Assessing Reliability in Hydrogen Supply Pathways

Prepared for:
National Hydrogen Association Annual Hydrogen Conference 2005
Washington, DC
March 29 – April 1, 2005

April 2005

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1. Introduction

Hydrogen offers potential remedies to several problems created by current energy supply and usage trends, and is gaining a great deal of attention as a possible alternative to existing energy carriers. It can be produced, stored, transported, and used in a number of ways, and derived from several primary energy resources. These characteristics allow hydrogen supply systems to take many different configurations (hereafter referred to as "hydrogen pathways"), which can commingle in a regional supply system to achieve desired characteristics such as reduced environmental impacts, reduced energy imports, or improved reliability in the energy sector.

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 economics and environmental merits of various hydrogen pathways are relatively well understood, and have been studied in some detail (e.g., [1], [2], [3]). But no studies have investigated reliability in hydrogen pathways. This paper describes a new methodology to assess reliability in hydrogen energy systems. It draws from the authors' recent work, which contains further details including strengths and weaknesses of the method, and opportunities for improvement and further research [4].

The methodology described here draws on other energy sectors to define appropriate considerations and assessment techniques for hydrogen pathways. First, we define reliability for hydrogen energy systems and select metrics to value it. Hydrogen pathways are then selected for comparison and described. A panel of experts rates the reliability and importance of three components of each pathway – the primary energy supply system, the hydrogen production process, and the hydrogen transport process – in terms of these metrics. The ratings are then aggregated to determine broad reliability scores that can be compared for different pathways.

An application of the methodology to assess reliability in two distinct hydrogen pathways is also described. One pathway 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 utilized onsite at refueling stations. Eleven hydrogen researchers from the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) served as the expert panel. They rated each pathway in terms of 20 metrics during a three-hour facilitated exercise. The aggregated results suggest that the experts perceived both pathways to have similar levels of adequacy, but the distributed pathway as more secure than the centralized pathway.

To the best knowledge of the authors, the work here represents the first effort to examine hydrogen reliability in depth. As such, it introduces a very broad question, and the methodology developed will undoubtedly benefit from future revision and insight. Hopefully, it will spawn several new research questions that may further our understanding of hydrogen and its relation to other energy systems.

2. Assessing Reliability in Existing Energy Systems

Although reliability has not been evaluated for hydrogen energy systems, it is often assessed in other energy sectors. We investigated methods used to assess reliability in existing energy systems (specifically the electricity, natural gas, and petroleum sectors), and tailored these to form a suitable assessment methodology for hydrogen systems.

Here we provide a brief background about some of these methods. Energy system reliability measures are broadly categorized according two general concepts: *adequacy* and *security*.

2.1. Adequacy

Adequacy is defined by the North American Electric Reliability Council (NERC) 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" [5]. Extrapolating this concept to the energy sector as a whole suggests that adequacy refers to the level of sufficiency within the infrastructure to supply end user energy demands. It considers the ability of systems to supply peak demands under normal operating conditions.

Several metrics exist to assess adequacy in energy systems. They are especially developed in the electricity sector, where adequacy is most explicitly defined. The NERC assesses adequacy in electricity systems by reducing them to three components – resource (i.e., generation), transmission, and fuel supply – and comparing projected capacity to projected demand over a given time period [5]. Planners often use a 50% projection in these probabilistic assessments, indicating a 50% chance that capacity or demand will exceed the projection. But high- or low-growth scenarios are also considered.

Resource adequacy is evaluated in terms of capacity margins – the percentage by which generation capacity exceeds peak demand. Projected resource additions and retirements are weighed against projected demand growth, which is based primarily on economic growth projections. If capacity margins are sufficient, resources are deemed adequate.

Adequacy can be gauged similarly for transmission infrastructure. That is, projected capacity additions are compared against projected demand growth, based on probabilistic projections. Transmission adequacy can also be determined by looking at the number of transmission load relief (TLR) procedures. These re-dispatch generation to maintain security in the system (e.g., prevent overload), and are classified according to severity (0 to 6, 6 being the most severe). Although TLRs are a mechanism used to maintain security in the electric system, trends in their frequency and severity can indicate a relative level of adequacy in the transmission system.

Fuel supply adequacy is more difficult to gauge, as the availability of fuel resources depends on several uncertain parameters. These include environmental regulations, extraction and conversion technologies, geopolitics, and weather patterns.

Adequacy assessments in the electricity sector can be extended to include the probability of future service interruptions. The aggregate system is divided into three “hierarchical levels,” and adequacy is assessed at each one according to a set of reliability indices [6]. Hierarchical Level I (HLI) considers adequacy only in generating facilities. The most common measure of adequacy at HLI is loss of load expectation (LOLE). It captures the number of days when the daily peak load is expected to exceed available generating capacity. A number often used is LOLE=0.1 days/year. The LOLE measure can be extended to include severity, frequency, and duration of expected outages as well. Hierarchical Level II adds transmission to the assessment, while HL III includes transmission and generation. These assessments are more complicated, and less often performed. But indices do exist to measure adequacy on these aggregated levels, either at specific load points or on the system level.

