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A Methodology to Assess the Reliability of Hydrogen-based Transportation Energy Systems

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A Methodology to Assess the Reliability of Hydrogen-based Transportation Energy Systems

By

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ABSTRACT

This paper introduces a method to assess the reliability of hydrogen supply systems for transportation applications. It relies on a panel of experts to rate the reliability and importance of various metrics as they pertain to selected hydrogen systems. These are aggregated to develop broad reliability scores to be compared across systems. A trial application of the methodology is presented, where a group of hydrogen researchers at the Institute of Transportation Studies at the University of California, Davis comprise the expert panel. Two hydrogen pathways supplying a hypothetical network of refueling stations in Sacramento were compared. The first uses centralized steam reforming of imported liquefied natural gas and pipeline distribution of hydrogen. The second electrolyzes water onsite from electricity produced independent of the grid, and no hydrogen transport is required. The panel determined the second pathway to be more reliable, primarily due to the lack of imports, the distributed nature of the system, and the lack of hydrogen transport. This preliminary application only intends to demonstrate how the method is applied, however, and the results presented here should not be taken as definite.

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INTRODUCTION

A transition to hydrogen as a primary transportation fuel offers potential societal benefits over the current paradigm. Some advocates claim that hydrogen would provide a more reliable energy system. But reliability benefits associated with a switch to hydrogen have not been studied. This research introduces a method to assess the reliability of hydrogen supply systems for transportation applications. The discussion here is limited to comparing reliability between hydrogen supply systems (“hydrogen pathways”), but the methodology itself is not so constrained. It could be applied to compare the reliability of other energy systems to hydrogen as well.

Motivation and Background

Existing energy infrastructures tend toward massive, highly integrated systems which can catastrophically fail with any link. The electric grid delivers energy from large, isolated power plants via a limited number of high-voltage transmission lines connected at a few critical nodes. Massive blackouts, such as the one that hit the East Coast on August 14, 2003, exemplify the fragility of the electric grid. During the outage, 61,800 MW of power serving 50 million people were lost, resulting in costs estimated between $4 billion and $10 billion (ELCON, 2004).

Petroleum systems are similarly centralized, with pipelines reliant on a few pumping stations delivering products from remote, aging refineries. The consequences of the centralized delivery system were felt nationwide when gasoline prices soared to record highs in the spring of 2004. Compounding reliability concerns is the concentration of petroleum resources in the tumultuous Middle East, and several “chokepoints” along delivery routes from the region.

As energy systems apparently grow more vulnerable, the prevailing business climate is such that reliable energy supply is valued more than ever. A new business environment characterized by automated operations, just-in-time logistics, and rapid changes has emerged with the coming of information technologies. Business today is utterly dependent on the numerous systems that support it, and cannot function without their reliable operation. Consequences stemming from infrastructure disruptions have grown more severe, and often no feasible manual backup processes exist (NPC, 2001).

Energy reliability has gained increased focus in political and social realms as well. Issues dominating the news and political debate include volatile gasoline prices and developments in the Middle East. The tragic events of September 11, 2001 prompted the creation of a new Cabinet position, overseeing the Department of Homeland Security. One of the Department’s five major directives is the protection of “critical infrastructure,” including energy systems (NPC, 2001, p.1). Since the attacks, the U.S. has gone to war and has seen anti-American sentiment rise. More attacks have been threatened, and energy systems are perceived as high-value targets. The result is increased public awareness and demand for reliable energy systems.

Many suggest that a switch to hydrogen as an energy carrier can relieve the environmental and reliability problems posed by current energy systems. Since hydrogen can be produced from any number of resources – including renewable electricity – and utilized essentially pollution-free in a fuel cell, it certainly presents the potential to serve as an environmentally sustainable fuel. But, hydrogen can also be produced and used in ways that would significantly increase emissions over their current levels. Several studies have considered hydrogen supply scenarios from the environmental slant, and confirmed these findings (e.g., NRC [2004], Weiss *et al.* [2000], GM *et al.* [2002]). But none have investigated in detail claims that hydrogen affords a more reliable system. A systematic assessment of hydrogen reliability is needed to assess these claims and to properly account for reliability in the potential development of a widespread hydrogen infrastructure.

This study introduces a methodology to assess the reliability of hydrogen energy systems. First, reliability is defined for hydrogen energy systems and metrics are selected to value it. Next, hydrogen pathways are selected and described. Three constituent components of the pathways are assessed by a panel of experts – the primary energy supply system, the hydrogen production process, and the hydrogen transport process. They rate the reliability and importance of each pathway component in terms of the metrics. Finally, their ratings are aggregated to determine broad reliability scores that can be compared across pathways.

The intent of this work is to provide a tool to guide decision makers to properly consider and design reliability into hydrogen systems for the public good. Selecting and promoting an individual pathway as the most reliable is not the goal. Indeed, results from an application of the methodology to two unrelated pathways are given, but they should not be considered definitive. The motivation of this preliminary application was to test the methodology and demonstrate its use, not to reach definite conclusions about the most reliable hydrogen pathways. Nevertheless, the results are interesting, and indeed telling of hydrogen reliability.

To the best knowledge of this author, the work here represents the first effort to examine hydrogen reliability in depth. It is that – a first attempt – and will undoubtedly benefit from future revision and the insights of others. But the hope is that the methodology will promote the fair consideration of reliability between hydrogen pathways, and potentially between energy sectors. We are in the unique position of creating an entirely new energy system where energy security, environmental awareness, safety, and infrastructure reliability can be ingrained in the system from the onset. At a time when these concepts have never been more highly valued in society, this opportunity should not be overlooked.

BACKGROUND

Statistical Approaches to Reliability Assessments

Reliability assessments are well developed for systems applications in the field of statistics. They generally define reliability in terms of the likelihood of a failure, and determine the reliability of a system based on the known reliabilities of its elements. Reliability assessments are usually quantitative, and results take the form of a probability, but when data is lacking they can take on a qualitative form.

Quantitative Reliability Assessments

Traditional reliability assessments use probabilistic techniques to establish the likelihood that a system will be found in some state of non-operation within a given time period. In that context, reliability is defined as "the probability that an item (component, equipment, or system) will operate without failure for a stated period of time under specified conditions" (Andrews and Moss, 2002, p. 3). Reliability is measured as a *probability* – that is, a value between 0 and 1 – over a given time period. So output from a probabilistic reliability assessment might read: "the 5000-hour reliability of *item x* is 0.95," meaning that *item x* has a 95% chance of operating without failure over the course of 5000 hours.

From this definition, the reliability of a simple system can be determined quantitatively.[1] *Reliability networks* represent the dependencies between components in a system. The simplest networks are *series networks* and *parallel networks*. A series network is a system that cannot tolerate component failure. There is no redundancy in the system, and if one component fails, the entire system fails. A parallel network includes redundancy, and all parallel components must fail for the system to fail (Andrews and Moss, 2002, pp.167-169). The two configurations are depicted in Figure 1. If the reliability of the two components is known, reliability of the system can be determined. Let r_1 be the reliability of *component 1* (i.e., probability that *component 1* works over a given time frame), and r_2 be the reliability of *component 2* over the same period. Then reliability can be determined quantitatively for the series network as follows:

---

[1] Leemis (1995) describes five ways to calculate reliability quantitatively, but that discussion is beyond the scope here.

$$Reliability_{series} = Prob[1\ works\ AND\ 2\ works]$$

$$= r_1 r_2\ .$$

Similarly for the parallel network:

$$Reliability_{parallel} = Prob[1\ works\ OR\ 2\ works]$$

$$= r_1 + r_2 - r_1 r_2\ .$$

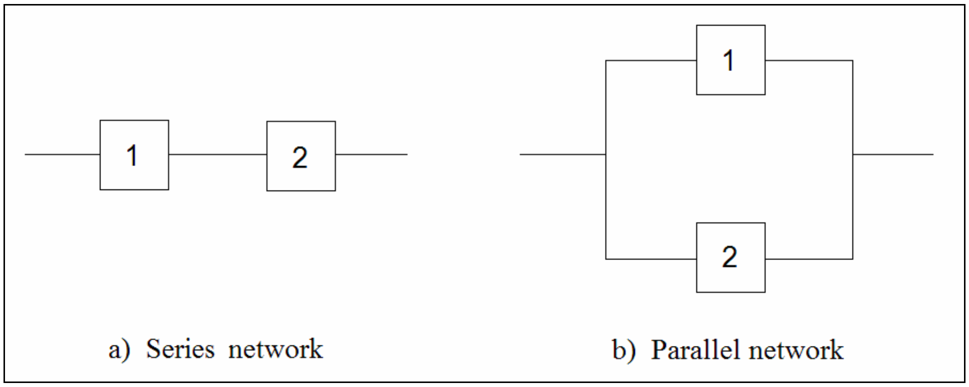

Figure 1. Reliability networks: a) series network, b) parallel network.

Qualitative Reliability Assessments

When probabilities cannot be quantified due to a lack of data, reliability assessments can take a qualitative approach, using expert opinion to establish elemental reliabilities. Contadini (2002) suggests several ways to collect expert opinions, including traditional surveys and the Delphi process. The Delphi process is used to build consensus among a panel of experts while avoiding the drawbacks of face-to-face interaction. Contadini reviews the literature, and summarizes four key features that characterize the process:

- Anonymity – allows more diverse responses
- Controlled feedback – multiple rounds of surveying are conducted, to build the experts' knowledge of the material and the process
- Interaction – meant to promote open discussion and aid in building consensus
- Statistical aggregation – group member responses are weighted, combined, and analyzed

When relying on expert opinion, proper selection of the expert panel is crucial. Ideally, the panel should include members from all slants on a particular topic. But in some cases, a more accurate analysis may result if representatives of some schools are actually excluded, if they are thought to be biased (Bedford and Cooke, 2001, p.192). The results of any qualitative study will be sensitive to the selection of the panel, and the level of expertise possessed by panel members. One method to minimize error is to include a weighting factor to account for the confidence an expert has in his or her responses. A more rigorous method is performance based weighting (Cooke, 1991). Experts are asked a series of questions whose responses are known to the analyst, but not the expert. Based on their responses to these questions, a weighting factor is computed to calibrate their responses to the survey questions.

Reliability in the Energy Sector

In *Brittle Power,* Amory and Hunter Lovins describe the "brittleness" of existing energy systems, and explain how to best design energy systems to be resilient against failures. According to the Lovins, energy systems in the U.S. are made up of complex components that are prone to failure, difficult to diagnose and fix, and interact with interdependent components in complicated ways. They also tend to be inflexible, and are unable to easily adapt to changes in demand or primary energy supply. These characteristics make energy systems incredibly vulnerable to potentially catastrophic failures. The Lovins argue that failures are inevitable, but resilient energy systems can minimize the damage by rapidly isolating and repairing disruptions. They claim that resilience can best be achieved in an energy system with numerous small modules which each have a low individual cost of failure.

The National Research Council (NRC) published a report following September 11th that includes many of the same concepts as *Brittle Power* (NRC, 2002). The report recognizes vulnerabilities in energy systems and describes ways in which science and engineering can work to protect against malicious attacks. It recommends actions that can be undertaken to reduce vulnerability in energy systems, and identifies further research areas to reduce risks. A key recommendation throughout is to increase cooperation with the national security and defense communities, who have dealt with such threats for many years.

These references apply broadly throughout the energy sector, but most of the literature reviewed focused on specific sectors. Below, background and literature reviews specific to the electricity, natural gas, and petroleum sectors are provided. Each considers the existing state of the sector and looks at how reliability is defined, valued, and assessed.

Electricity Sector

Reliability in the electricity sector is defined in terms of two components – adequacy and security. Adequacy considers average supply and demand over the long term, while security is concerned with dynamic operating conditions in the immediate term. The North American Electricity Reliability Council (NERC) defines the terms as follows:

> Reliability – The degree to which the performance of the elements of the system results in power being delivered to consumers within accepted standards and in the amount desired (as cited in: Kirby and Hirst, 2002, p.9).
>
> Adequacy – 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 and system elements (NERC, 2002, p.7).
>
> Security – The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements (NERC, 2002, p.7).

Reliability – Adequacy

The NERC produces annual assessments of the adequacy of the North American electricity system (NERC, 2002). They reduce the electricity system into its resource, transmission, and fuel supply components, and determine adequacy by comparing the projected capacity of each component to projected average demands over ten years.

Resource (i.e., generation) adequacy considers the ability of projected electricity generation facilities to supply future demand. Growth of peak demand is projected over the time frame of the study, primarily based on the expected future economic growth of the region.[2] Generation supply additions are also predicted over the time period. From these projections, the capacity margin (the percentage by which resource capacity exceeds peak demand) is predicted. If capacity margins are within acceptable levels, resources are deemed adequate.

