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Publication Date

2005-11-01

Year 2005

UCD—ITS—RR—05—20

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November, 2005

ABSTRACT

With recent economic, political, and social events worldwide, reliability in the energy sector is growing more valuable, and the surrounding issues are gaining visibility. Increasingly, concerns about energy supply security (and climate change) have led to proposals to shift away from oil dependence to wide use of alternative transportation fuels, such as biofuels or hydrogen. Hydrogen is of particular interest because it offers multiple societal benefits. It is often asserted that hydrogen would enhance energy reliability because it can be made at diverse scales from many primary resources. But no studies have systematically assessed reliability. There are many questions surrounding energy system reliability – especially when considering a future fuel like hydrogen. How should reliability be defined and evaluated? And would a transition to hydrogen increase or decrease reliability? This paper presents a general method to assess reliability in energy supply systems. The technique uses qualitative ratings from an expert panel regarding a set of reliability metrics. We illustrate the method by evaluating two hydrogen pathways: 1) centralized steam reforming of imported liquefied natural gas and pipeline distribution of hydrogen, and 2) on-site electrolysis of water using electricity produced independent of the grid. We found the second pathway to be more reliable, primarily due to the distributed nature of the system and the lack of hydrogen transport. The application intends to demonstrate how the method is applied, however, and the results should be regarded as preliminary. In future work, the method could be extended to compare reliability among different fuel pathways.

1. INTRODUCTION

As energy consumption continues to increase worldwide, energy supply systems are being stressed to their limits and are growing ever more vulnerable to disruptions along increasingly centralized supply chains. These factors, coupled with persistent political instability in many energy-rich regions, mean that global energy supplies may be less reliable than ever.

Several trends and recent events support such claims for each of the major energy sectors. Electricity infrastructure is aging, and congestion is increasing along transmission and distribution lines. Increasingly, steps have to be taken during periods of peak demand to redirect loads from constrained facilities or curtail them altogether to maintain stability in the electricity grid (*1*). Massive blackouts – such as those that shut off 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 (*2*) – exemplify the fragility of these centralized systems.

Petroleum and natural gas are supplied by similarly centralized infrastructure, relying on large pipelines dependent on a few pumping or compressor stations and delivering energy products from distant refineries or natural gas processing plants. In the United States, reliability concerns were amplified in the aftermath of Hurricane Katrina. While oil prices already dominated the news as they approached record highs, average gasoline prices spiked by a record $0.46 (15%) over the course of a single week (*3*).

Petroleum imports and the concentration of global oil supplies in unstable regions are increasing, while the global ability to respond to a supply shortage through excess production capacity is near an all time low (*4*, Kreil E, unpublished data). Aside from the obvious vulnerability of the domestic infrastructure to accidental or malicious disruptions, this arrangement extends the reliability burden to the global market. Acts of piracy are also increasing and have tripled in the last decade – with 445 reported attacks in 2003 – threatening oil tankers navigating strategic shipping passages such as the Strait of Malacca in Southeast Asia (*5*,*6*).

Liquefied natural gas (LNG) imports are projected to increase dramatically in coming decades worldwide, subjecting natural gas supply to many of the same vulnerabilities facing the global oil supply infrastructure today – including the likely formation of a natural gas cartel in some likeness to the Organization of Petroleum Exporting Countries (OPEC). Volatile energy prices are also indicative of reliability concerns in the sector. Natural gas prices are growing more volatile, apparently conforming to cyclic trends characteristic of most commodities, but which have yet to persist with natural gas (*7*).

As energy supply reliability is increasingly at risk, prevailing business, political, and social climates are such that it is now valued more than ever. A new business environment has emerged with the coming of information technologies, characterized by automated operations, just-in-time logistics, and rapid changes. Business today depends entirely on the systems that support it, and cannot function without their reliable operation. The consequences stemming from infrastructure disruptions have grown more severe, and often no feasible manual backup processes exist (*8*). Nations are placing increasing emphasis on securing energy and other infrastructure against malicious attacks, and issues dominating the news and political debate include volatile gasoline prices and developments in the Middle East. These conditions compound to create high public awareness and demand for reliable energy supply.