Adequacy can be assessed in the natural gas and petroleum sectors according to general metrics such as production capacity, capacity within the distribution system, and reserve levels. These are analogous to the three components assessed by the NERC. Production capacity (resource adequacy) relates to drilling, processing, and refining capabilities. Capacity within distribution systems (transmission adequacy) includes levels of utilization in pipelines, ocean tankers, and other transport options. Reserve levels are analogous to fuel supply adequacy. Each can be projected over a given time frame and compared to demand projections to determine adequacy in natural gas and petroleum systems.

2.2. Security

The measures (and several others) discussed above indicate the ability of an energy system to supply end user requirements under normal operating conditions. But they tell nothing of system stability in real time, or the likelihood of unscheduled equipment outages and energy supply disruptions. Metrics to evaluate these conditions are covered under the concept of *security*. In the electricity sector, security is defined as “The ability of the electric system to withstand sudden disturbances…or unanticipated loss of system elements.” [5] Like that for adequacy described above, this definition is broadly applicable across energy sectors.

In the electricity sector, security primarily involves maintaining stability of the grid. Normal operating conditions exist when frequency and voltage are within acceptable bounds, no component is overloaded, and no load is involuntarily disconnected [7]. These gauges – frequency, voltage, and component loadings – provide some metrics of security in the electricity sector. When they suggest conditions that deviate from normal, reserves can be deployed to manage security.

Security is the primary focus in maintaining reliability in the natural gas and petroleum sectors. Security concerns increasingly revolve around securing the supply infrastructure (wells, processing facilities, and pipelines) against third party damage, and securing supplies from exporting nations. Disruptions resulting from such indeterminate concerns are difficult to predict, and thus metrics to assess security in these systems are accordingly indefinite. Evaluating security threats to the infrastructure generally requires qualitative assessments from experts. Judging from the history of the infrastructure, its age, location, surrounding environment, and value as a target of malicious attack, experts can estimate the likelihood of a disruption. Some of these assessments amount to little more than speculation, but may be quite accurate in gauging vulnerabilities against accidental damage or natural disasters. Considering malicious intent complicates things, however, as attackers are likely to circumvent mitigation measures and conventional wisdom.

Judging security in terms of energy supplies amounts to evaluating energy independence in a country, or region. Import levels, the geographical concentration of imports, political and social conditions in supplying nations, and the supply routes bringing the energy resource from its origin to destination are all considerations in evaluating security of supply. Storage levels (for example, the Strategic Petroleum Reserve) and the level of excess production capacity existing within the country of concern or on the global market relate a level of security should there be a disruption.

Reliability assessments in the energy sector are increasingly focusing on indefinite security concerns regarding the likelihood of accidental or intentional damage. Consequently, qualitative assessments by a panel of experts are becoming more popular in the industry. Each sector has outlined methodologies for conducting such assessments (e.g., [8], [9], [10], [11]). Typically, a group of industry experts identify vulnerabilities and threats (facing both physical and cyber assets), and offer recommendations to best improve security based on a cost/benefit analysis of mitigation options.

3. Assessing Reliability in Hydrogen Energy Systems

We adapted assessment methods from other energy sectors to develop a distinct methodology that was applied to assess the reliability of two hydrogen pathways. The methodology is qualitative in nature, and relies on ratings from a panel of experts regarding various aspects of reliability along an energy pathway. These ratings combine to form broad reliability scores that are easily comparable across pathways.

The reliability of two hydrogen pathways was assessed by a panel of 11 hydrogen researchers at ITS-Davis as part of a three-hour facilitated exercise. The exercise was limited by time and logistical constraints, and was only intended to test the methodology and provide insight into the reliability of the two pathways. We do not purport the results from this study to be definitive, only demonstrative of reliability concerns and considerations in the hydrogen sector.

The methodology and its trial application are summarized below. For a complete description of the methodology and the exercise, including all of the documentation provided to the expert panel, see [4].

3.1. General Considerations for Expert Panel Assessment Methods

Initial Steps

First, the organization conducting the assessment should establish the scope of the study and identify experts to serve on the panel. The scope includes the objectives of the study, the level of detail desired in the results, and – for hydrogen pathways – considerations such as geography, timeframe (e.g., near term or far in the future), and demand scenarios (e.g., initial niche markets or large-scale usage). These bound and shape the course of the assessment, and influence the composition of the expert panel.

Defining Metrics

Initially, reliability is defined broadly according to the objectives of the study. This definition is then dissolved into a set of metrics that effectively summarizes the elements it captures. These are tangible concepts that can be readily evaluated by the experts, and together value reliability in terms of the broad definition. Care should be taken to select an appropriate set of metrics while balancing real-world constraints such as time, resources, and human cognitive ability.

Developing Importance Ratings

Associated with each metric is an importance rating, which reflects the degree to which the experts perceive the metric to contribute to the reliable operation of the system. The importance ratings weight the reliability ratings of the metrics when they are aggregated. This allows a fair accounting of metrics thought to have varying degrees of impact on the reliability of the system.

Expert Panel Methodology

The expert panel evaluates the reliability and importance of each metric based on rating scales and criteria developed for the assessment. Each pathway is divided into three components – primary energy supply system, production/refining process, and transport of the final energy product. The experts rate the reliability and importance of the metrics for each component.

The methodology and all inputs into the assessment should be clearly described to the panel prior to the rating process. The definition of reliability for the energy systems under consideration and the metrics selected to value it should be clearly defined, as well as the rating scale and criteria used to evaluate them. The process by which the ratings are obtained (e.g., anonymous or not) may vary depending on the composition of the expert panel and the scope of the study, but a discussion of survey methods is beyond the scope of this paper.