Transmission adequacy considers the ability of the transmission system to handle new load patterns resulting from increased electricity transfers and demand. Similar to resource adequacy, demand levels are projected over the time frame of the study and compared to projected capacity expansions.[3] Another gauge of transmission adequacy is the number and severity of transmission line relief (TLR) procedures. They are classified according to severity, on a scale of 0 to 6 (6 being the most severe), and indicate a degree of instability in the electric grid. Although the procedures are used to maintain security in the system, studying their trends can shed light on its adequacy as well.

Fuel supply adequacy depends on several factors for each resource. The availability of fuel resources can be projected in a similar fashion as generation and transmission were above, but it also depends on characteristics far more uncertain. For example, the availability of fossil resources is influenced by geopolitics, environmental regulations, extraction technologies, and weather. The availability of renewable resources similarly depends on future policy measures, conversion technologies, and weather patterns. End

---

[2] These forecasts are probabilistic in nature, and planners usually use a 50% projection, which indicates that there is a 50% chance that demand will exceed the projection, and a 50% chance that demand will fall below the projection.

[3] New capacity includes line construction, voltage upgrades to existing lines, utilization of empty tower positions, additional capacitor banks or transformers, and upgrading limiting circuitry at substations.

use technologies and consumer behavior affect all fuel resources, and are impossible to predict.

Applied Probabilistic Methods

The percentage reserve method and others described above can be extended to include the probability of future service interruptions. Probabilistic methods allow the stochastic nature of system behavior, customer demands and component failures to be included in analyses. Understanding the likelihood of service interruptions also allows a balance to be reached between economics and reliability, according to a cost/benefit framework.

Probabilistic assessments consider adequacy of the electricity system on three "hierarchical levels." Debnath and Goel (1995) describe the assessments and outline reliability indices at each level. Hierarchical Level I (HLI) evaluates the adequacy of generation facilities, ignoring that of the transmission and distribution systems.[4] Multiple indices can be used to evaluate reliability at HLI. Loss of Load Expectation (LOLE) captures the average number of days in which the daily peak load is expected to exceed available generating capacity. It is determined from the daily peak loads and the probability that a generating unit will be found in some state of incapacity. A benchmark adequacy index used by many utilities is LOLE = 0.1 days/year. LOLE is the most common index, but it does not translate to customer losses and cannot be used in a cost/benefit analysis. Loss of Energy Expectation (LOEE), and Frequency and Duration (F&D) extend LOLE and can be used in a cost/benefit framework, but are less common.

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[4] Akin to *resource adequacy* as defined by the NERC (2002).

LOEE, defined as the ratio of energy supplied to energy demanded, includes the severity of an interruption. F&D identifies the expected frequency and duration of deficiencies.

Hierarchical Level II (HLII) considers the ability of generation and transmission together to supply electricity at bulk supply points (Billinton, 1969). HLII assessments are usually performed using analytical techniques or Monte Carlo simulation. Reliability indices can be considered either at load points or on the system level. Load point indices are used to identify weak points in the system, and include the probability, frequency and duration of outages, unsupplied energy, and curtailed loads. System indices are used to describe the adequacy of the complete system, without regard to specific load points. Some system indices are system unsupplied energy, bulk power supply disturbances (occurrences/year), bulk power interruption index (MW/MW yr), and system-minutes (annual unavailability if all interruptions occurred at peak loads).

Hierarchical Level III (HLIII) considers the adequacy of electricity generation, transmission, and distribution facilities altogether. This presents an enormous task, and is rarely conducted. As in HLII, indices are determined at load points and on the system level. Load point indices include: expected rate of failure, the average duration of failure, and the average annual outage time. System performance indices are: system average interruption frequency index, customer average interruption frequency index, system average interruption duration index, customer average interruption duration index, energy not supplied index, average service availability index, and average service unavailability index (Billinton and Allan, 1984).

Reliability – Security

Security assessments look at the ability of the system to prevent disruptions of service to end users in real time. Important to assessing security is defining normal (i.e., non-disrupted) operating conditions. Normal operation of the electricity grid can be described as the condition when frequency and voltage are within acceptable bounds, no component is overloaded, and no load is involuntarily disconnected (Alvarado and Oren, 2002, p. 3). Conditions that deviate from these suggest a security failure.

Providing security in the electricity sector is complicated by the passive nature of the transmission network and the need to continuously balance generation and load in real time (Kirby and Hirst, 2002). These force readiness for the next contingency, rather than current operating conditions, to dominate the design and operation of the grid. They also require instantaneous actions, which imposes a dependency on automatic computing, communication, and control actions.

Security Planning

Securing the bulk electric supply system requires preparing for contingencies. A single contingency is almost always planned for, regardless of cost. To protect against a single contingency, the "N-1 criterion" must be satisfied. It requires systems to have sufficient reserve capacity to withstand the loss of any (i.e., the largest) generator or transmission line in the system. Maintaining N-1 security requires having sufficient spinning reserves to meet demand following the loss of generation, and sufficient supplemental reserves to then restore spinning reserve margins.[5] These reserves must be located so that power may be delivered under any possible outage condition. Systems may design for N-2 or N-3 security (i.e., multiple contingencies), but only when it is determined cost effective to do so (Alvarado and Oren, 2002, pp.6-7).

Increasingly, security planning is also taking on the role of protecting the system against deliberate attacks. Leading this effort are federal agencies with the intent of establishing guidelines for industry participants to follow. The Office of Energy Assurance within the U.S. Department of Energy (U.S. DOE) has spearheaded this effort with the development of the *Vulnerability and Risk Analysis Program.* This program aims to develop and validate vulnerability assessment methodologies in response to increased concern about the security of the nation's critical infrastructure. Upon its completion, the *Program* will outline assessment methodologies for the electric, natural gas, and petroleum sectors. Methods for the electricity sector exist, but are still under development for the natural gas and petroleum sectors.

The *Program* uses a three-phase approach to assess the vulnerability of industry assets in the electricity sector (U.S. DOE, 2002). First is the *pre-assessment*, where the scope and objective of the assessment are defined. It involves the collaboration of individuals from all sectors of the company to define the concept of criticality, rank assets according the criticality definition, and determine the consequence of disruption or loss of each asset. Next is the *assessment*, which addresses ten items:

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[5] "Spinning reserves are generators that can instantaneously increase their output when a decrease in frequency signals that load is exceeding generation" (Alvarado and Oren, 2002, p.7).

1. *Network architecture.* Evaluate existing security plans and identify concerns with the system architecture or operating procedures.
2. *Threat environment.* Characterize threats, trends in threats, and mechanisms by which threats can exploit vulnerabilities.
3. *Penetration testing.* Identify vulnerabilities in information systems, and test to determine whether access can be gained.
4. *Physical security.* Evaluate existing or planned physical security systems.
5. *Physical asset analysis.* Examine physical assets for vulnerabilities.
6. *Operations security.* Identify and protect information pertaining to sensitive activities.
7. *Policies and procedures.* Review policies and procedures, and identify areas for improvement.
8. *Impact analysis.* Determine the consequences of exploitation of critical facilities or information systems on markets and/or physical operations.
9. *Infrastructure interdependencies.* Examine the interdependencies and vulnerabilities of infrastructures supporting critical facility functions.
10. *Risk characterization.* Provide a framework to prioritize investment and implementation recommendations.

The final phase is the *post-assessment,* where recommendations from the *assessment* are prioritized based on an evaluation of the costs and benefits of each, and an action plan is developed. Lessons learned and best practices are captured here, as well.

Similarly, the NERC has proposed a four-tiered model to guard against physical and cyber threats (NERC, 2001). The four tiers are *avoidance*, *assurance*, *detection*, and *recovery*. *Avoidance* is the most cost effective means of action. It aims to prevent the exploitation of threats by promoting awareness and sharing information and data through an Electricity Sector Information Sharing and Analysis Center (ES-ISAC). *Assurance* promotes reliability through the regular evaluation of physical and cyber security measures. *Detection* focuses on monitoring, identifying, reporting, and analyzing operational, physical, and cyber threats or incidents. *Recovery* encourages timely investigation of incidents and rapid recovery and restoration of services.

Governance and Oversight

Governance and oversight are fundamental to the notion of security in a deregulated electricity market, where reliability decisions have shifted from vertically-integrated utilities to a system operator. In the past, large utilities controlled generation, transmission, and distribution operations, and could make reliability-based decisions relatively easily. But in the deregulated environment, assets are distributed among several more industry players, and reliability is now under the control of an independent system operator (ISO). Kirby and Hirst (2002, p.10) offer six questions to guide reliability decisions in a deregulated environment:

- What risks to take?
- When to take those risks?
- How much money to spend on risk mitigation?

- Who pays for reliability?
- Who is exposed to any remaining risks?
- Who decides on these matters?

Managing Security

Managing security in the electricity system is mainly a real-time effort by operators to manage transience in the system. Transmission operators have two basic ways to ensure reliability – by deploying reserves (Kirby and Hirst, 2002), or controlling commerce (Alvarado and Oren, 2002). Security in the electricity sector is currently managed primarily through the deployment of reserves. Reserves insure against the sudden loss of a generator or transmission line, and include additional generation and transmission, or load that is willing to curtail. Most regional reliability councils set contingency reserve requirements equal to the largest single contingency within the region (N-1 criterion), and require at least half to be spinning (Kirby and Hirst, 2002).

Transmission operators can also ensure reliability through the control of commerce, by redistributing generation away from the typical pattern of the free market. Generators can indicate a price at which they are willing to increase or decrease production, creating a market for contingency reserves. This is attractive in a deregulated environment, and might push reliability to be increasingly managed through the control of commerce.

Summary

Reliability in the electricity sector encompasses two concepts – adequacy and security. Adequacy refers to the sufficiency of system throughput to supply long-term, average demands. Security refers to the ability of the system to withstand disruption under dynamic conditions. Factors influencing the adequacy of the system are primary energy resource availability, and generation and transmission capacities. Sufficiency of capacity can be measured deterministically in terms of reserve margins, or probabilistically in terms of expected outages.

Although security predominately involves real-time management of system operations, it has recently taken on a long-term planning approach as well, to secure assets against vulnerabilities. Vulnerability assessments and mitigation plans can identify threats and vulnerable assets early, and prevent future disruptions. Another concept important to security in the electricity sector is that of governance and oversight. Increased competition from industry deregulation has reduced the incentive for independent reliability assurance measures in the industry. Thus, the role of an independent authority to assure reliability has grown significantly. This body must be independent and fair in its directives. Two mechanisms exist to manage security in the electric grid. Most common is the deployment of reserves. Mandatory reserve margins are set so that the loss of any generation or transmission facility (or sometimes set of facilities) will not cause a disruption of service. The other mechanism is to ensure reliability through market-based principles. One example would be the creation of a reserve market, where reserves could be brought online or taken off, according to real-time demands.

Natural Gas Sector

Unlike in the literature pertaining to the electricity sector, no recurring definition of reliability was found in the natural gas sector. Perhaps the most concise definition was found in the Infrastructure Reliability Program of the DOE. It suggests that reliability efforts in the natural gas sector focus on securing the physical infrastructure, and are less concerned with the concept of adequacy (U.S. DOE and NETL, 2002, pp.3-4):

> Ensure Reliability – Allowing operators to prevent damage or disruption, to detect and diagnose leaks and failures more quickly, and to enhance the flexibility and responsiveness of the system in response to losses in capacity

Another important factor weighing on reliability in the natural gas sector is cost. Price fluctuations strongly influence natural gas reliability considerations. Indeed, the Energy Information Administration (EIA) has said that a key challenge facing the natural gas industry over time is "moderating the recurrence and severity of 'boom and bust' cycles while meeting increasing demand at reasonable prices" (EIA, 2001a, p.20).

Natural Gas Supply

Recent trends in the natural gas industry have seen significant demand increases and price volatility, resulting in projections of future shortages. Exacerbating bleak projections is a cyclic behavior commonly visible with commodities, and beginning to manifest itself with natural gas. The trend sees a cycle of surpluses and shortages, and low and high prices. These considerations have prompted calls for reviving and expanding the liquefied natural gas (LNG) infrastructure in the U.S., which has been essentially dead since the early 1980s.