Hydrogen is gaining a great deal of attention as a possible alternative to existing energy carriers, and may offer opportunities to improve reliability in the energy sector. It can be derived from several primary energy feedstocks, and can be produced, stored, transported, and used in a number of ways. These characteristics allow hydrogen supply systems to take different configurations (hereafter referred to as “hydrogen pathways”), which can commingle in a regional supply system to achieve desired characteristics such as improved reliability. But it is not necessarily the case that a given hydrogen pathway will be more reliable than today’s transportation fuel supply. Whether incorporating hydrogen systems into the energy sector would improve reliability over the current paradigm remains uncertain, and deserves further investigation.

The design and selection of pathways to meet future hydrogen demands should be based on thorough assessments of all pertinent criteria – including economics, environmental impact, and reliability. The economic and environmental aspects of various hydrogen pathways have been studied in detail by many authors (*9-12*). But few studies have investigated reliability in hydrogen pathways. This paper describes a new methodology to assess reliability in hydrogen energy systems.

2. THEORY AND PRACTICE OF ENERGY SYSTEM RELIABILITY

There are several methods in use today for assessing the reliability of energy systems. Studies of energy reliability are founded on several concepts which can be classified according to two overarching categories – adequacy and security. Together, these broadly encapsulate the concepts of availability, flexibility, vulnerability, and resource security. We review them here as they are applied in theory and practice to energy system reliability assessments in today’s electricity, natural gas, and petroleum systems, and classify them according to the two general categories.

2.1. Adequacy

Adequacy relates to energy supply availability under normal operating conditions, and is based upon concepts such as capacity, utilization, and flexibility. In the electricity sector, adequacy is defined as “The ability of the electric system to supply the aggregate electrical demand and energy requirements of customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.” (*13*) Although not explicitly defined in the other sectors, the same theoretical concepts apply when assessing adequacy for any energy product.

Availability depends on demand and capacity. Demand drives supply, and dictates the capacity required for a given level of adequacy. The capacity of a system must be large enough to allow sufficient energy flow to meet peak demands (temporally and spatially), while accounting for reasonably expected demand fluctuations and equipment outages. In the electricity sector, capacity is assessed separately for the three primary components of the infrastructure: primary energy supply, electricity generation, and transmission. Planners project future demand and supply for each component, and the probability that capacity will be sufficient to maintain adequate reserve margins (*1*). These projections are relatively straightforward for the latter two components, production and distribution of the final energy product, which usually depend on proposed facility additions and retirements. It is more difficult to project capacity in terms of reserves and extraction of the primary energy resource, as they depend on uncertainties such as environmental regulations, geopolitics, technological advancement, and weather patterns. Capacity can be similarly assessed for the three analogous components of natural gas and petroleum infrastructure: (1) primary energy supply, (2) petroleum refining or natural gas processing, and (3) transmission and distribution.

The concepts of 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 (*14*). Utilization is more difficult to measure for electricity transmission, as system throughput may be limited by operational, thermal, or voltage constraints (*15*).

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 levels of centralization, diversity, redundancy, and storage in the system. The latter concepts are also critical to infrastructure security, and are commonly associated with that category in the literature (e.g. *16,17*). But to the extent they contribute to the reliable supply of an energy product under normal operating conditions, they apply to adequacy as well.

2.2. Security

Security relates to the ability of an energy system to endure unexpected disruptions. It involves a deviation from the “normal” operating conditions assumed for adequacy, and often relates to dynamic conditions and the ability to react in real time. In their classic work, *Brittle Power*, Amory and Hunter Lovins define security in terms of resilience – the ability to absorb unexpected disturbances “gracefully” (*17*). Put differently, security is the ability to maintain adequacy under conditions of stress.

Various metrics can indicate a deviation from normal operating conditions and push reliability practice into the security realm. These vary across energy sectors, as their primary security concerns are somewhat different. For example, the electricity sector focuses on maintaining grid stability, so frequencies or voltages that fall outside set bounds indicate stress conditions (*18*). In natural gas systems, a primary emphasis is protecting pipelines against third party damage (accidental or not) (*19*), and the unexpected loss of some portion of pipeline capacity suggests a break from normality. And in the petroleum sector – where securing international oil supply is fundamental – a disruption on the global market stresses the system. Although these indicators apply differentially across sectors, the theoretical concepts of security are similar, and relate to vulnerabilities in the supply infrastructure and the supply of the primary energy resource (i.e. energy security).