Estimating Reliability

Finally, the reliability and importance ratings are aggregated across the metrics and pathway components to develop broad scores which reflect the overall reliability of the pathways consonant with the original definition. Rather than exhaustively examining the ratings for each metric, the broad scores allow a simple comparison of reliability across energy pathways.

Several aggregation techniques could be applied for a given assessment. Two possible techniques are discussed in [4]. One takes a simple weighted average of the reliability and importance ratings, while the other establishes a utility function based on the perceived importance of each metric. Either is an appropriate aggregation method – we present results using the utility function approach.

3.2. Applying the Methodology to Hydrogen Pathways

The initial application primarily intended to test the methodology and provide insight as to how reliability is perceived in hydrogen energy systems. The assessment considered a hypothetical network of hydrogen refueling stations in the Sacramento (CA) area, and the upstream hydrogen production and delivery systems supplying those stations. The expert panel consisted of 11 graduate students, staff, and faculty researching in the hydrogen arena. Reliability was defined for hydrogen systems by adapting definitions from the NERC pertaining to the electricity sector (as cited in [12]). Similar to its definition, we defined reliability in hydrogen systems in terms of adequacy and security. The terms were defined as follows:

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.

We selected 20 metrics to value reliability in terms of the two categories adequacy and security. These were organized under five subcategories captured by the definitions of the two concepts. Adequacy includes capacity and flexibility within the supply infrastructure. Security includes vulnerabilities facing the infrastructure, consequences that might result from a disruption, and energy security. Each subcategory is shown in Figure 1, along with the metrics used to value it. Definitions of all the terms can be found in [4].

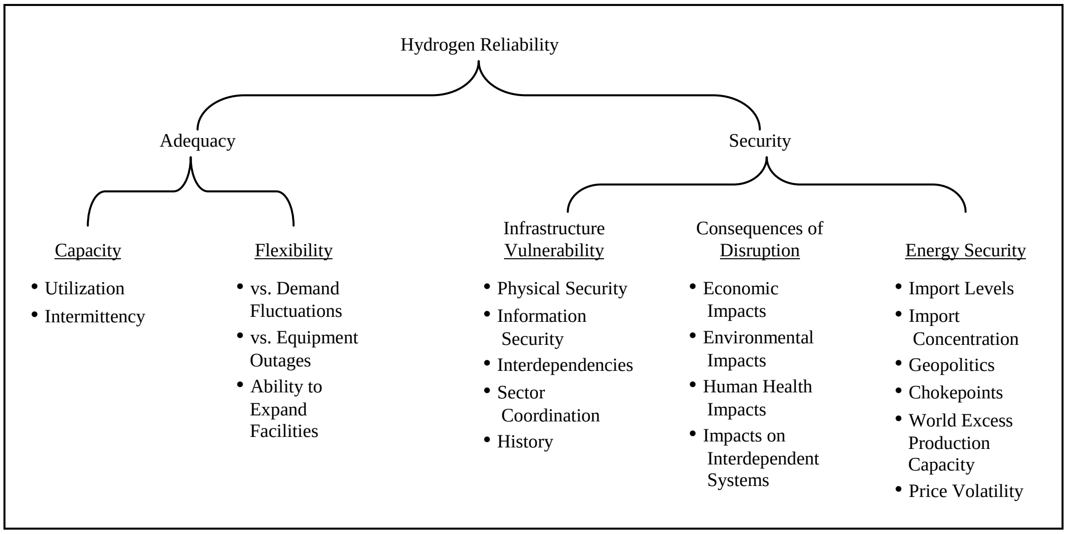


Figure 1. List of metrics used to evaluate hydrogen pathway reliability.

A modified five-point Likert scale including two additional rating options – *0* and *?* – was used for both the reliability ratings and the importance ratings. The scales are depicted in Table 1. The Likert scale associates integer values with qualitative descriptions to simplify statistical analyses [13]. Here, a scale of *1*-*5* was implemented, with *1* corresponding to high reliability and *5* to poor reliability. The rating *0* related the perception that the system was perfectly reliable in terms of the metric (i.e., under no feasible circumstances would the metric jeopardize the reliable operation of the system). A similar *1*-*5* scale was used for the importance ratings, with *1* connoting low importance and *5* representing high importance. The rating *0* implied that the metric carried no importance to the reliability of the overall system. A rating of *?* implied that the expert felt the metric did not apply or did not know how to rate it. In either case, the metric was excluded from the analysis.

Table 1. Scale used to rate reliability and importance of metrics.

	?	**0**	**1**	**2**	**3**	**4**	**5**
Reliability	Unknown, or N/A	Perfect	High	Moderately -high	Moderate	Moderately -poor	Poor
Importance	Unknown, or N/A	None	Low	Moderately -low	Moderate	Moderately -high	High

Rating criteria for the reliability of each metric were provided to the panel for ratings of *0*, *1*, *3*, and *5*. The experts were left to interpolate the criteria for ratings of *2* or *4*. Example criteria are shown in Table 2 for the metric *intermittency*. The criteria were qualitative and somewhat vague in an effort to draw out expert perceptions of reliability in terms of the metrics.

Table 2. Sample rating criteria for the metric *intermittency*.