Recent Trends

The recent price spikes can be partially attributed to the increase in the construction of natural-gas-fired power plants and cogeneration that has significantly increased natural gas demand. The expansion was initially obscured by abnormally warm winters in 1997-1998 and 1998-1999, but in the two very cold winters that followed, demand skyrocketed. Prices spiked in the winter of 1999-2000, and remained high through the beginning of April 2000, the beginning of storage refill season. High prices encouraged operators to delay injecting gas into storage, and by November, storage was at a 20-year low. When the cold winter hit, demand soared and prices spiked. On the coldest days in December of 2000, utilization reached 90–100% in some areas, and prices exceeded $10 per million Btu at the Henry Hub (compared to the average price for the entire year, which was $2.40 per million Btu) (EIA, 2001b).

These price fluctuations might indicate that natural gas is entering a trend of cyclic pricing behavior. Such trends are typical in commodity markets, but until recently, have not affected the natural gas sector. The cycles follow periods of overinvestment or underinvestment in production, and might develop as follows. A surge in demand during a cold spell results in a price spike due to the inelasticity of supply. Sustained high prices encourage producers to invest in new production. Peak demands fall during subsequent warm winters, causing a surplus of supply and prices to fall. Sustained low prices discourage investments in new production. When a cold season hits, production lags demand causing a price spike, and the process repeats (EIA, 2001b).

Future Projections

The EIA developed a model projecting natural gas supplies in the U.S. through 2025 (EIA, 2001b). The model considers six scenarios, including cases where restrictions to natural gas exploration in the Rocky Mountains and the Outer Continental Shelf (OCS) are eased, and where carbon dioxide (CO_2) emissions are limited. The reference case for the model uses projections from the *Annual Energy Outlook 2002,* and assumes no policy changes. Table 1 shows the results for the reference case and the limited CO_2 emissions cases. All models predict an increasing reliance on imports over levels today (about 16% in 2003), especially the limited CO_2 emissions cases.[6] The model also predicts higher prices and greater price volatility in the CO_2 emissions limit cases. Similar effects as seen in the CO_2 emissions limit models might be expected with a burgeoning hydrogen economy, as both add marginal natural gas demand.[7]

The reference case is based on models the EIA uses in their *Annual Energy Outlook* to generate future projections of energy markets. Their most recent projections, in the *Annual Energy Outlook 2004 (AEO2004),* extend from 2002 to 2025 (EIA, 2004f). They project an increase in U.S. natural gas demand from 22.8 trillion cubic feet (tcf) in 2002 to 31.4 tcf in 2025. But domestic production is only expected to grow from 19.1 tcf in

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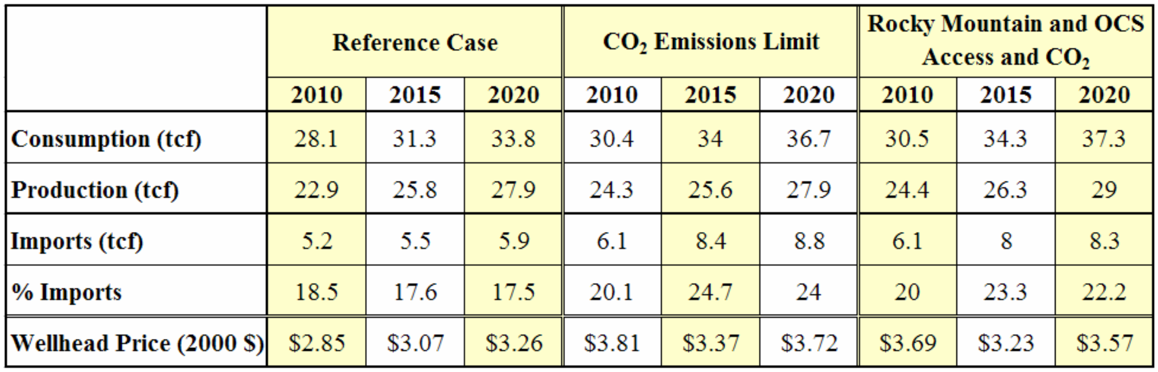
[6] Although not shown here, supply and demand both increased in the Rocky Mountain and OCS access cases, but absolute imports were about the same as the reference case

[7] Policies limiting CO_2 emissions increase natural gas demands because some coal-fired power plants that emit large amounts of CO_2 would likely be replaced with natural gas-fired electricity generation.

2002 to 24.1 tcf in 2025. They conclude that "growth in U.S. natural gas supplies will be dependent on unconventional domestic production, natural gas from Alaska, and LNG" (EIA, 2004f, p.8).

Table 1. Natural gas supply projections through 2025 (adapted from EIA, 2001b, pp.22-23).



	Reference Case			CO_2 Emissions Limit			Rocky Mountain and OCS Access and CO_2		
	2010	2015	2020	2010	2015	2020	2010	2015	2020
Consumption (tcf)	28.1	31.3	33.8	30.4	34	36.7	30.5	34.3	37.3
Production (tcf)	22.9	25.8	27.9	24.3	25.6	27.9	24.4	26.3	29
Imports (tcf)	5.2	5.5	5.9	6.1	8.4	8.8	6.1	8	8.3
% Imports	18.5	17.6	17.5	20.1	24.7	24	20	23.3	22.2
Wellhead Price (2000 $)	$2.85	$3.07	$3.26	$3.81	$3.37	$3.72	$3.69	$3.23	$3.57

Liquefied Natural Gas (LNG)

LNG is projected to become a larger source of natural gas supply in the U.S. as domestic supplies are expected to lag and the availability of Canadian imports is projected to decline (see Figure 2). Increasing LNG import levels carries interesting implications for reliability in the natural gas sector. They could have a positive effect by leveling costs and supplying demands that would otherwise be met with production from higher cost sources (EIA, 2001b, p.37). With sufficient infrastructure, seasonal price spikes could be moderated by increasing LNG imports. Similarly, during periods of low demand, LNG imports could be curtailed to push prices up. But reliance on imported energy supplies creates a dependence on foreign suppliers, thus detracting from reliability. Natural gas reserves are concentrated in a few regions of the world. Ten countries control 77% of global natural gas reserves, and the top three over 55% (see Table 2). Conceivably, as world natural gas demand grows and countries rely more on LNG imports, a natural gas cartel could form that could control global trade with monopolistic power, similar to the Organization of Petroleum Exporting Countries (OPEC) (EIA, 2001b, p.29).

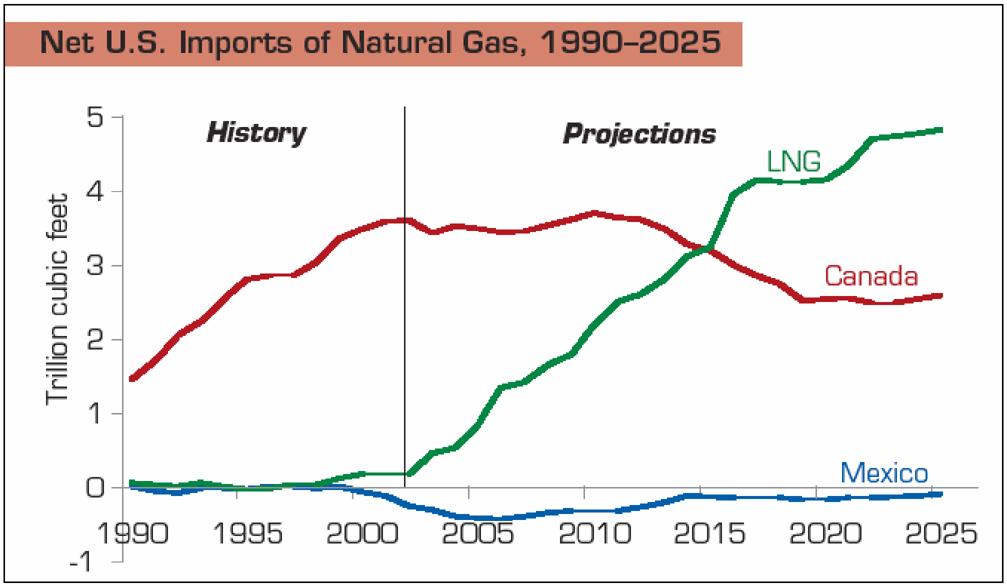


Figure 2. Net U.S. imports of natural gas, 1990-2025 (EIA, 2003, from *AEO2004* reference case).

Table 2 lists global reserves by country and current (darkly shaded) and potential (lightly shaded) exporters (EIA, 2003, p.5). It can be seen that current and potential export capacity resides predominantly in countries with somewhat unstable political and/or social situations. This is similar to current conditions in the petroleum sector, and introduces geopolitical threats into the reliability of natural gas supply.[8]

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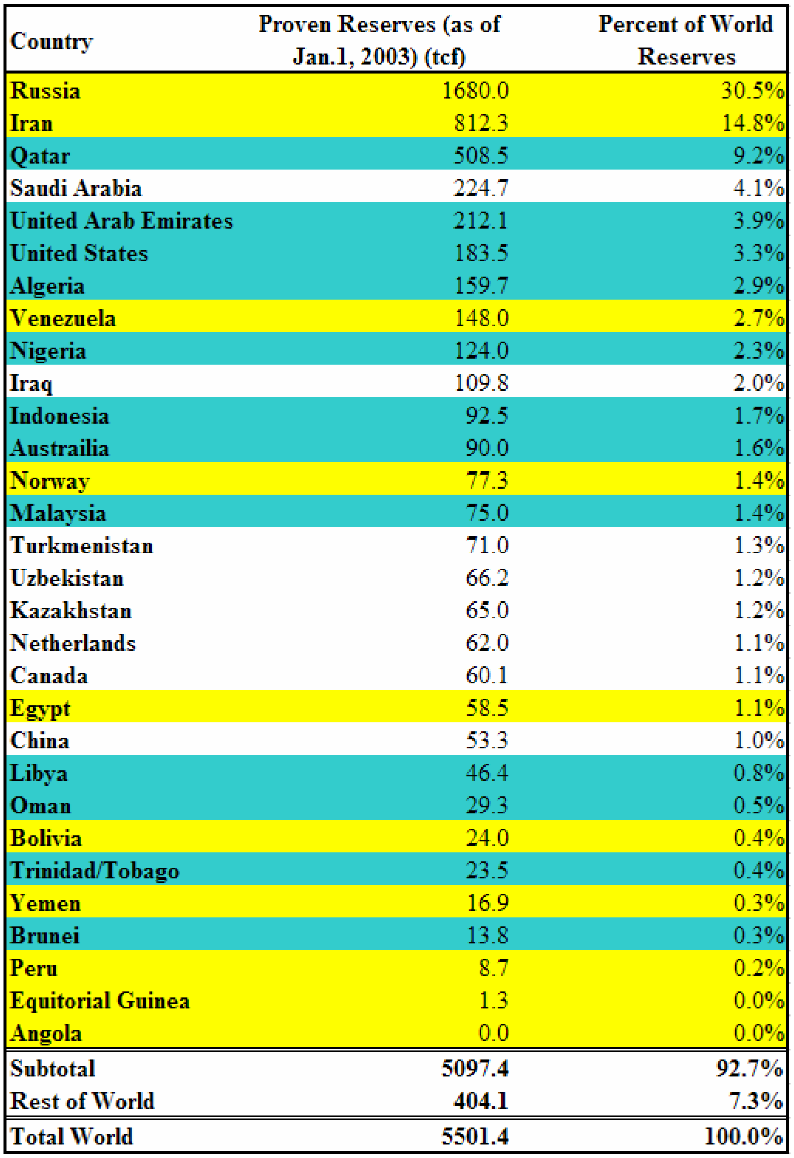
[8] Geopolitics is discussed in greater depth in the petroleum section of the literature review.

Table 2. Natural gas reserves by selected country. Current LNG exporters are darkly shaded, potential LNG exporters are lightly shaded (adapted from: EIA, 2003, p.5).