Infrastructure security has always been a concern for the energy sector, and also for national security. Although the focus has shifted over the years from cold war concerns of nuclear warfare to today’s emphasis on cyber security and localized attacks, similar theoretical concepts appear (e.g. *8,17,20-22*). Farrell et al. summarize several generalized infrastructure security concerns, including attack modes, stress, routine security, cyber security, diversity, storage, redundancy, survivability, interdependency, and centralization (*16*). 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. Diversity, redundancy, storage, and survivability describe the inherent flexibility of a particular infrastructure, and its resilience under stress conditions. Interdependency (the degree to which two or more infrastructures depend on one another) and centralization present their own vulnerabilities, but are also important in assessing potential impacts of an infrastructure disruption. Altogether, these concepts elucidate vulnerabilities faced by an infrastructure, potential impacts of an infrastructure disruption, and mitigation measures, and are usually implemented on a cost/benefit basis (e.g. *23,24*).

Energy security can be seen as a special case of infrastructure security. The same concepts that describe vulnerabilities, consequences, and mitigation for the infrastructure do so for primary energy supply as well. But energy security also takes on added elements, particularly when acquiring resources extends the infrastructure to the global scale. These are most apparent in the petroleum sector, but increasing LNG imports worldwide add relevance to the natural gas sector as well. Concepts 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. Global markets extend regional vulnerabilities worldwide, so the level of excess world production capacity, price stability, and the associated economic implications pertaining to balance-of-trade are important concepts as well.

3. A METHODOLOGY TO ASSESS RELIABILITY IN ENERGY SUPPLY SYSTEMS

Selecting a best solution among alternatives grows increasingly difficult (and interesting) as the number of evaluation criteria increases. Various multicriteria decision making methods exist to sort the complex relationships between often competing objectives, including utility models, fuzzy integrals, and the analytic hierarchy process (e.g. *25-27*). These have been applied to address a broad array of multidimensional issues, such as siting nuclear facilities and handling nuclear waste (*27,28*), selecting energy feedstocks for electricity production (*29*), judging the viability of investments and projects (*30*), and evaluating potential employees (*25*). Their formulation is similar – developing from a hierarchical organization of relevant criteria – but the methods diverge in their assessment of the attributes and subsequent aggregation.

Here, we develop a multiattribute utility (MAU) model to assess the reliability of various energy supply pathways. Multiattribute utility bases from a hierarchical organization of relevant attributes, which describes the relationships between them and their relative magnitudes. Experts rate the attributes in terms of their importance and “utility” (i.e., the degree to which an attribute contributes to the reliable performance of the overall system). These ratings are subsequently aggregated to develop broad reliability scores.

We describe the method generally in this section, in a way that it can be applied to any decision based on any set of conceptual parameters. In *Section 4* we develop it further through a sample application by applying it to compare the reliability of two hydrogen pathways.

3.1. Define the problem

A sound assessment begins by appropriately formulating the problem and the evaluation process. A clear definition of reliability based on the objectives of the decision maker guides the assessment. It should describe the item(s) of interest, the time frame, conditions which constitute adequate performance, and the surrounding environment in which the item operates (*31*).

The decision maker should also clearly describe the energy pathways to be evaluated. A supply pathway includes several elements, which we classify according to three components: primary energy supply, energy processing and conversion, and transport. Other important aspects are the demand scenarios and end uses of the final energy product (we do not explicitly consider these in our preliminary analysis). 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. This includes considerations regarding the primary feedstock itself (e.g. reserves), its extraction and transport processes, and any intermediate conversion or processing required before conversion into the final energy product. Energy processing and conversion relates to the production of the final energy product. Examples include petroleum refining for gasoline pathways, electricity generation, or hydrogen production processes. Important parameters here include the technologies used and the size and geographical reach of the processes. Similar parameters apply to the final pathway component, which considers the transportation of the final energy product to its point of end use.

3.2. Organize relevant concepts

Based on the general reliability definition, the decision maker identifies salient reliability concepts, and metrics to value them. These decompose the broad objectives into discernable elements to be evaluated by the experts. Care should be taken to select an effective set of concepts and metrics that fully encapsulate the reliability definition. While limiting their number simplifies the assessment, it may also limit accuracy. Conversely, including superfluous metrics could skew the results. Real-world constraints such as time, resources, and human cognitive ability of the expert panel must be balanced as well.

The attributes are organized in a hierarchy to reflect their relationships and relative magnitudes (*25*). Logic flows from general to specific; attributes grow increasingly tangible moving down the hierarchy. We divide the attributes into three levels: *general objectives*, *concepts*, and *metrics.* The general objectives pertain to the broad reliability scores we look to develop through our decision making process (i.e., reliability, adequacy, and security). These are assessed in terms of the concepts, which are wide-ranging ideas that embody them. The metrics, in turn, are more specific, and characterize the concepts. Figure 1 shows the general structure of a hierarchy.