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

Two contrasting, hypothetical pathways were assessed in the exercise (see Figure 2). *Pathway #1* represents large, centralized operations, while *Pathway #2* represents a distributed infrastructure. In *Pathway #1,* hydrogen is produced from imported liquefied natural gas (LNG) at a large, central steam reformation facility, and is transported via pipeline to its points of end use. *Pathway #2* electrolyzes water onsite at refueling stations using electricity produced independently from the grid from locally available, renewable resources. The two pathways were devised as supposed opposite ends of the gamut of hydrogen pathway designs.

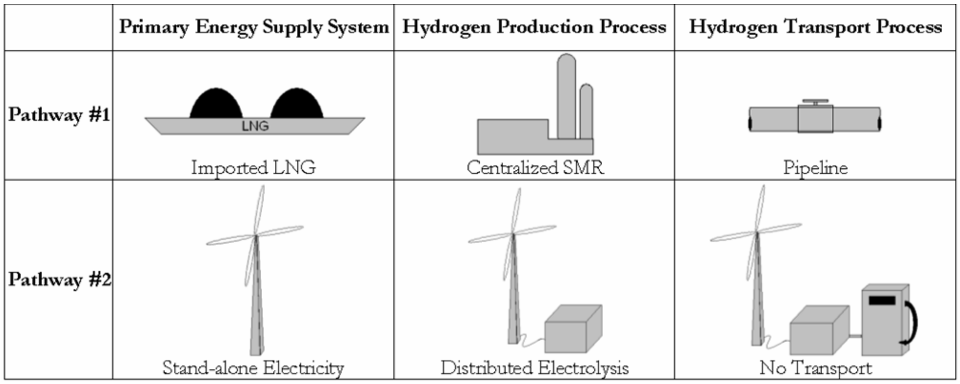
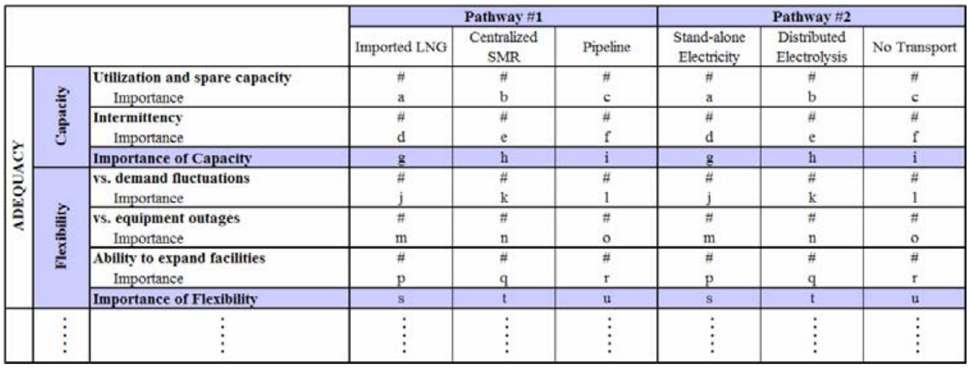


Figure 2. Hydrogen pathways considered in this study.

The expert panel rated the importance of each metric in terms of the three pathway components, and the reliability of each (see Table 3). The importance ratings were ascertained first because they were intended to be uniform across pathways in terms of generic pathway components (i.e., primary energy supply system, hydrogen production process, and hydrogen transport process). Thus, they were assessed prior to introducing the two pathway options to prevent consideration of specific pathways from influencing them.

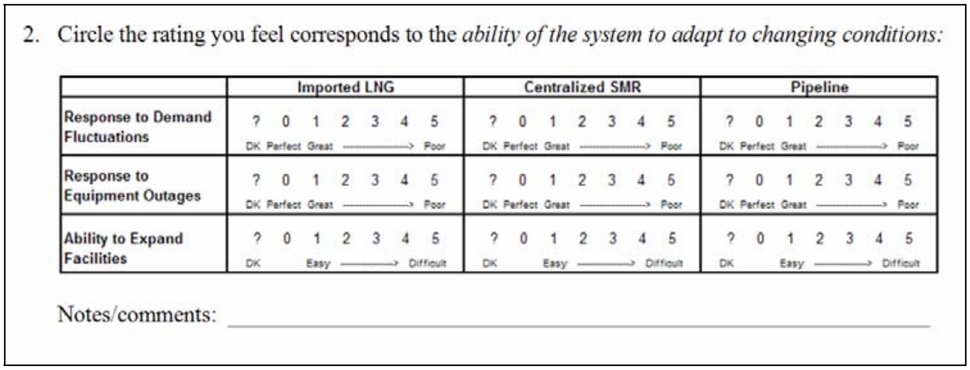
The experts rated importance in terms of two relationships. First, they rated the importance of each metric to its subcategory. Next, they rated the importance of the subcategory to overall reliability. Both were done for each pathway component, but were identical across pathways. The dichotomous scheme allowed less important metrics to be included in subcategories of high importance to overall reliability, without artificially lowering the perceived importance of that subcategory.

Table 3. Sample ratings for importance and reliability of the *adequacy* metrics for the two pathways. Importance ratings are uniform across pathways, while reliability ratings vary.