Country	Proven Reserves (as of Jan.1, 2003) (tcf)	Percent of World Reserves
Russia	1680.0	30.5%
Iran	812.3	14.8%
Qatar	508.5	9.2%
Saudi Arabia	224.7	4.1%
United Arab Emirates	212.1	3.9%
United States	183.5	3.3%
Algeria	159.7	2.9%
Venezuela	148.0	2.7%
Nigeria	124.0	2.3%
Iraq	109.8	2.0%
Indonesia	92.5	1.7%
Austrailia	90.0	1.6%
Norway	77.3	1.4%
Malaysia	75.0	1.4%
Turkmenistan	71.0	1.3%
Uzbekistan	66.2	1.2%
Kazakhstan	65.0	1.2%
Netherlands	62.0	1.1%
Canada	60.1	1.1%
Egypt	58.5	1.1%
China	53.3	1.0%
Libya	46.4	0.8%
Oman	29.3	0.5%
Bolivia	24.0	0.4%
Trinidad/Tobago	23.5	0.4%
Yemen	16.9	0.3%
Brunei	13.8	0.3%
Peru	8.7	0.2%
Equitorial Guinea	1.3	0.0%
Angola	0.0	0.0%
Subtotal	**5097.4**	**92.7%**
Rest of World	**404.1**	**7.3%**
Total World	**5501.4**	**100.0%**

Infrastructure Reliability

The National Petroleum Council (NPC) addresses issues of natural gas infrastructure security in their report, *Securing Oil and Natural Gas Infrastructures in the New Economy* (NPC, 2001). Part of the report investigates physical vulnerabilities facing the natural gas infrastructure. Figure 3 outlines the natural gas infrastructure generally, and presents the Council's vulnerabilities ratings for some physical assets. The ratings are based on the following scale (NPC, 2001, p.33):

> Low – Key assets that if damaged could cause disruptions with local impacts of short duration.
>
> Medium – Key assets that if damaged could cause disruptions that would have regional impacts. These disruptions would last long enough to cause end users hardship, economic loss, and possible loss of human life.
>
> High – Key assets that if damaged could cause major disruptions that would have regional and possibly national or international impacts, and of sufficient duration to cause death and end users major hardship and economic loss.

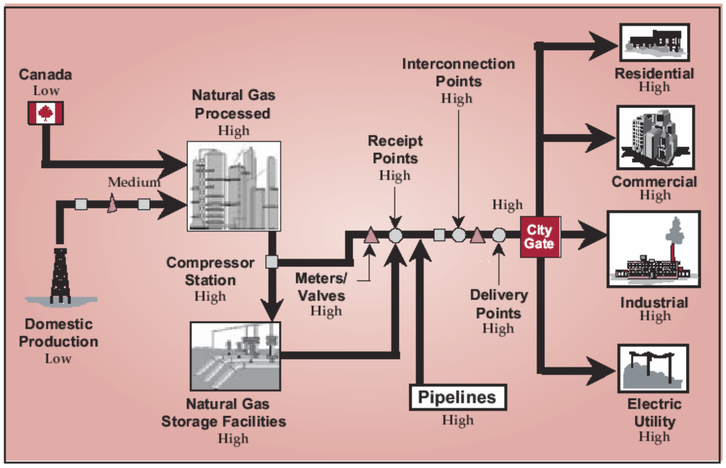


Figure 3. The National Petroleum Council's assessment of physical vulnerabilities facing natural gas infrastructure (NPC, 2001, p.34).

Pipelines

The DOE and the National Energy Technology Laboratory (NETL) sponsored two industry-based workshops focused on security concerns facing natural gas pipeline networks. The first workshop identified security concerns and technological solutions (SCNG, 2000). Predominant concerns included reducing the cost and incidence of damage to underground pipelines,[9] and expanding and improving the flexibility of pipeline networks. Technological solutions were posed to address these concerns, such as developing better monitoring capabilities and integrity assessments, improving pipeline and storage systems, developing cost-effective construction techniques, and developing the ability to detect underground facilities and provide real-time proximity warnings. The other workshop focused on securing the natural gas infrastructure against malicious attacks (U.S. DOE and NETL, 2002). The large, diffuse, and remote nature of the infrastructure makes it quite vulnerable to attack. While much of the network is somewhat protected underground, several portions are not. Those that are underground can be easily located from warning markers. Few technologies exist to detect intrusions or evaluate, inspect, and respond to pipeline problems. Automated control systems are also vulnerable, lacking secure technologies or industry standards to direct information and communication protocols. The group concluded that few options exist to prevent physical attacks in the near term, but with increased coordination, effective steps can be taken to better secure the infrastructure.

The level of utilization in the pipeline network conveys the degree to which end user demands can be met, and the extent of consequences that might stem from a disruption (EIA, 1998, p.9). Utilization can be determined in a number of ways. One common measure is *average-day utilization*, which is determined by dividing the average daily throughput (annual flow between states divided by the number of days in the year) by the estimated capacity in the system. An obvious shortcoming in this measure is that it tells

---

[9] More than half of all subsurface pipeline damage is caused accidentally by third parties, usually construction crews (SCNG, 2000, p.5).

nothing of availability during peak demand periods. The use of monthly, weekly, or daily throughput data helps circumvent this limitation. If several measures are developed – for example, peak-day, high month, low month, average month, and average summer (i.e., off-peak) – one can gauge variability throughout the system.

LNG

The implications of widespread LNG infrastructure are not well known. But it is thought that the high capital costs and fuel concentrations associated with LNG infrastructure make it an attractive target to attack. Natural disasters, especially earthquakes, are significant threats as well. In the case of an LNG spill, a potentially very serious situation could ensue. If LNG pools on water and is ignited, the resulting fire would burn uncontained until all of the gas was consumed. Experimental spills of 10,000 gallons resulted in cylindrical fires 50 feet wide and 250 feet high. This is quite intimidating considering that an LNG tanker may carry up to 33 million gallons (Havens, 2003).

Interdependencies

The natural gas sector is interdependent with several other infrastructures, and vulnerable to disruptions in them. Five types of failure can occur between interdependent systems (NPC, 2001, p.30):

- Cascading failures – failure in one infrastructure leads to failure in another
- Escalating failures – duration of outage in one infrastructure increases due to a failure in another

- Common mode failures – one incident impacts multiple infrastructures
- Marketplace failures – e-commerce links multiple infrastructures in the same market
- Compounding failures – multiple independent incidents lead to additional failures

Figure 4 illustrates some of the many infrastructure interdependencies with natural gas. A disruption in any of the eight other infrastructure systems shown in the ovals could have consequences for the natural gas system described in the boxes. For example, if a disruption occurred in the water supply system, the natural gas system would lose its ability to control emissions, and production and cooling processes would be inhibited.

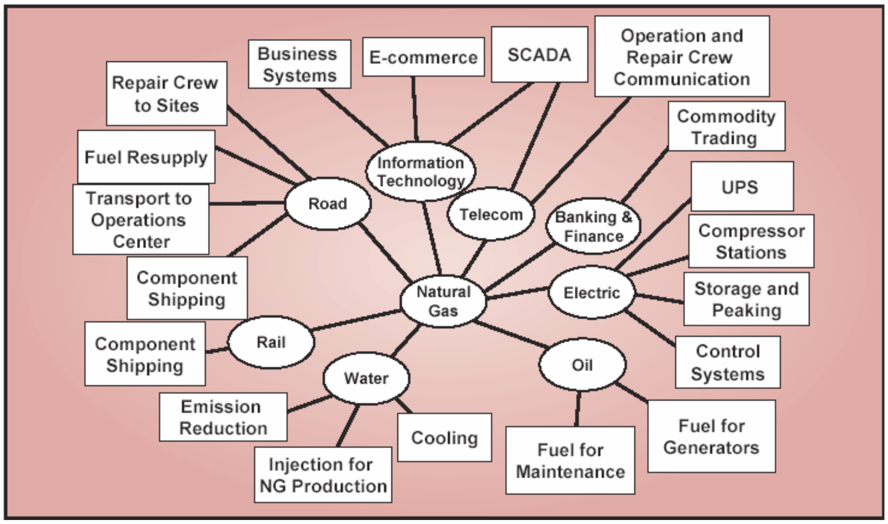


Figure 4. Natural gas sector interdependencies (NPC, 2001, p. 29).

Summary

Unlike the electricity sector, no set definition of reliability was found in literature specific to the natural gas sector. Nevertheless, reliability efforts throughout the sector revolve around common concerns: securing sufficient supplies, securing the infrastructure (especially pipelines), and moderating prices. The U.S. and much of the developed world will likely grow increasingly dependent on imported LNG in the mid-term. This prospect exposes natural gas supplies to threats and vulnerabilities on the global scale,[10] but may also enhance reliability by mitigating prices. Another major concern for reliability in the natural gas sector is securing widespread pipeline networks from accidental and malicious attacks. Such a task is daunting, and its success may require technological solutions which do not yet exist.

Petroleum Sector

Reliability concerns in the petroleum sector center around broad issues such as national and international security and economic prosperity. The differences from the other sectors reviewed stem from the global nature of petroleum supply. Petroleum importers depend on global suppliers to feed their demand and maintain their economy. An interruption in production from any major suppler has consequences that can ripple through the global market, and have damaging effects on national and global economies. Growing dependence in developed nations on petroleum links national security with petroleum supply security. Dwindling petroleum reserves and lagging extraction rates in those same countries exacerbate the problems, and lead to conflicts which can threaten international security.

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[10] A more detailed discussion involving reliability concerns associated with global trade follows in the section covering the petroleum sector.

In recent years, risks facing the sector have changed substantially. The transformation is due in large part to changing business practices, brought by increasing globalization and the influx of information technology. Traditionally, reliability efforts focused on protecting assets from human error and natural disasters. But in this new business environment, the focus has shifted to securing foreign supply sources and guarding against cyber attacks. The post-September 11th atmosphere has invigorated efforts to secure the physical infrastructure as well, but now with a focus on malicious attacks, rather than accidents and natural disasters.

Reliability Perspectives from the Petroleum Industry

The NPC report *Securing the Oil and Natural Gas Infrastructures in the New Economy* details the petroleum industry's perspective on reliability in the petroleum sector. Its recommendations intend to protect companies from financial loss, which somewhat conflicts with our efforts to develop a hydrogen reliability assessment which places society as a whole as the stakeholder. Nevertheless, the issues addressed carry over to the end user and provide insight for our study.

The New Business Environment

The assimilation of information technologies and telecommunications in the petroleum sector has dramatically altered the way the industry conducts business. The business environment today is characterized by automation, rapid changes, new business models, new business organizations, and globalization. These trends create new markets and make business more efficient, but also compound reliability concerns. In the new environment, reliability cannot be examined or planned for from a domestic slant alone. Increasingly, reliability in the petroleum sector depends on that of the *weakest link* in the global supply system. Interdependencies between the petroleum sector and other critical infrastructures have grown more intricate as information technologies and telecommunications take on dominant roles. The new environment has also expanded potential consequences of incidents. Disruptions historically resulted in primarily local consequences. But today the potential for regional, national or even global ones exists. Compounding matters is the fact that increased automation and retirement of individuals with the necessary skills makes a return to manual methods of business almost impossible (NPC, 2001).

Risk Management

The NPC recommends that companies address risk proactively through routine risk management. Typically, risks are measured in terms of likelihood of occurrence and expected level of financial loss. The Council offers a six-step risk management process to mitigate risks in the new business environment (NPC, 2001, pp.40-47):

1. *Identify and characterize key assets.* Key assets include facilities, information, people, processes, programs, and services. Each is assigned a value reflecting the consequence of losing that asset.

2. *Identify and characterize vulnerabilities and threats.* Identify targets and weaknesses, and review the ability of security measures to guard against them.

Usually covered are cyber systems, supervisory control and data acquisition (SCADA) systems, physical assets, security measures, and interdependencies. Threat assessments should consider ability to access an asset, ability to harm an asset, intent to harm an asset, history (including the past targeting of an asset), and the effectiveness of existing security measures against the threat.

3. *Perform risk assessments.* Risk is the product of the probability of an incident and the consequence of the incident, and can be determined by multiplying the value of the asset (i.e., the consequence) as determined in *Step 1,* with the likelihood of an incident (i.e., the vulnerability) as determined in *Step 2.* Risk can be measured qualitatively, quantitatively, or using a mixture of both methods.

4. *Identify and characterize potential risk abatement options.* Risk abatement generally focuses on deterring threats, reducing vulnerabilities, reducing consequences, reducing severity during an incident, and ensuring rapid recovery after the incident.

5. *Select cost-effective risk abatement options.* The options identified in *Step 4* are analyzed and prioritized on a cost/benefit basis.

6. *Implement risk management decisions.* Attractive abatement options identified in *Step 5* are implemented. Implementation involves preparing plans and procedures, training staff, and continuing to monitor the risk environment.

Risks

The new business environment has transformed the risks facing the petroleum industry. Traditionally, primary risks in the petroleum sector were incidents resulting from human error or natural disaster, and were mitigated by hardening assets (NPC, 2001, pp.2-4). But industry operations in the new business environment face an entirely new set of risks, against which the industry remains unprepared. The NPC ranks seven risks facing the industry today, in decreasing order of preparedness against them (NPC, 2001, pp.17-37):

1. Information technology and telecommunications
2. Globalization
3. Business restructuring
4. Interdependencies
5. Legal and regulatory issues
6. Physical and human factors
7. Natural disasters

U.S. Petroleum Dependence and Its Economic Implications

Dependence on foreign energy sources has imposed tremendous costs on the U.S. economy over the past 30 years. Metrics exist to gauge the level of petroleum dependence in an economy, and its vulnerability to a supply disruption. These measures indicate that the U.S. is more dependent on petroleum and more vulnerable to an interruption in its supply than ever before.