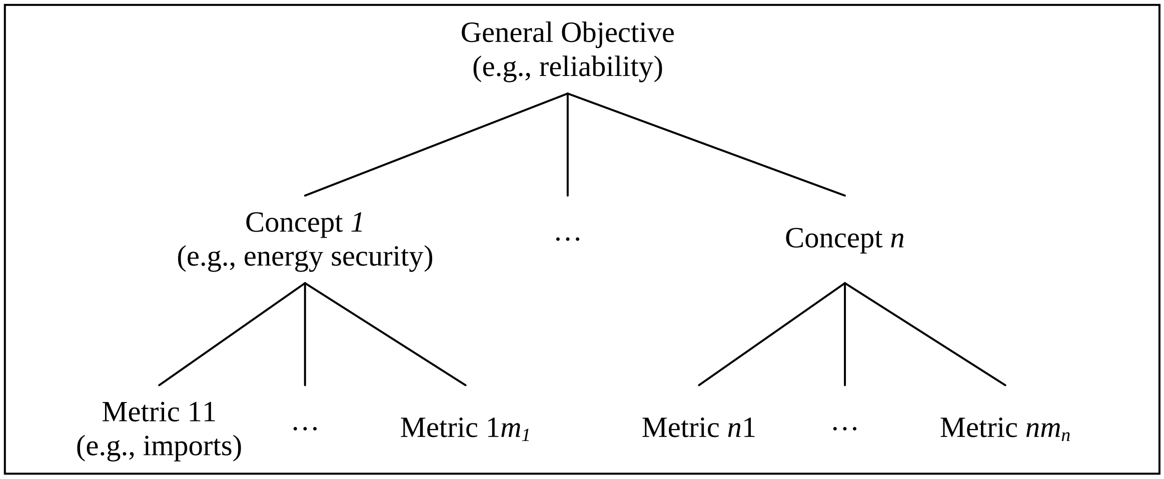

FIGURE 1 Structure of the hierarchy used in this assessment.

3.3. Collect expert ratings

The expert panel rates the reliability of the pathway alternatives in terms of the metrics and the importance for each attribute. Their reliability ratings (or perceived "utilities") reflect the degree to which they feel a pathway is reliable in terms of each metric. These are pathway-specific and the panel rates reliability for each metric for each component of each pathway.

Associated with each metric and concept is an importance rating. It expresses the degree to which the experts perceive attributes that are lower on the hierarchy to influence those above them, and is used to weight the reliability ratings during the aggregation. The importance ratings are pathway-independent, but can vary across pathway components.

Expert ratings can be ascertained in several ways, depending on the objectives of the study, the desired results, and the time and resources available. Possibilities include group discussion, facilitated exercises, personal interviews, and surveys.

3.4. Aggregate ratings and formulate results

The expert's ratings – of which there could be hundreds from each – are aggregated at each level of the hierarchy using the additive MAU model. The ratings of the metrics are aggregated to develop utility scores at the concept level, which are subsequently combined to develop scores for the general objectives. The MAU model 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 (i.e., reliability rating) of attribute i, scaled from 0 to 1. The importance weights reflect the degree to which attributes at a lower level of the hierarchy contribute to the attribute above it, relative to each other. Thus, for a set of n lower-level importance weights, $\sum_{i=1}^{n} w_i = 1$.

4. RELIABILITY IN HYDROGEN PATHWAYS

We applied the methodology to two distinct hydrogen pathways using a group of hydrogen researchers from the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) as the expert panel. One considers large, centralized processes and relies on imported primary energy resources. The second is a distributed pathway where hydrogen is produced from locally available feedstocks and produced onsite at refueling stations.

Through this preliminary application, we aim to demonstrate and further develop the methodology for the reader, and hope to discuss energy sector reliability in a transparent way. It is not our intention to identify a definite winner; we emphasize that our application lacks the rigor that would be necessary to do so, because of the relatively small size and composition of the expert panel, and the exploratory nature of the exercise. But that is not to say that the methodology is so limited. Certainly, as we become more familiar with reliability and the attributes considered (and neglected) here, we should develop assessments that shed more light on uncertainty and sensitivities to various attributes and among stakeholders.