			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
ADEQUACY	Capacity	**Utilization and spare capacity**	#	#	#	#	#	#
		Importance	a	b	c	a	b	c
		Intermittency	#	#	#	#	#	#
		Importance	d	e	f	d	e	f
		Importance of Capacity	g	h	i	g	h	i
	Flexibility	**vs. demand fluctuations**	#	#	#	#	#	#
		Importance	j	k	l	j	k	l
		vs. equipment outages	#	#	#	#	#	#
		Importance	m	n	o	m	n	o
		Ability to expand facilities	#	#	#	#	#	#
		Importance	p	q	r	p	q	r
		Importance of Flexibility	s	t	u	s	t	u
	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

After obtaining the importance ratings, the pathways were described to the experts, and they were asked to rate reliability in terms of the metrics for both pathways. A sample question from the reliability rating portion of the survey is given in Figure 3.



2. Circle the rating you feel corresponds to the *ability of the system to adapt to changing conditions:*

	Imported LNG	Centralized SMR	Pipeline
Response to Demand Fluctuations	? 0 1 2 3 4 5 DK Perfect Great ——> Poor	? 0 1 2 3 4 5 DK Perfect Great ——> Poor	? 0 1 2 3 4 5 DK Perfect Great ——> Poor
Response to Equipment Outages	? 0 1 2 3 4 5 DK Perfect Great ——> Poor	? 0 1 2 3 4 5 DK Perfect Great ——> Poor	? 0 1 2 3 4 5 DK Perfect Great ——> Poor
Ability to Expand Facilities	? 0 1 2 3 4 5 DK Easy ——> Difficult	? 0 1 2 3 4 5 DK Easy ——> Difficult	? 0 1 2 3 4 5 DK Easy ——> Difficult

Notes/comments: ____________________

Figure 3. Sample question to ascertain reliability in terms of metrics under the subcategory *flexibility*.

After collecting the experts' ratings, they were aggregated to develop reliability scores in terms of the broad concepts of adequacy and security. We used the *scaled utility* model because the panel felt that the importance and reliability ratings both influenced reliability equally. To maintain the scale used in the reliability ratings, the utility model was scaled by the product of the highest reliability rating (five) and the number of components aggregated, according to the following equation:

$$Scaled\ Utility = \frac{\sum_{i=1}^{n}\left(R_i \times I_i\right)}{5n},$$

where: R_i= Reliability rating of metric i,

I_i = Importance rating of metric i,

n = Number of metrics included in the aggregation.

Each expert's ratings were aggregated three times to develop various reliability scores. The average and standard deviation of these scores was then taken across all experts to determine the final reliability scores. The aggregation steps are illustrated in Figure 4 as they were used to determine pathway adequacy scores. Similar steps were used to determine security scores. In *Step 1*, metrics are aggregated within their subcategory for each pathway component. The two subcategory scores are aggregated in *Step 2* to determine adequacy scores for each pathway component. The adequacy scores reflect the influence of each pathway component on overall adequacy, but are not used in subsequent aggregations. Finally, the six subcategory scores found in *Step 1* all are aggregated to determine one adequacy score for the entire pathway. The scores from *Step 1* – rather than those found in *Step 2* – were used to determine pathway adequacy because the importance ratings varied across pathway components. Had the importance ratings been fixed across pathway components, each component would be weighted equally, and an average of the three scores from *Step 2* could be used to determine pathway adequacy.

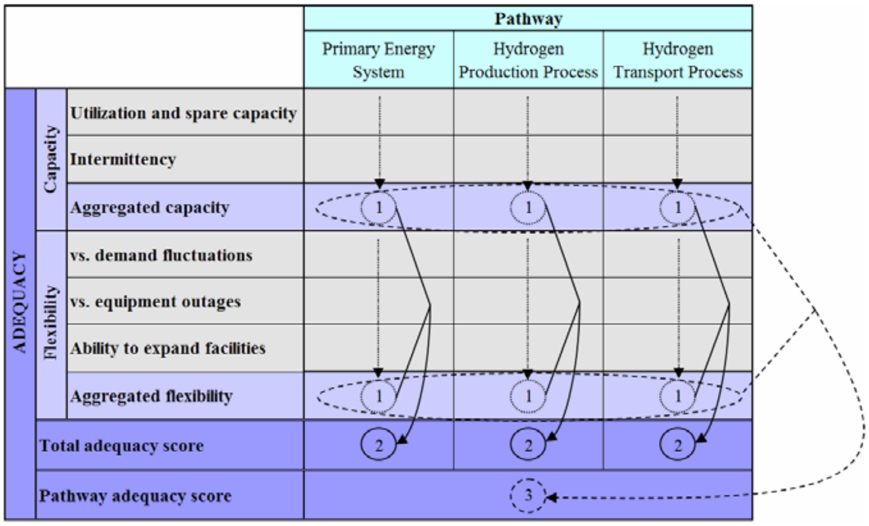


Figure 4. Three steps used to aggregate the reliability scores.

4. Results

The aggregated reliability scores are given in Table 4 for both pathways. The experts perceived both pathways to have similar reliability in terms of adequacy. Pathway #1 received an average adequacy score of 1.88, while Pathway #2 received an average score of 1.54. But Pathway #1 was judged to be much less reliable than Pathway #2 in terms of security. The two pathways received security scores of 1.74 and 0.86, respectively.