Measures of Petroleum Dependence

Greene and Tishchishyna define U.S. petroleum dependence as "the product of (1) a non-competitive world oil market strongly influenced by the OPEC cartel, (2) high levels of U.S. oil imports, (3) the importance of oil to the U.S. economy (especially the transportation sector), and (4) the absence of economical and readily available substitutes" (Greene, 2000, p.2). It can be measured several ways. Alhajji and Williams (2003) gauge dependence according to four metrics, which consider imports, reserve levels, and the percentage of total energy consumption met by petroleum.

Imports

One measure of petroleum dependence is the percentage of petroleum consumption met by imports. Figure 5 shows the average annual U.S. petroleum consumption met by imports. According to this metric, U.S. petroleum dependence hit a record high in 2001 when net imports averaged 57% of petroleum supplied.

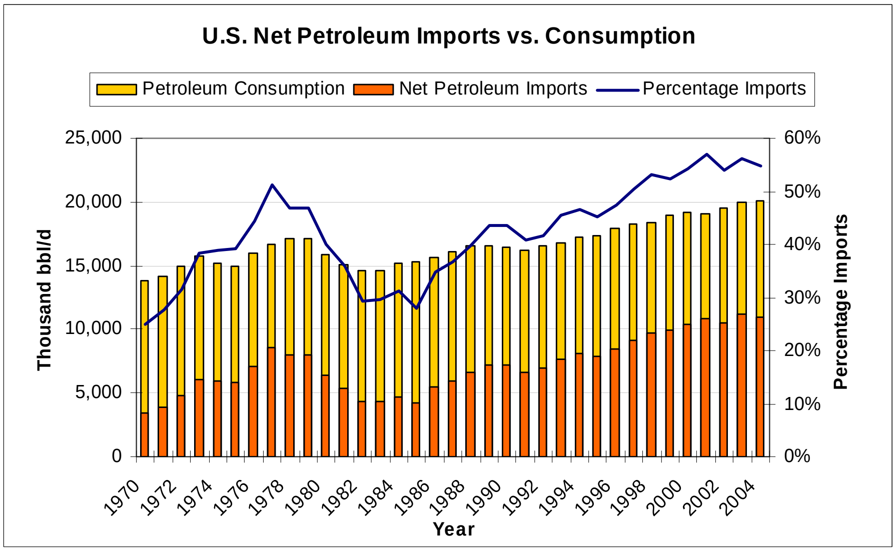

Figure 5. U.S. net petroleum imports since 1970 (EIA).

Number of Days Stocks Cover Imports and Total Consumption

Two additional measures suggested by Alhajji and Williams are the amount of total petroleum reserves compared to net imports and total consumption. Figure 6 shows average annual U.S. petroleum stock levels since 1970, and their average coverage against imports and consumption. Stocks here include both commercial stocks and reserves such as the Strategic Petroleum Reserve (SPR), which was created in 1977. Total petroleum stock coverage against imports has constantly decreased since the mid-1980s, from a peak of 300 days in 1985 to 116 days in January of 2004. Against total consumption, total petroleum stock coverage has also decreased, from a peak of 102 days in 1984 to 77 days in January 2004.

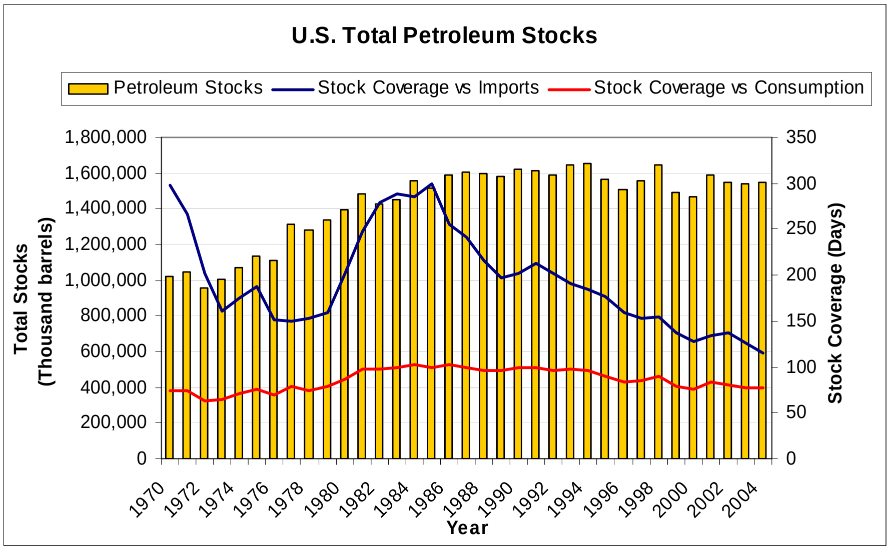

Figure 6. U.S. petroleum stocks and their coverage against imports and consumption (EIA).

A minimum stock level, known as the Lower Operational Inventory Level (LOIL), is required to operate and maintain the system.[11] If it is included (see Figure 7), coverage

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[11] The LOIL in the U.S. is currently 862 million barrels of crude oil and petroleum products.

levels drop compared to Figure 6. As of January 2004, coverage against imports was 52 days and coverage against consumption was 34 days when the LOIL was included.

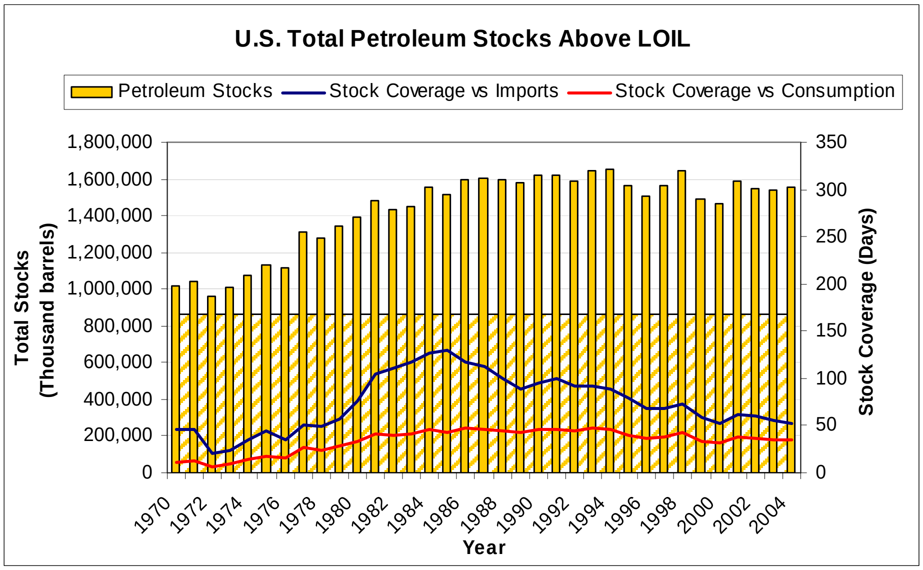

Figure 7. U.S. petroleum stocks and their coverage against imports and consumption, minus Lower Operational Inventory Levels (EIA).

Percentage of Petroleum in Total Energy Consumption

The final measure of petroleum dependence according to Alhajji and Williams is the percentage of total energy consumption met by petroleum. It indicates the importance of petroleum to an economy. Total energy and petroleum consumption are shown in Figure 8. The percentage of total energy consumption met by petroleum is also shown. It peaked in the late 1970s at 48% before falling to 38% in 1995. Since then, it has slowly increased to its current level of approximately 40%.

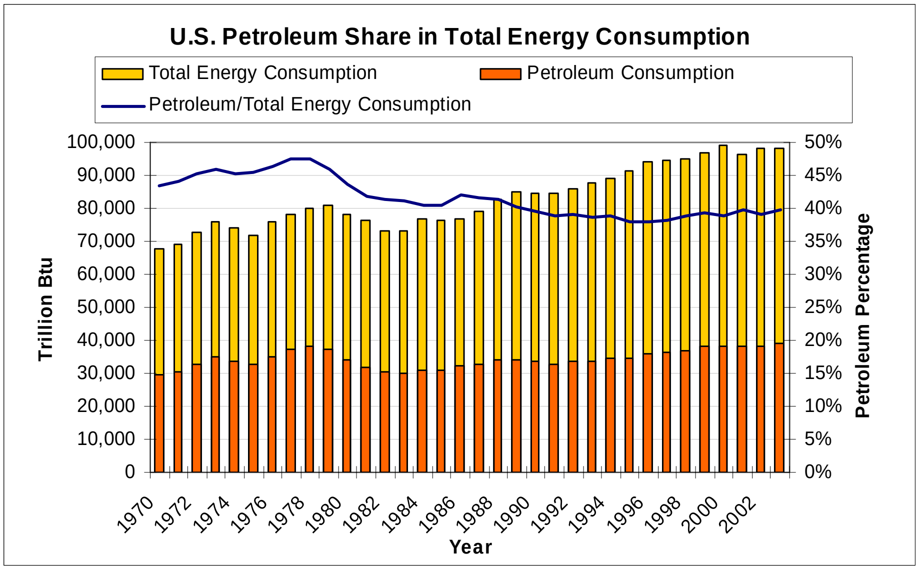

Figure 8. Percentage of total energy consumption met by petroleum in the U.S. (EIA).

<u>Oil as a percent of GDP</u>

A similar measure of the importance of petroleum to an economy is the percentage of gross domestic product (GDP) of petroleum expenditures (Green, 2000, p.3). Higher expenditures (as a percentage of GDP) indicate a greater dependence of an economy on petroleum. Figure 9 shows annual U.S. petroleum expenditures in nominal dollars from 1970 to 2000, and their percentage of GDP. Expenditures as a percentage of GDP peaked in 1982 at about 5.3%, and most recently were about 4% in 2000.

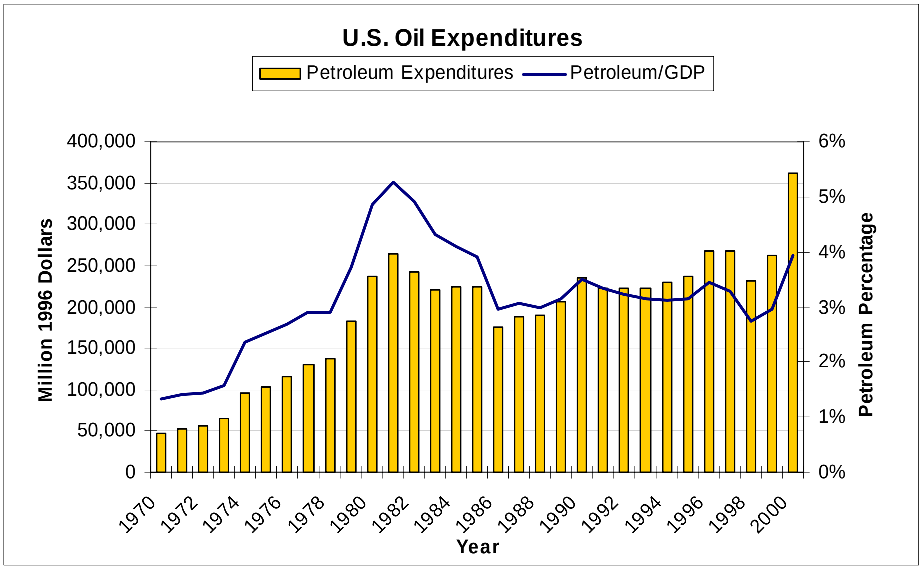

Figure 9. U.S. oil expenditures as a percent of GDP (EIA).

Measures of Vulnerability to Supply Disruption

Similar to petroleum dependence, Alhajji and Williams define measures of vulnerability to a supply disruption. While the previous measures related to the importance of petroleum to an economy, the measures here reflect the likelihood that imports might be disrupted. They are based on the global distribution of supply sources, and essentially gauge the influence of large suppliers on the global market.

Degree of Import Concentration

Alhajji and Williams define import concentration as the percentage of imports coming from the top five suppliers. The consequences of a disruption from a supplying country increases with import concentration. The top five exporters of petroleum to the U.S. over the past thirty years are shown in Table 3. Canada, Saudi Arabia, Mexico, Venezuela, and Nigeria have generally dominated U.S. petroleum imports.