4.1. Problem description

We define reliability for hydrogen pathways broadly by adapting the NERC's definition of reliability in electricity systems (*32*). Similar to the other energy sectors, reliability for hydrogen was considered in terms of adequacy and security components. These definitions were adapted to apply to hydrogen systems from those cited above:

Reliability – The degree to which the performance of the elements of the system results in hydrogen being delivered to consumers within accepted standards and in the amount desired.
Adequacy – The ability of the system to supply the requirements of customers at all times, taking into account reasonably expected outages in the system.
Security – The ability of the system to minimize and withstand unexpected interruptions.

Myriad concepts may be used to assess the reliable operation of hydrogen systems according to these definitions. Any direct or indirect influence on deliverability along a pathway feasibly applies. The terms also encompass multiple stakeholders: the viewpoint of both consumers and suppliers can be incorporated in the assessment as both direct economic and social costs and benefits can be included.

The problem was framed in concrete terms to give the experts a well-defined scenario. We described a hypothetical network of hydrogen refueling stations in the Sacramento (CA) area and specified two disparate pathways to supply them. A near-term time frame was implied, and we instructed the experts to consider their ratings based on current technologies and operating environments – regardless of the likelihood of sufficient near-term demand to necessitate such a network. We selected the pathways to capture comparative advantages and disadvantages between primary energy feedstocks and centralized versus distributed systems. In the Pathway #1, hydrogen is transported to the refueling stations via pipeline from a centralized steam reformation production facility using imported liquefied natural gas (LNG). The LNG supplies were specified to come primarily from Trinidad and Tobago, but also from Alaska and other countries in the Pacific and Middle East. In Pathway #2, hydrogen is produced at its points of end use via electrolysis of water, so no transport of hydrogen is needed from offsite. The electricity used is produced from locally-available renewable resources, independent from the electric grid.

4.2. Hierarchical organization of relevant attributes

From a review of the literature outlined in *Section 2*, we identified five concepts and selected 20 metrics to value them from our societal perspective. The concepts and metrics are shown in Figure 2, along with their relationship to the pathway components and the general objectives outlined in the reliability definition. The general objectives apply to each of the three pathway components, which are independently evaluated in terms of the concepts and metrics for each pathway alternative. We describe the objective *adequacy* with 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 15 metrics. Each attribute is defined below (*33*).