Under the *scaled utility* model, the maximum possible aggregated score will not be equal to the maximum reliability rating (*5*) unless all importance ratings included in the aggregation are the maximum. This is illustrated in Table 5, where the average reliability scores are juxtaposed with the average maximum possible reliability scores based on the importance ratings (although the importance ratings were the same across pathways, some of the maximum possible scores vary between pathways because experts sometimes felt that metrics applied to one pathway but not the other). Also shown is each score's percentage of the average maximum possible reliability score. Judged in terms of the maximum possible score (many of the scores are about 60% of the maximum possible), the pathways appear less reliable than they do on a scale with a maximum score of *5* (where a reliability score of 2.0 only corresponds to 40% of the assumed maximum score).

Table 4. Average aggregated reliability scores for the two pathways.

			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
Adequacy	**Aggregated capacity**	Average	2.10	2.45	2.49	2.80	1.62	0.43
		Std. Dev	0.42	1.14	0.90	0.71	0.86	0.87
	Aggregated importance	Average	4.36	4.55	4.18	4.36	4.55	4.18
		Std. Dev	0.67	0.69	1.25	0.67	0.69	1.25
	Aggregated flexibility	Average	2.41	2.37	2.38	2.37	1.86	0.75
		Std. Dev	0.52	0.65	0.95	0.83	0.76	0.79
	Aggregated importance	Average	3.64	3.82	3.55	3.64	3.82	3.55
		Std. Dev	1.12	0.75	1.21	1.12	0.75	1.21
	Aggregated adequacy	Average	1.79	2.06	1.91	2.10	1.50	0.40
		Std. Dev	0.52	0.87	0.83	0.71	0.80	0.62
	Pathway adequacy score	Average	1.88			1.54		
		Std. Dev	0.67			0.73		
Security	**Aggregated infrastructure vulnerability**	Average	2.24	1.90	1.76	1.31	1.17	0.64
		Std. Dev	0.61	0.46	0.34	0.45	0.65	0.73
	Aggregated importance	Average	3.64	3.55	3.73	3.64	3.55	3.73
		Std. Dev	0.92	0.52	0.65	0.92	0.52	0.65
	Aggregated consequences	Average	2.63	2.17	1.93	1.39	1.24	0.61
		Std. Dev	0.96	1.06	0.98	0.68	0.83	0.81
	Aggregated importance	Average	4.36	4.18	4.18	4.36	4.18	4.18
		Std. Dev	0.92	0.87	0.98	0.92	0.87	0.98
	Aggregated energy security	Average	2.72	N/A	N/A	0.74	N/A	N/A
		Std. Dev	0.69	N/A	N/A	0.52	N/A	N/A
	Aggregated importance	Average	4.00	N/A	N/A	4.00	N/A	N/A
		Std. Dev	0.77	N/A	N/A	0.77	N/A	N/A
	Aggregated security	Average	2.01	1.60	1.49	0.91	0.98	0.50
		Std. Dev	0.74	0.65	0.51	0.24	0.49	0.63
	Pathway security score	Average	1.74			0.86		
		Std. Dev	0.57			0.21		

Table 5. Average aggregated reliability scores, and maximum possible aggregated scores.

			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
Adequacy	**Aggregated capacity**	Average Rating	2.10	2.45	2.49	2.80	1.62	0.43
		Ave. Max Possible	3.59	4.27	4.36	3.64	4.27	4.38
		% of Max	58%	57%	57%	77%	38%	10%
	Aggregated flexibility	Average Rating	2.41	2.37	2.38	2.37	1.86	0.75
		Ave. Max Possible	3.65	3.89	3.68	3.61	3.89	3.39
		% of Max	66%	61%	65%	66%	48%	22%
	Aggregated adequacy	Average Rating	1.79	2.06	1.91	2.10	1.50	0.40
		Ave. Max Possible	2.91	3.46	3.22	2.90	3.46	3.14
		% of Max	62%	60%	59%	72%	43%	13%
	Pathway adequacy score	Average Rating	1.88			1.54		
		Ave. Max Possible	3.20			3.19		
		% of Max	59%			48%		
Security	**Aggregated infrastructure vulnerability**	Average Rating	2.24	1.90	1.76	1.31	1.17	0.64
		Ave. Max Possible	3.52	3.50	3.19	3.68	3.56	3.11
		% of Max	64%	54%	55%	35%	33%	21%
	Aggregated consequences	Average Rating	2.63	2.17	1.93	1.39	1.24	0.61
		Ave. Max Possible	4.05	3.52	3.16	4.00	3.58	3.54
		% of Max	65%	62%	61%	35%	35%	17%
	Aggregated energy security	Average Rating	2.72	N/A	N/A	0.74	N/A	N/A
		Ave. Max Possible	3.97	N/A	N/A	4.00	N/A	N/A
		% of Max	68%	N/A	N/A	19%	N/A	N/A
	Aggregated security	Average Rating	2.01	1.60	1.49	0.91	0.98	0.50
		Ave. Max Possible	3.08	2.72	2.52	3.16	2.76	2.72
		% of Max	65%	59%	59%	29%	36%	18%
	Pathway security score	Average Rating	1.74			0.86		
		Ave. Max Possible	2.80			2.94		
		% of Max	62%			29%		

The adequacy and security scores are compared graphically in Figure 5. Included on the graph are the maximum possible adequacy and security scores, depicted by the vertical and horizontal lines, respectively (the horizontal line represents the average of the maximum possible security scores for the two pathways). The standard deviation of the responses is represented by the error bars emanating from each point. It can be seen that there was general consensus among the panel members regarding the reliability and importance of the security metrics for Pathway #2, indicated by the relatively small standard deviation for the aggregated pathway security score.