Table 3. Top five petroleum supplying nations into U.S. from 1973 to 2003 (EIA).

	Supplier and Imports (Mbbl/d)									
Year	#1 Supplier		#2 Supplier		#3 Supplier		#4 Supplier		#5 Supplier	
1973	Canada	1325	Venezuela	1135	Netherlands Antilles	585	Saudi Arabia	486	Nigeria	459
1974	Canada	1070	Venezuela	979	Nigeria	713	Netherlands Antilles	511	Iran	469
1975	Canada	846	Nigeria	762	Saudi Arabia	715	Venezuela	702	Virgin Islands	406
1976	Saudi Arabia	1230	Nigeria	1025	Venezuela	700	Canada	599	Indonesia	539
1977	Saudi Arabia	1380	Nigeria	1143	Libya	723	Venezuela	690	Algeria	559
1978	Saudi Arabia	1144	Nigeria	919	Libya	654	Algeria	649	Venezuela	646
1979	Saudi Arabia	1356	Nigeria	1080	Venezuela	690	Libya	658	Algeria	636
1980	Saudi Arabia	1261	Nigeria	857	Libya	554	Mexico	533	Algeria	488
1981	Saudi Arabia	1129	Nigeria	620	Mexico	522	Canada	447	Venezuela	406
1982	Mexico	685	Saudi Arabia	552	Nigeria	514	Canada	482	United Kingdom	456
1983	Mexico	826	Canada	547	Venezuela	422	United Kingdom	382	Other Non-OPEC	378
1984	Mexico	748	Canada	630	Venezuela	548	Other Non-OPEC	411	United Kingdom	402
1985	Mexico	816	Canada	770	Venezuela	605	Other Non-OPEC	394	Indonesia	314
1986	Canada	807	Venezuela	793	Mexico	699	Saudi Arabia	685	Nigeria	440
1987	Canada	848	Venezuela	804	Saudi Arabia	751	Mexico	655	Nigeria	535
1988	Saudi Arabia	1073	Canada	999	Venezuela	794	Mexico	747	Nigeria	618
1989	Saudi Arabia	1224	Canada	931	Venezuela	873	Nigeria	815	Mexico	767
1990	Saudi Arabia	1339	Venezuela	1025	Canada	934	Nigeria	800	Mexico	755
1991	Saudi Arabia	1802	Venezuela	1035	Canada	1033	Mexico	807	Nigeria	703
1992	Saudi Arabia	1720	Venezuela	1170	Canada	1069	Mexico	830	Nigeria	681
1993	Saudi Arabia	1414	Venezuela	1300	Canada	1181	Mexico	919	Nigeria	740
1994	Saudi Arabia	1402	Venezuela	1334	Canada	1272	Mexico	984	Nigeria	637
1995	Venezuela	1480	Saudi Arabia	1344	Canada	1332	Mexico	1068	Nigeria	627
1996	Venezuela	1676	Canada	1424	Saudi Arabia	1363	Mexico	1244	Nigeria	617
1997	Venezuela	1773	Canada	1563	Saudi Arabia	1407	Mexico	1385	Nigeria	698
1998	Venezuela	1719	Canada	1598	Saudi Arabia	1491	Mexico	1351	Nigeria	696
1999	Canada	1539	Venezuela	1493	Saudi Arabia	1478	Mexico	1324	Iraq	725
2000	Canada	1807	Saudi Arabia	1572	Venezuela	1546	Mexico	1373	Nigeria	896
2001	Canada	1828	Saudi Arabia	1662	Venezuela	1553	Mexico	1440	Nigeria	885
2002	Canada	1971	Saudi Arabia	1552	Mexico	1547	Venezuela	1398	Other Non-OPEC	720
2003	Canada	2068	Saudi Arabia	1772	Mexico	1639	Venezuela	1385	Nigeria	873

The average annual concentration of U.S. imports from its top five supplying countries over the last thirty years is illustrated in Figure 10. After a decline in import concentration following the energy crisis in 1973, import concentration has been steadily increasing since the late 1970s. Import concentration in the U.S. from its top five suppliers peaked near 71% in 1991, and averaged about 63% in 2003.

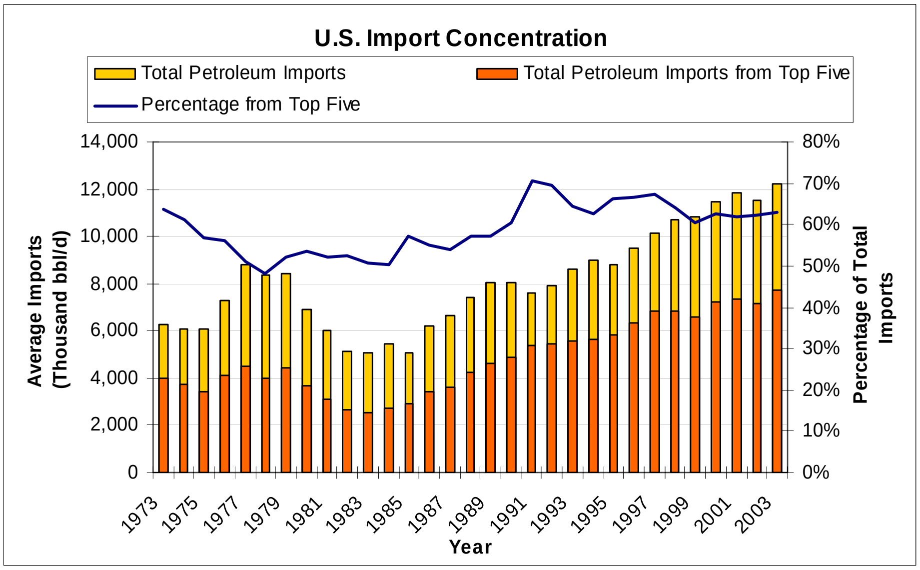

Figure 10. Concentration of U.S. petroleum imports from its top five supplying countries (EIA).

<u>OPEC Share of World Petroleum Supply</u>

The Organization of Petroleum Exporting Countries (OPEC) is a collection of several oil rich countries that together exert tremendous influence on global supply. As their control of global production increases, so does the vulnerability facing each importing nation. Figure 11 shows OPEC's average daily crude oil production from 1970 to 2004, and its share of global production. Its percentage of global production declined dramatically in the late 1970s and early 1980s, from a peak of 55% in 1973 to a low of 30% in 1985. Since then, their share has been increasing, and as of January 2004, constitutes about 41% of global production.

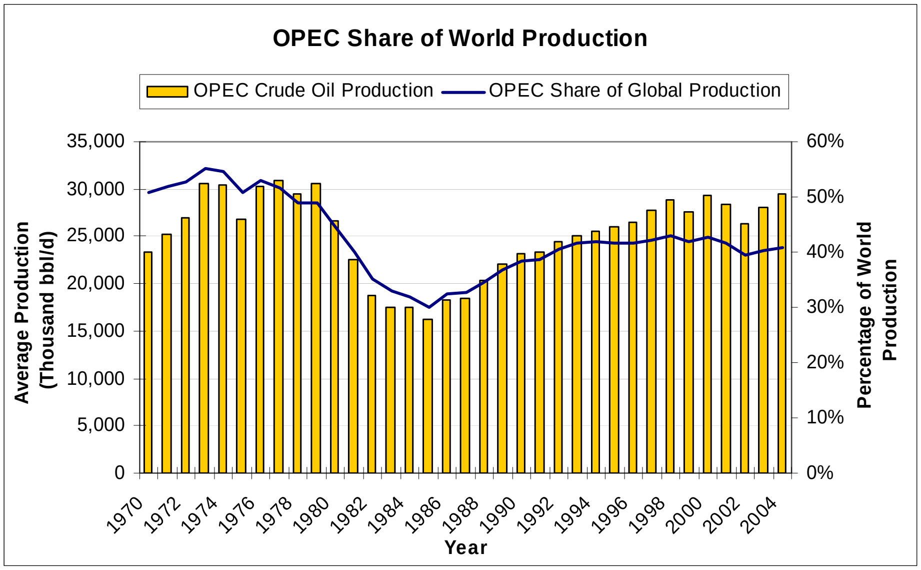

Figure 11. OPEC share of global crude oil production (EIA).

Persian Gulf Share of World Petroleum Supply

Social and political turmoil have afflicted several Persian Gulf nations for years, and incidents in the region have been responsible for each energy crisis over the last 30 years.[12] Growing animosity in the region against western states compounds matters and increases the vulnerability of a supply disruption in the region. Figure 12 shows the average daily crude oil production in the Persian Gulf from 1970 to 2004, and its share of global production. The trends essentially mirror those from OPEC over the same period, but with a peak of about 38.2% in 1974 and a low of 17.8% in 1985. In 2003, Persian Gulf supplies averaged 27.7% of global production.

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[12] Energy crises followed the Arab oil embargo in 1973, the Iran-Iraq war in 1979, and the Iraqi invasion of Kuwait and subsequent war with the U.S. in 1990-1991.

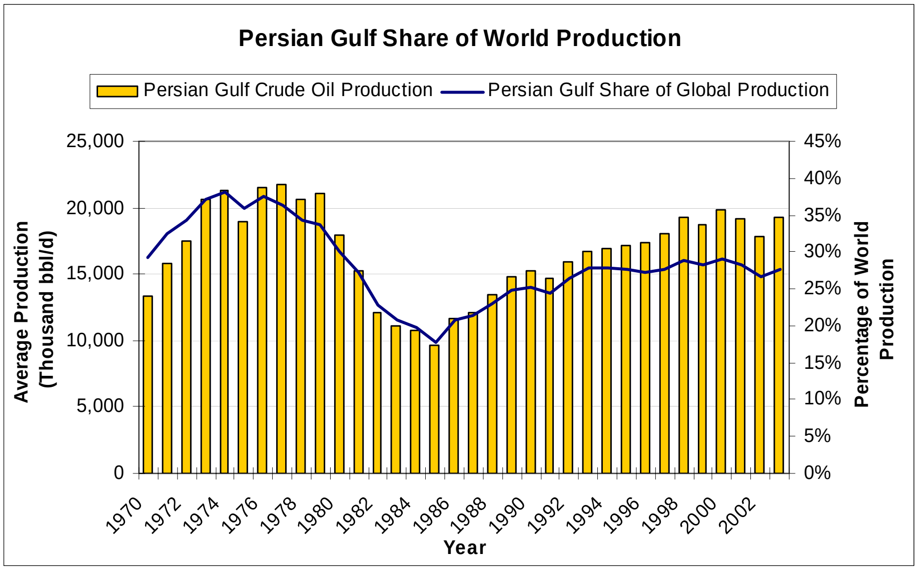

Figure 12. Persian Gulf share of global crude oil production (EIA).

<u>World Excess Production Capacity</u>

Excess production capacity provides an element of flexibility in the global market to withstand disruptions from individual suppliers. Essentially all spare production capacity in the world is controlled by OPEC and Persian Gulf countries (Kreil, 2004). Figure 13 shows the annual average world excess production capacity versus price since 1970. It can be seen that current excess capacity is lower than any other time during that period except the Gulf War in 1991.

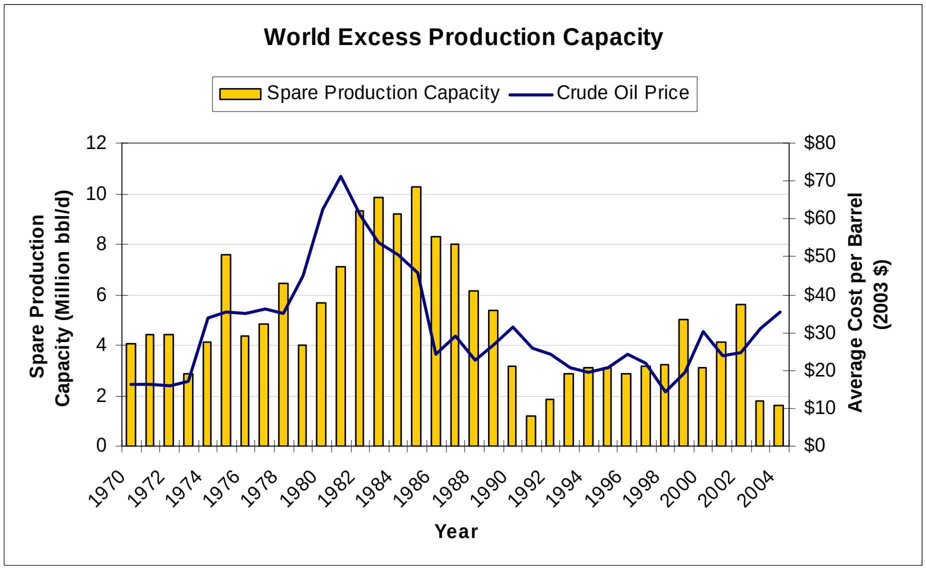

Figure 13. World excess petroleum production capacity vs. price (EIA).