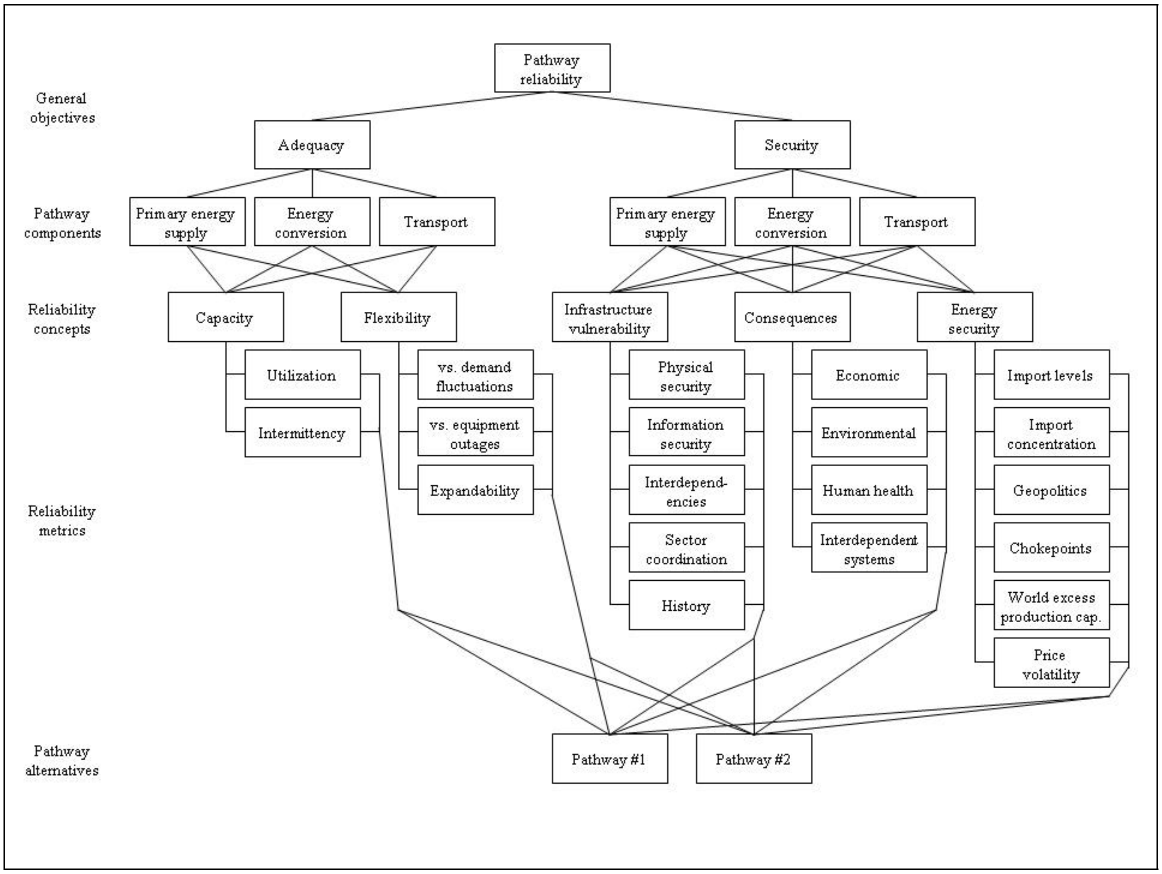

FIGURE 2 Hierarchy of attributes to value reliability in hydrogen pathways. For each of three components of two pathways, 20 metrics value five concepts which describe the general objectives of maintaining adequacy and security in an energy supply.

4.2.1. Adequacy

As defined in *Section 4.1*, *adequacy* captures two ideas – *capacity* and *flexibility*. *Capacity* conveys the ability of the system to produce and transport sufficient quantities of hydrogen to supply end user demands, and is assigned two metrics:

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

Flexibility refers to the degree to which the system can adapt to changing conditions, and is valued by three metrics:

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

4.2.2. Security

Security encompasses concepts of risk and supply security. Typically, risk is defined in terms of the likelihood and associated consequence of a failure – captured here with *infrastructure vulnerability* and *consequences of infrastructure disruption*, respectively. Also included in the definition is security of resource supply, covered by the concept *energy security*.

Infrastructure vulnerability refers to the degree to which the system is susceptible to disruption. The following metrics define the concept:

- *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 gauges the degree to which a disruption in the system could cause harm. It is measured in terms of four metrics:

- *Economic impacts:* The degree to which a disruption in the system might cause economic damage to industry stakeholders, the government, or the public.
- *Environmental impacts:* The degree to which a disruption in the system might cause environmental damage.
- *Human health impacts:* The degree to which a disruption in the system might harm the health of employees and/or the public.
- *Impacts on interdependent systems:* The degree to which a disruption in the system might cause damage to interdependent systems.

Finally, *energy security* refers to the degree to which the primary energy system is secure against threats to global supply infrastructure. It includes the following metrics:

- *Import levels:* The degree to which the 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.

4.3. Facilitated exercise to collect expert reliability ratings

We conducted the assessment as a facilitated exercise with 12 researchers from the Hydrogen Pathways Program at ITS-Davis comprising the expert panel. Only three hours were allotted for the study, and participation was limited to ITS-Davis researchers due to logistical constraints. During the exercise, the methodology was presented to the experts and they were walked through the rating process for an unrelated infrastructure pathway. A complete description of the exercise – including all of the documentation provided to the expert panel – can be found in (*33*).

The experts first rated the importance of the attributes as they pertained to each pathway component, to prevent consideration of specific pathways from influencing them (recall that the importance ratings are uniform across pathways). Two relationships were captured in their ratings (refer to Figures 1 and 2) – the importance of each metric to the concept it valued, and the importance of concepts to the general reliability objectives. After obtaining the generic importance ratings, we described the pathways to the experts and asked them to rate the reliability in terms of the metrics for each pathway.

We used a variation of the well known five-point Likert scale to rate the attributes. Likert assigned a value to each position in a qualitative rating scale to capture attitudes in a way that simplified statistical analysis (*34*). Integer values from *1* to *5* were assigned to qualitative positions regarding the reliability of each metric (later scaled appropriately for use in the aggregation). Although it was sometimes counterintuitive, *1* always corresponded to high reliability and *5* always represented poor reliability. The experts could also rate the metrics as *0*, reflecting the attitude that the metric could never perform unreliably or have any repercussions for reliability of the overall system, or as not applicable, if they felt that the metric did not apply to the pathway component. A similar scale was used for the importance ratings (*0* corresponded to no importance, *5* corresponded to high importance).