Graphically, the relative difference between the perceived reliability of the two pathways is easy to grasp. We sectioned the scale into thirds and attributed qualitative descriptions associated with the Likert scale (good, moderate, and poor) to each. Under the scheme the adequacy of both pathways appears to be *moderately-good*. Security appears *good* for Pathway #2 and *moderately-good* for Pathway #1. But recall that the worst possible reliability scores for the pathways are not *5*. Consequently, these descriptors based on the five-point scale (included to relate to the rating scale) might be somewhat misleading.

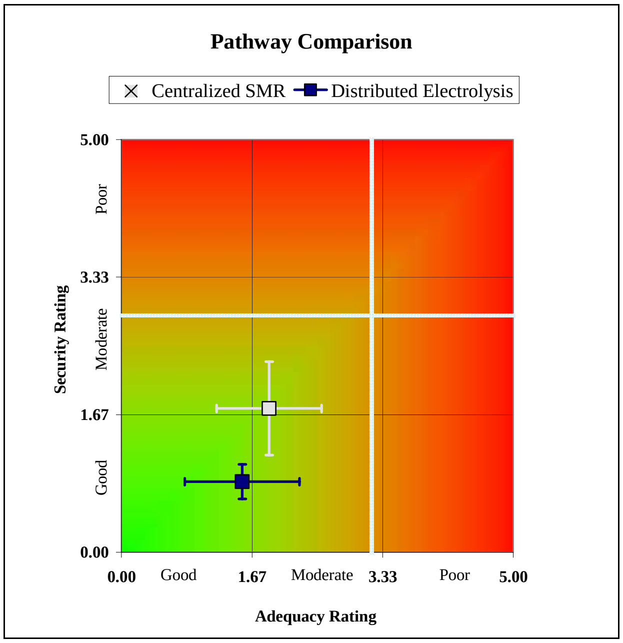


Figure 5. Average aggregated reliability scores. The vertical and horizontal lines represent the maximum possible adequacy and security scores, respectively.

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 (i.e., centralized production and pipeline transport) for every metric except *history*. The experts felt that distributed production of hydrogen and onsite utilization at refueling stations offers added adequacy by providing flexibility to adapt to volume and geographical fluctuations in demand. They perceived the small scale of the process and its use of stable energy feedstocks to add to the security of Pathway #2. These isolated processes can be easily monitored against threats, and the onsite facilities can be easily hardened against accidental or intentional third party damage. Also, the small scale of the process and the lack of volatile or toxic agents 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 station, as well.

Discerning which primary energy supply system offers better reliability is more difficult. The panel felt that the established, global LNG infrastructure provided more adequate primary energy supply than a reliance on intermittent, renewable energy resources whose availability depends 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 impossible 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 [14].

These and other considerations influencing the panel's ratings are described in Table 6. The figure exemplifies some issues and concerns surrounding reliability in Pathway #1, but is by no means exhaustive. Further research from the perspective of all stakeholders is needed, and will undoubtedly generate greater wisdom on the subject.

Table 6. Sample considerations influencing reliability ratings for Pathway #1.

Category	Sub-category	Metric	PATHWAY #1		
			Imported LNG	**Centralized SMR**	**Pipeline**
ADEQUACY	**Capacity**	**Utilization and spare capacity**	• Demand projections • Expected capacity expansion • Capacity and utilization in: – Import terminals – Global LNG tanker fleet – Domestic natural gas pipelines	• Demand projections • Expected capacity expansion • Capacity and utilization of production facility	• Demand projections • Expected capacity expansion • Capacity and utilization along pipeline network
		Intermittency	• Unlikely to exist in production, processing, or transport processes • Intermittency due to lack of capacity, security disruption, or equipment outage covered by other metrics (not considered here)	• Probably not applicable here • Intermittency due to lack of capacity, security disruption, or equipment outage covered by other metrics	• Probably not applicable here • Intermittency due to lack of capacity, security disruption, or equipment outage covered by other metrics
	Flexibility	**vs. demand fluctuations**	• Imports can be adjusted with demand • Storage at LNG terminals provides some flexibility against fluctuations • Storage within pipelines (if not fully utilized) can provide flexibility against fluctuations as well	• Production facilities are important to safeguard against demand fluctuations, but do so by increasing output, which is akin to the metric *utilization* covered above	• Pipeline pressure can be increased (to the extent allowed by codes) to allow pipeline to store excess hydrogen, which can be extracted during periods of high demand – But limited geographically
		vs. equipment outages	• Long lead time before LNG tanker could arrive to relieve an outage • Storage at LNG terminals provides some flexibility against outages	• Amount of lost production • Amount of hydrogen stored onsite • Size, location, and accessibility of nearest plant(s)	• Pipeline storage can relieve outage up- or downstream of pipeline, within geographical constraints • Availability of trucks to supply hydrogen to pipeline loadpoints
		Ability to expand facilities	• Import terminal expensive, and difficult to site and permit • Pipeline expansions growing more expensive and difficult to site – Rights-of-way difficult to obtain	• Difficult to site • Capitally intense • Long payback times	• Capitally intense • Long payback times • Difficult to site • Couple with existing rights-of-way? • Utilize existing pipelines?