Costs of Oil Dependence

Dependence on oil supplies from other countries has profound consequences on the U.S. economy. It increases the trade deficit, the costs of securing resource supply, and slows GDP growth. Figure 14 shows annual U.S. expenditures on imported petroleum and the U.S. trade deficit since 1970, based on real prices in 2003 dollars. Expenditures on imported petroleum are approaching record values not seen since the second energy crisis, when the U.S. spent approximately $145 billion on net imports in 1980. In 2004, if the price of oil averages $40 per barrel and net imports remain close to 11 million barrels per day, the U.S. will spend $160 billion on imported oil. Since 1975, the last year the U.S. had a trade surplus, expenditures on net imports of petroleum have consistently accounted for over 20% of the total trade deficit. Over the last decade, increases in spending on imported oil have corresponded well with increases in the trade deficit. The connection is especially apparent since 1997. In 2003, with spending on imported oil supplies amounting to $128 billion and the trade deficit at $490 billion, dependence on imported oil accounted for over 25% of the total trade deficit.

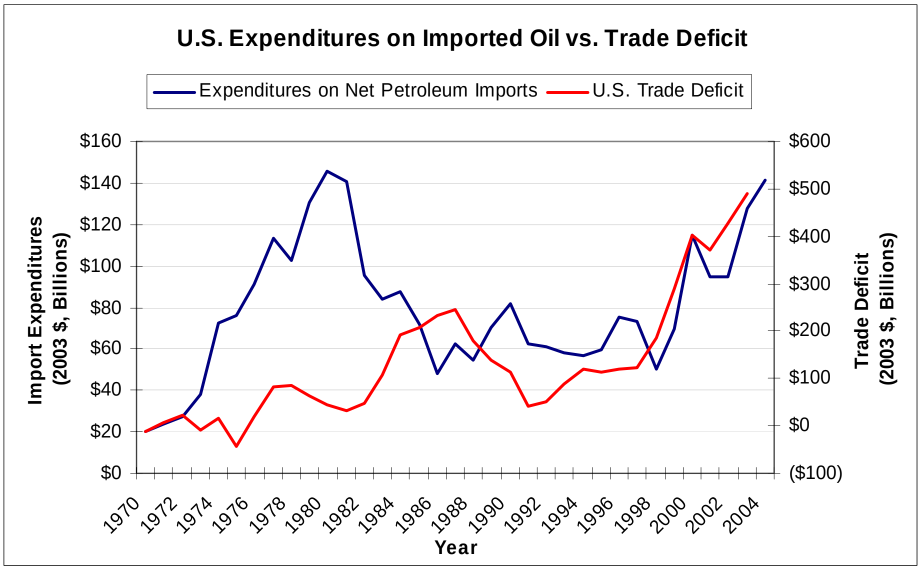

Figure 14. U.S. expenditures on imported oil and the trade deficit, in 2003 $ (EIA and the Bureau of Economic Analysis).

In addition to compounding the trade deficit, oil dependence increases the burden of securing supply. The average annual peacetime cost to the U.S. of maintaining a military presence in the Middle East is about $50 billion (e.g., IAGS [2003a], Delucchi and Murphy [1996]). Military conflicts add additional costs. The cost of the 1990-1991 Gulf War to the international community totaled about $80 billion (IAGS, 2003b). Final cost figures for current operations in Iraq will be in the hundreds of billions.[13] Another cost associated with international suppliers is insurance. Increased fear of attack on supertankers has caused insurance rates to skyrocket. Insurance rates recently tripled for

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[13] The author does not intend to suggest motives for the current operations in Iraq, nor necessarily attribute their financial costs to securing oil supplies. But they certainly carry implications for the global oil market.

tankers passing through Yemen, adding about \$0.15/barrel (bbl) to the price of petroleum traveling through the region (IAGS, 2003c).

The EIA has established "rules of thumb" to assess the impacts of oil supply disruptions on economic growth, specifically GDP. First, every 1 MMbbl/day of lost oil causes world oil prices to increase by \$3-\$5 per barrel. Second, each 10% increase in the price of oil lowers the real U.S. GDP growth rate by 0.05 percentage points in the first year and 0.10 percentage points in the second year. So, if 1 MMbbl/day were disrupted and prevailing oil prices were \$30 per barrel, oil prices could increase to \$33-\$35 per barrel. This is equivalent to a price increase of 10%-17%, which equates to possible reduction in the U.S. GDP growth rate of 0.05-0.08 percentage points in the first year, and 0.10-0.17 percentage points in the second year (EIA, 2004g).

Multiple studies have aggregated these and other costs to estimate the true cost of U.S. oil dependence. Greene and Tishchishyna present a model developed by Oak Ridge National Laboratories to estimate the costs of oil dependence to the U.S. from 1970 to 1999 (Greene, 2000). They consider three categories of cost in their study: (1) loss of potential GDP, (2) macroeconomic adjustment losses, and (3) wealth transfer. The loss of potential GDP results from monopolistic pricing practices by global oil suppliers, who keep oil prices above the level which would exist in a competitive market. Higher oil prices constrain the economy, allowing less production with the same amount of capital, labor, and materials than if oil was less expensive. Macroeconomic adjustment costs account for delays in adjusting prices, wages, and interest rates following oil price spikes, during which there is a less than optimal use of available resources. They depend on policy responses to price shocks, and are sensitive to the elasticity of GDP with respect to the price of oil. Wealth transfer is equal to the quantity of imported oil times the difference in the actual and competitive prices. Combining these costs, Greene and Tishchishyna conclude that oil dependence cost the U.S. $3.4 trillion from 1970 to 1999.

The National Defense Council Foundation (NDCF) also studied the economic impacts of oil dependence, and presents the costs on a per-gallon of gasoline basis to determine the "real price" of gasoline (Copulos, 2003). The study includes three hidden imported oil costs: (1) military expenditures in the Persian Gulf, (2) a diversion of financial resources, and (3) periodic oil price shocks. Military expenditures are defined in terms of the portion of the budget of U.S. Central Command (whose area of responsibility is the Middle East and the Horn of Africa) that goes towards defending Persian Gulf oil. It does not include the cost of the current engagement in Middle East. The diversion of financial resources includes direct costs from the transfer of wealth, and indirect costs from lost employment and investment. The costs stemming from the oil price shocks of 1973-74, 1979-80, and 1991 were estimated to be $2.3 trillion – $2.5 trillion, and amortized over three decades to determine an annual cost. They conclude that the real price of gasoline paid by the U.S. consumer, when taking oil dependence into account, is between $5.01/gallon and $5.19/gallon.

Reliability of Global Supply Infrastructure

The oil supply chain is composed of a vast infrastructure of interdependent physical assets that stretches worldwide. Supply resources tend to be centralized in tumultuous regions far from the final demand, creating a long and complicated transportation network of ships, trains, trucks, and pipelines. Geopolitics influence oil extraction rates, transportation routes traverse dangerous terrain and hostile territory, refineries are aging and are not being replaced, and global oil consumption is expected to increase by 50% over the next twenty years (EIA, 2004f, p.2). Every asset throughout the infrastructure faces unpredictable threats presented by the new business environment, natural disasters, human error, and hostile attacks. This section investigates the reliability of the physical petroleum supply infrastructure, and discusses its vulnerabilities and threats.

Supply Outlook

As world consumption continues to grow and reserves deplete, global distribution of petroleum resources should grow more concentrated. Members of OPEC stand to gain an even greater share of the world market, and nations dependent on imported oil will grow increasingly vulnerable to a disruption in supply. Figure 15 shows the estimated distribution of oil reserves as of January 1, 2001. Over half of the remaining oil in the world is located in the Middle East.

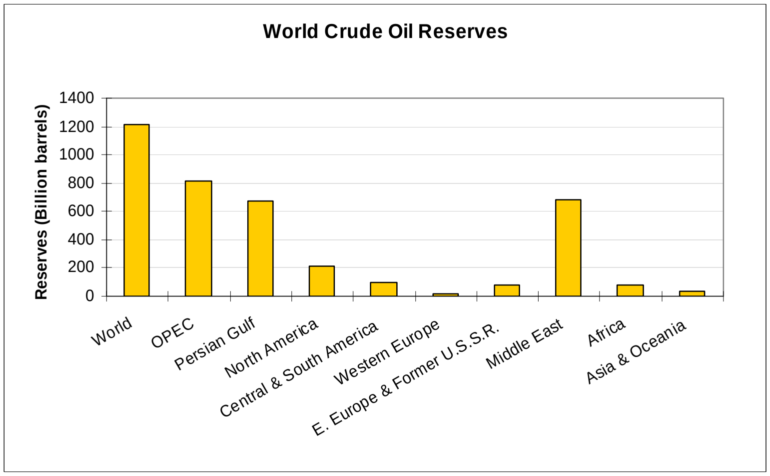

Figure 15. Distribution of global crude oil reserves (EIA, from Oil & Gas Journal).

Geopolitics

The Oxford American Dictionary defines geopolitics as "the politics of a country as determined by its geographical features." Here, the geographical feature of concern is the abundance – or lack thereof – of oil. Geopolitics weighs heavily on international energy markets, and will impose increasing threats on global oil supply as reserves grow more concentrated and demand continues to increase.

The Center for Strategic and International Studies (CSIS) investigated the "symbiotic relationship" between oil and politics from 2000 to 2020 (CSIS, 2000). Four geopolitical trends could have significant impacts on global energy demand and supply reliability before 2020 (CSIS, 2000, pp.7-13):

- *World powers and conflict.* The wake of the Cold War has left the role of the world's major powers still somewhat undefined, and as they each pursue their national interests, conflicts could disrupt world energy supplies. The politics of global and regional powers will shape oil production from the Caspian Sea and Central Asia.

- *Political instability among key energy suppliers.* Several key oil producing states face internal conflict, which could disrupt global oil supplies.
- *Economic globalization.* The globalization of all forms of trade is increasingly making producers and consumers interdependent.
- *The growing impact of non-state actors.* Information technology has allowed non-governmental organizations to gain greater control in the political process.

Similarly, trends in energy usage effects geopolitics (CSIS, 2000, pp.13-18):

- *Swings in energy demand.* The economies of oil producing states are heavily dependent on oil revenue. A drop in revenues could cripple these countries and make them more vulnerable to internal crises.
- *Competition for energy supplies in Asia.* Competition for oil imports and territorial disputes over regions rich in oil could ignite tensions between Asian countries that have deep, historical roots. China's increased oil dependence could lead to strategic relationships with Middle Eastern countries and Russia, which could be damaging to relations with the U.S., Europe, and other Asian countries.
- *Energy and regional integration.* Energy can also serve to strengthen ties between rival countries. Infrastructure projects and trade liberalization can cut through boundaries and bring economies together, serving to ease conflicts in many regions.

- *Energy and the environment.* Debates regarding the role of the environment in energy supply and consumption could create conflicts between nations, especially between developed and developing countries.

A brief evaluation of the geopolitical situations in each OPEC member state is given in Appendix A. Similar looks into the socio-political situations in other significant oil-producing and -consuming states could provide further insights into the future reliability of global petroleum supply.

Threats

Changes in the global business and political climates intensify threats facing oil supply infrastructure. The new business environment has exposed the industry to great threats, as discussed earlier. Natural disasters and human error also continue to threaten operations. An increasing source of threats is from malicious attacks, whether from disgruntled employees, thieves, or ideologues. Oil infrastructure provides an attractive target because it is so vital to global economies, and the infrastructure is dispersed and generally unprotected. One source of increasing attacks is “oil terrorism.” Most are kidnappings, but attacks on personnel, pipelines, rigs, and wells are also included (Adams, 2003, pp.5-12). Acts of piracy are also increasing, and have tripled in the last decade (Luft and Korin, 2003). According to the International Maritime Bureau (IMB), 445 attacks were reported in 2003. Pirates have become better organized, and coordinated attacks involving several boats are on the rise (ICC, 2004). Strategic shipping passages, especially the Strait of Malacca,[14] experience frequent piracy which threatens oil tankers traversing their waters.

Infrastructure Risks

Oil infrastructure is vast and difficult to harden, creating vulnerabilities throughout the supply chain. The extent of the U.S. infrastructure is described in Table 4, and its vulnerabilities are classified in Figure 16 (NPC, 2001, pp.32-33). Compounding supply vulnerability are global interdependencies and trans-oceanic supply lines.