4.4. Aggregation and results

We normalized the experts' ratings according to the MAU specification, and aggregated them as described in *Section 3.4*. The reliability (utility) ratings were scaled from *0* to *1*, and the importance ratings were transformed to proportions, maintaining the requisite of MAU that $\sum_{i=1}^{n} w_i = 1$ for a given set of *n* subordinate attributes on the hierarchy.

The expert's ratings were each aggregated three times to develop various reliability scores. The metric-level ratings were aggregated to develop scores in terms of the concepts for each pathway component, which were then aggregated to determine *adequacy* and *security* scores for each pathway component. These were combined finally to determine similar scores for the overall pathways. The average and standard deviation was taken across all experts to determine the reliability scores for the panel.

The average aggregated reliability scores and their standard deviations are given in Table 1 for both pathways. Our MAU model indicates that the experts perceived Pathway #2 to be more reliable in terms of both *adequacy* and *security*, although the difference is more apparent for security. Pathway #1 received average scores of 0.56 and 0.57 for *adequacy* and *security*, respectively, while Pathway #2 received scores of 0.39 and 0.23.

TABLE 1 Average aggregated reliability scores for Pathway #1 and Pathway #2.

			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
Adequacy	**Aggregated capacity**	Average	0.54	0.51	0.53	0.72	0.37	0.07
		Std Dev	0.18	0.17	0.20	0.21	0.20	0.18
	Aggregated importance	Average	0.56	0.55	0.54	0.56	0.55	0.54
		Std Dev	0.07	0.05	0.07	0.07	0.05	0.07
	Aggregated flexibility	Average	0.61	0.58	0.62	0.66	0.45	0.10
		Std Dev	0.21	0.12	0.15	0.14	0.18	0.18
	Aggregated importance	Average	0.44	0.45	0.46	0.44	0.45	0.46
		Std Dev	0.07	0.05	0.07	0.07	0.05	0.07
	Aggregated adequacy	Average	0.56	0.54	0.58	0.70	0.41	0.08
		Std Dev	0.15	0.12	0.13	0.13	0.15	0.16
	Component weights	Average	0.32	0.36	0.32	0.32	0.36	0.32
		Std Dev	0.04	0.06	0.06	0.04	0.06	0.06
	Pathway adequacy score	Average	0.56			0.39		
		Std Dev	0.07			0.10		
Security	**Aggregated infrastructure vulnerability**	Average	0.57	0.48	0.50	0.35	0.29	0.09
		Std Dev	0.15	0.14	0.08	0.14	0.18	0.16
	Aggregated importance	Average	0.30	0.46	0.47	0.30	0.46	0.47
		Std Dev	0.05	0.06	0.09	0.05	0.06	0.09
	Aggregated consequences	Average	0.63	0.61	0.58	0.33	0.32	0.10
		Std Dev	0.20	0.21	0.19	0.15	0.17	0.17
	Aggregated importance	Average	0.37	0.54	0.53	0.37	0.54	0.53
		Std Dev	0.05	0.06	0.09	0.05	0.06	0.09
	Aggregated energy security	Average	0.63	N/A	N/A	0.16	N/A	N/A
		Std Dev	0.24	N/A	N/A	0.10	N/A	N/A
	Aggregated importance	Average	0.34	N/A	N/A	0.34	N/A	N/A
		Std Dev	0.04	N/A	N/A	0.04	N/A	N/A
	Aggregated security	Average	0.61	0.55	0.55	0.28	0.31	0.09
		Std Dev	0.15	0.14	0.11	0.07	0.13	0.16
	Component weights	Average	0.35	0.33	0.33	0.35	0.33	0.33
		Std Dev	0.04	0.03	0.02	0.04	0.03	0.02
	Pathway security score	Average	0.57			0.23		
		Std Dev	0.12			0.08		

The *adequacy* and *security* scores are compared graphically in Figure 3. We sectioned the scale into thirds and attributed the qualitative descriptions associated with our Likert rating scale (*good*, *moderate*, and *poor*) to each. The standard deviations of the responses are represented by the error bars. Again, we notice the difference between the pathways is more noticeable for *security* than for *adequacy*.