SECURITY	**Infrastructure Vulnerability**	**Physical Security**	• Begins at import terminal - everything upstream covered by energy security • Amount of energy stored at facility • Pipeline infrastructure difficult to harden against third party damage • Import terminals and pipelines attractive targets for sabatoge	• Existence of volatile compounds • Accessibility of facility • Ability to disrupt operations • Level of security present at facility: – Fences – Security guards and cameras – Key cards and access codes	• Accessibility of facilities: – Location of pipeline – Pipeline buried? • Relatively simple to disrupt operation • Often relatively little security
		Information Security	• All cyber systems are vulnerable • Complicated, expansive networks associated with global trade • Dispersed assets might be located in countries with poor security	• All cyber systems are vulnerable • Operations highly automated • Centralized information assets leave entire operation vulnerable to single incident	• All cyber systems are vulnerable • Operations highly automated • Centralized information assets leave operation of vast pipeline network vulnerable to single incident
		Interdependencies	• Global infrastructure exacerbates interdependencies with: – Transportation infrastructure – Water infrastructure – Energy infrastructures – Information systems – Telecommunications – Banking and finance	• Especially interdependent with upstrean natural gas infrastructure • Other interdependencies similar to LNG infrsatructure	• Especially interdependent with upstream systems • Also dependent on: – Information systems – Telecommunications – Banking and finance – Transportation infrastructure
		Sector Coordination	• According to the National Petroleum Council, biggest threat facing the industry are threats to information systems. It claims the best protection is effective information sharing [11] • Existence and effectiveness of mechanisms and policies to facilitate information sharing	• To early to tell what sector coordination will look like in developed hydrogen economy	• To early to tell what sector coordination will look like in developed hydrogen economy
		History	• LNG industry claims no major fires or explosions over the past 45 years [15] • Pipelines have a more extensive history of damage stemming from accidental or intentional actions	• Do not know. There is a history here, but details unknown	• Do not know. There is a history here, but details unknown
	Consequences of Disruption	**Economic Impacts**	• LNG makes up a small, but increasing portion of natural gas supply – As percentage increases, so will economic consequences • Effects likely worse on regional scale than ntional one	• Consequences depend on level of demand supplied by facility • Worst effects in region directly served by facility • Similar to effects seen recently from disruptions to petroluem refineries?	• Consequences depend on level of demand supplied by pipeline • Worst effects in region directly supplied by pipeline • Similar to effects seen recently from disruptions to petroluem pipelines?
		Environmental Impacts	• Volatile compound, but relatively clean fuel • Extent of emissions and effects on marine and terrestrial habitats depends on amount of energy stored	• Volatile compounds, but relatively clean fuel • Extent of emissions and effects on terrestrial habitats depends on size of operation and amount of energy present	• Hydrogen can be volatile, but is a clean fuel • Emissions and effects on terrestrial habitats minimal
		Human Health Impacts	• Amount of energy present • Existence of toxic substances • Number of employees and level of exposure to volatile compounds • Proximity to populated areas	• Similar to effects from imported LNG	• Amount of energy present • Proximity to populated areas
		Impacts on Interdependent Systems	• Several systems highly dependent on natural gas supply infrastructure • LNG percentage of natural gas supply • Dependence of other systems on natural gas supply • LNG dependence on other systems	• Significant effects on downstream systems • Less significant impacts on upstream systems	• Significant effects on downstream systems • Less significant impacts on upstream systems
	Energy Security	**Import Levels**	• Essentially 100% imports • Some LNG could come from Alaska, however	• Not applicable	• Not applicable
		Import Concentration	• Only a handful of possible suppliers, so import concentration always high • Trinidad and Tobago supplied about 75% of U.S. LNG imports in 2004 • 7 countries together supplied 99.8% of imports in 2004	• Not applicable	• Not applicable
		Geopolitics	• Trinidad and Tobago has parliamentary democracy, and ranked "partially free" by Freedom House – Economy depends on natural gas and petroleum exports • Other suppliers pose greater threats	• Not applicable	• Not applicable
		Chokepoints	• (Potential) imports to the western U.S. from Trinidad and Tobago must traverse the Panama Canal • Imports from Middle East go through several dangerous chokepoints	• Not applicable	• Not applicable
		World Excess Production Capacity	• Reserves, production capacity and liquefaction capacity within exporting country • Excess capacity within global LNG tanker fleet	• Not applicable	• Not applicable
		Price Volatility	• Imported LNG prices fluctuate, but not as wildly as domestic prices • LNG could mitigate price fluctuations to some extent	• Not applicable	• Not applicable

It deserves to be noted again that these results and the associated implications are not definitive. They are presented here to demonstrate the methodology and motivate discussions regarding reliability in hydrogen (and other) energy systems. While they are certainly interesting and indicative of perceived reliability in these proposed systems, their significance should not be overstated, nor should the primary motivation or imperfect conditions of this application be obfuscated.

5. Conclusions

This paper intends to promote the fair consideration of reliability issues in hydrogen discourse. By introducing a methodology to assess reliability in hydrogen energy systems, and describing a preliminary application of the method to two hypothetical pathways, it works effectively towards that goal. But much work remains before we fully understand the issues. Further research and greater insight from a variety of stakeholders is necessary. Also, while the discussion here was limited to comparing reliability between hydrogen pathways, the methodology itself is not so constrained. It could (and should) be applied to other energy systems (for example, the gasoline supply system or future bio-fuels systems) to compare with hydrogen from a reliability perspective as well.

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