than a reliance on local, renewable energy resources whose availability may rely on favorable weather patterns (*imported LNG* received an average *adequacy* score of 0.56, while the average score for *stand-alone electricity* was 0.70). But, they agreed that a local stand-alone electricity system greatly improved security of primary energy supply over the vast LNG network, which is more difficult to secure and exposes hydrogen supply to the uncertainties associated with imported energy (an average *security* score of 0.61 for *imported LNG* compared to 0.28 for *stand-alone electricity*).

While the method provides an effective mechanism to compare the reliability of various pathways, an absolute quantitative meaning cannot be extrapolated from the aggregated reliability scores. That is, we cannot predict the future performance of an energy pathway supplying hydrogen via pipeline from a centralized plant reforming imported LNG from *adequacy* and *security* scores of 0.56 and 0.57 for Pathway #1. But the method does allow us to conclude that these experts perceive Pathway #2 to be more reliable than Pathway #1 in terms of the attributes we selected. This provides a valuable tool as we consider prospects for entirely new energy systems – one that is indeed meaningful to the extent the assessment is transparent and accepted among stakeholders.

5. Opportunities for future research

The work presented here scratches the surface of an enormous subject, and intends to promote systematic consideration of reliability in energy systems. Ultimately, we strive to compare reliability among pathways for various energy products that may comprise a future transportation fuel supply infrastructure – for example, among pathways to supply biofuels, gasoline, hydrogen, and synthetic fuels. But understandings of reliability must be greatly enhanced before this can be done with confidence. The following additional research is needed:

- Insights of experts and interests of all stakeholders must be considered and incorporated to an appropriate extent. We do not purport to have perfectly captured reliability with the concepts and metrics we evaluated; additional viewpoints would undoubtedly broaden our understanding and assessment of reliability in the energy sector.

- Ultimately, the method should be used to compare the reliability of pathways for various energy products, especially if considering a transition away from petroleum-based fuels. Appropriate attributes should be identified; those we consider here for hydrogen are broad enough to apply to non-hydrogen pathways as well, but additional or different attributes may be justified. Additionally, some workings of the method may change, and it should be optimized to account for multiple fuels. For example, we might allow the importance ratings to vary among fuels (still fixing them among pathways for a similar fuel) to account for fundamental differences in the resources and processes used along their respective supply chains.

- Reliability considerations at the point of end use should be incorporated into assessments that compare different fuels. The interaction with consumers is a critical factor in determining reliability; an assessment is not complete without this component. When comparing pathways for a single energy product it is often not of concern, as the user interface is presumably similar (although not always, as with home refueling of hydrogen). But when comparing energy products, such as gasoline and hydrogen, reliability differences (e.g., safety) at the point of end use are crucial.

- The method does not allow an absolute quantification of reliability for a particular pathway. Does an *adequacy* score of 0.10 constitute a reliable system? How about 0.25? And how unreliable is a system with a *security* score of 0.75? While the method does not allow us to answer these questions, if it were applied to diverse energy systems and tied to their measured performance, perhaps future results of similar assessments could be attributed an expected level of performance.

- If investments are to be made for the sake of improving reliability, an evaluation of cost must be included to balance benefits. Other considerations such as environmental impacts can be included as well, to develop a more general assessment of societal benefits and costs associated with various energy pathways.

6. Conclusion

Energy reliability has always been a pressing issue, but is of increasing concern as businesses and economies grow increasingly dependent on abundant and dependable energy supplies, and as political turmoil and escalating energy demands are perceived to threaten and stress the capabilities of energy infrastructure. In this paper, we provided a first attempt at a comprehensive assessment of energy sector reliability that encompasses both adequacy and security in a qualitative sense. In doing so, we hope to spawn research and dialogue regarding issues of reliability and encourage systematic consideration of reliability in future decision making. As knowledge progresses, we should develop statistically significant models that shed more light on uncertainty and sensitivity of reliability to various attributes and among different stakeholders, and that allow a comparison of reliability across pathways for various fuels and energy supply systems.

Subaru, Total, Toyota, U.S. Department of Energy, U.S. Department of Transportation, U.S. Environmental Protection Agency.

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