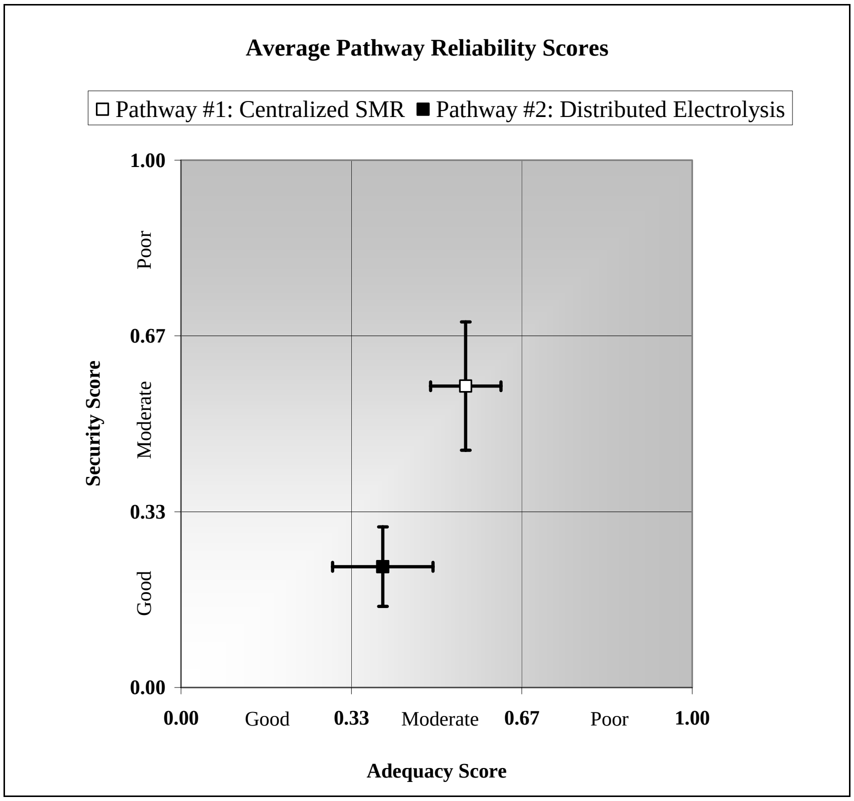

FIGURE 3 Graphical representation of the average aggregated *adequacy* and *security* scores of the two pathways.

The results from this exercise suggest that distributed production and limiting hydrogen transport may improve reliability of hydrogen supply pathways. On average, the experts rated these two components 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 the hydrogen at the 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 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 ripple to 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 more adequate primary energy supply than a reliance on local, renewable energy resources whose availability may rely on favorable weather patterns. But, they agreed that a local stand-alone electricity system greatly improved security of energy supply over the vast LNG network. The global supply chain and national pipeline distribution network is difficult to completely secure, and

LNG supply remains subject to the whims and politics of exporting nations. Additionally, LNG tankers and import/export terminals are incredibly attractive targets for malicious attack due to their visibility and representation, economic value, and the vast potential for damage stemming from the huge concentration of a volatile energy product (*21*).

5. OPPORTUNITIES FOR FUTURE RESEARCH

Again, the results and associated implications presented here are not definitive. They are included to demonstrate the methodology and motivate discussions regarding reliability in hydrogen (and other) energy systems. Certainly they are interesting and may be indicative of perceived reliability in these proposed hydrogen energy systems, but thorough assessments incorporating all stakeholder opinions – and comparing hydrogen to gasoline and other alternative fuels – are needed to guide policy decisions. Several opportunities for future research emerged from this work:

- The 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, and recognize our focused expertise and perspective. Future wisdom and additional contribution will undoubtedly broaden our understanding and assessment of reliability in the energy sector.
- Reliability considerations at the point of end use should be incorporated where appropriate. When comparing between fuels or pathways with different user interfaces (e.g., home refueling), reliability differences at the point of end use are important.
- Ultimately, the method should be applied to compare the reliability of pathways for various energy products. Appropriate attributes should be identified and the method 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.
- 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. ACKNOWLEDGEMENTS

We would like to thank our colleagues at UC Davis: Dr. Daniel Sperling, Dr. Patricia Mokhtarian, Anthony Eggert, and Dr. Christopher Yang for their comments and suggestions throughout; the researchers who volunteered to serve on the expert panel; and the Hydrogen Pathways Program at ITS-Davis and the National Science Foundation's Integrative Graduate Education and Research Traineeship (IGERT) for financial support.

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