Table 4. Physical U.S. oil infrastructure components (NPC, 2001, p. 32).

Production	602,200 wells
Gathering	74,000 miles of crude pipeline 30,000 miles of gathering pipeline 74,000 miles of product pipeline
Processing	161 petroleum refineries
Transmission	74,000 miles of crude pipelines 74,000 miles of product pipelines
Storage	2,000 petroleum terminals
Distribution Modes	616.5 billion ton miles via pipeline 295.6 billion ton miles via water 27.2 billion ton miles via road 16.7 billion ton miles via railroads

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[14] See the discussion regarding *international chokepoints* below and in the Appendix.

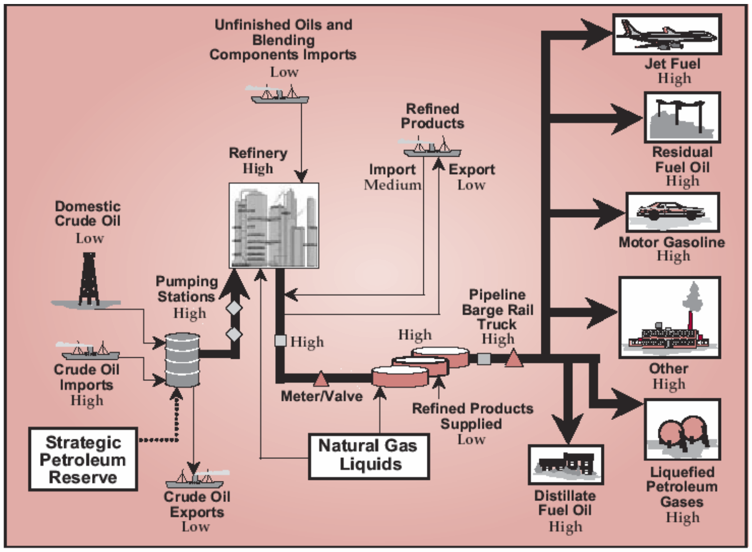


Figure 16. The National Petroleum Council's assessment of physical vulnerabilities facing oil infrastructure (NPC, 2001, p.33).

<u>Reservoirs</u>

A direct attack on a reservoir would be highly unlikely and difficult to carry out, but a successful attack on a reservoir could devastate the producer state, and severely reduce global production (Adams, 2003, p.102).

<u>Wells</u>

Adams (2003) estimates that onshore wells are the most vulnerable component of the supply system. Wells can be highly pressurized, posing a continuous fire risk. If ignited, well fires create pollution and toxicity problems. Most wells are remotely located, minimizing the consequence of an incident beyond lost production. But this also makes them difficult and impractical to secure.

Offshore wells often provide attractive targets for attack, as they tend to be expensive and have high output flow rates. They have been attacked on numerous occasions, especially in Africa. Higher-producing wells far offshore are more hardened and less attractive for attack than the softer targets offered by the often unstaffed wells closer to shore. Besides lost production, the primary consequence of an offshore attack is pollution. Some wells are equipped to continuously ignite any released product to avoid water pollution. But burning oil presents toxicity and air pollution problems (Adams, 2003, pp.125-127).

Transport

According to the IAGS, the "transportation system has always been the Achilles heel of the oil industry," and it has become even more so in recent years (IAGS, 2003c). Long haul distances typical of the petroleum supply system increase vulnerabilities to every hazard. Three-fifths of internationally-traded oil is transported by sea, and the rest primarily via pipeline (EIA, 2002). Both methods face considerable vulnerabilities and threats, and pose serious consequences. But, unlike other components of the supply system, the transport system is somewhat flexible. Trucking capacity can easily be expanded, and provides the most flexibility, followed by rail and waterway, and finally pipelines (Lovins, 1982, p.40).

- *Pipelines.* Pipelines tend to be unsecured in remote areas and are incredibly vulnerable. They are often buried, but are exposed at junctures and where terrain dictates. Signage calls out the location of buried lines to warn against inadvertent third-party damage, but similarly alerts wrongdoers. Oil pipelines often follow the same paths as natural gas pipelines, so an incident on one line could damage the other as well (Adams, 2003, pp.106-114). One especially vulnerable pipeline in the U.S. is the Trans-Alaska Pipeline System (TAPS), which is currently the only route to deliver Alaskan oil to the contiguous U.S. TAPS has been bombed twice and shot more than 50 times in recent years, and cannot be repaired in the winter (Luft and Korin, 2003).

Pump stations along pipelines are similarly vulnerable. They are located approximately every 50 miles, and are often remote and unsecured. The loss of a pump station would have the same effect as losing the pipeline it serves, but pump stations take longer to repair (Adams, 2003, pp.15-16).

- *Tankers and ports.* Tankers are vulnerable to attack and are facing greater and more frequent threats. They serve as large, expensive and symbolic targets, and often travel through dangerous waters. Loading terminals are critical to supply, and vulnerable to interruption. They are difficult to secure, and if damaged, would disrupt infrastructure facilities served by the port. Loading terminals may pose a greater risk than refineries or storage sites (Adams, 2003, p.124).

- *International chokepoints.* Chokepoints are vulnerable transportation routes through which the flow of oil could be easily disrupted. Most only have long, inaccessible alternate routes, if any at all. If flow through any chokepoint were disrupted, it could carry significant consequences for the global market. About 40% of total world petroleum consumption and more than 55% of all exports flow through these chokepoints daily. Descriptions of each chokepoint, and threats and consequences facing each, are given in Appendix B.

Storage

Storage facilities can include tank farms or underground storage. Tank farms are more vulnerable and tend to be located in oil fields, refineries, loading terminals, or even residential areas. They are visible, and their contents highly flammable. If ignited, toxic fumes pose health risks to proximate populations. Underground storage sites have larger capacities, but better security (Adams, 2003).

Refineries

Refineries are probably the most vulnerable component of the supply system aside from wells. Major damage can be done without many explosives, as refineries contain hot, pressurized, and explosive gases and liquids. They also depend on one type of crude, and are vulnerable to impurities (Lovins, 1982). Refineries in the U.S are aging, and are no longer being built due to environmental constraints and financial risks (NPC, 2001, p.32).

Refineries employ a large number of workers (usually 1000-2000 people on average) and tend to be less remote than wells. Consequences stemming from an incident may be more likely to reach populated areas, and include significant direct financial costs associated with rebuilding, a high loss of life potential, and possible costs associated with lawsuits if incident damages reach surrounding communities (Adams, 2003, p.27).

Summary

Reliability in the petroleum sector is considered in terms of broad concerns such as national and economic security. This designation emanates from the dependence of developed economies on imported petroleum supplies, which often originate in volatile regions. Reliability in the sector is measured in terms of imports, origin of imports, storage levels, and reserve levels. Economic indicators exist as well, such as petroleum expenditures as a fraction of GDP, wealth transfer, military expenditures, and the effects of oil price spikes. The sector faces quickly-evolving risks as a result of automation and globalization, and the supply infrastructure is incredibly vulnerable – due to age, location, size, and long haul distances typical of global trade.

METHODOLOGY

Methodology Overview

This study aims to develop a methodology to assess the reliability of hydrogen energy systems. The intention is to promote fair consideration of reliability in hydrogen discourse by introducing methods allowing complete, ordered assessments. To the best knowledge of the author, it represents the first systematic effort in this regard.

This study uses qualitative methods to assess the perceived reliability of hydrogen energy systems. First, reliability is defined and metrics are selected to value it. Next, hydrogen pathways are selected and described. Three constituent components of the pathways are assessed by a panel of experts – the primary energy supply system, the hydrogen production process, and the hydrogen transport process. They rate the reliability and importance of each pathway component in terms of the metrics. Finally, their ratings are aggregated to determine broad reliability scores that can be compared across pathways. The methodology is summarized by the following steps, each detailed separately below:

1. *Define scope of study, and select participants*
2. *Define reliability in hydrogen energy systems*
3. *Select metrics to value reliability in hydrogen energy systems*
4. *Specify hydrogen energy systems to evaluate*
5. *Develop evaluation matrix*
6. *Develop rating scales and rating criteria*
7. *Collect expert reliability and importance ratings*
8. *Aggregate expert ratings to determine reliability scores*
9. *Compare reliability scores across pathways*

The discussion in this section introduces the method and generally describes its application. The next section details the methodology for a specific application.

1. Define Scope of Study and Select Participants

The first step of an evaluation of a system is to define the scope of study. The scope will depend on details of the system being considered, the objectives of the organization conducting the study, and the motivation for the research. Some parameters of the energy systems being evaluated will be known or postulated. These include geographical extent, volume of hydrogen demand, geographical- or time-distribution of demand, and others. The composition and reach of the systems as described by these parameters shape the boundaries and processes of the assessment. The objectives of the organization and its motivation for conducting the study will also influence the scope. The organization could be a company, a governmental organization, an industry group, a non-governmental organization (NGO), a research institution, or a university. Each holds a different slant and motivation, and would define the scope uniquely.

The organization conducting the study also selects experts to evaluate reliability, and determines their involvement in the assessment process. The organization may select to use in-house experts, involve a wide group of experts comprising all stakeholders and schools of thought, or a combination of the two. If a panel of experts representing multiple parties is used, there are three roles it could take (Contadini, 2002, p.62). First, a single modeler could decide on the inputs for the analysis, and involve other parties later in the process. The modeler could define reliability and select the metrics and pathways to consider, and the expert panel could rate reliability. This method allows the organization to shape the study to its liking. But Contadini warns that this practice can lead to missed information, and to large modifications late in the process.

The other two roles Contadini describes involve the experts in the entire process. In addition to rating the reliability of the metrics, the expert panel also defines reliability and selects the metrics and pathways to be evaluated. These options add a greater level of consensus, but also introduce complications and could allow an overrepresented group to bias the results. They could also reduce the ability of the organization conducting the study to define reliability in line with its objectives. The two vary by the method in which consensus is reached. In one, selections are made by majority vote. In the other, final decisions are established via technical discussion based on information provided by the organizations with which the experts are affiliated.

2. Define Reliability in Hydrogen Energy Systems

The participants selected to develop the inputs for the analysis begin by defining reliability in hydrogen energy systems. A thorough definition is essential to set a foundation for the assessment. It establishes boundaries and outlines key parameters to include in the study. The definition could vary among organizations. Each is likely to perceive reliability differently, to encapsulate concepts it feels are important.

Important issues of semantics emerge when defining reliability. Leemis discusses these as they apply to defining reliability of any system, not specific to hydrogen (Leemis, 1995, pp.2-4). He emphasizes the importance of clearly specifying within the definition the *item* of interest, what constitutes *adequate performance* (or non-failure), a *time* duration, and the *environmental conditions* in which the item operates. The *item* can be a component or an entire system. It should be clearly specified exactly what the item is, and the boundaries that delineate components comprising the item. *Adequate performance* must be clearly defined for the item as well. The simplest way is to establish a binary criterion, that the item is either operational or has failed. An example of a binary criterion in a hydrogen transport subsystem might be that a pipeline is either able or unable to deliver hydrogen. But this model can be difficult to apply, because performance of an item often degrades over time. In these cases, Leemis suggests setting a threshold below which the item is considered to have failed. Here, the example above might be modified to include a level of throughput under which the subsystem is considered "failed". A *time period* should also be clearly specified in the definition. Any item has a finite lifespan after which it will invariably fail, so adequate performance cannot be defined without providing a context of time. Finally, the *environmental conditions* under which the item is expected to operate profoundly affect the reliability of an item, and must be specified. Two identical items operating under different surrounding conditions will undoubtedly fail at different times. For example, a garaged pickup truck used as a commuter vehicle will probably demonstrate greater reliability than the same truck kept outside and used on a farm or construction site.

3. Select Metrics to Value Reliability in Hydrogen Energy Systems

Once hydrogen reliability has been thoroughly defined, metrics to value it are selected. They are what the experts ultimately rate for each system. The idea is to decompose the broad reliability concepts captured in the definition into tangible elements that can be easily evaluated. Upon measuring and rating these basic elements, they are recombined to develop overall reliability scores. The number of metrics selected and their precision depends on the level of specificity included in the definition, the objectives of the study, and the resources and time available. Limiting the number of metrics reduces the burden on the experts significantly, but can also limit the scope of the assessment. Conversely, including superfluous elements could skew the results. Conflicting issues should be balanced to develop measures which fully encompass the concepts in the reliability definition, while accounting for real-world constraints such as time, resources, and human cognitive ability.

Several methods can be used to select the metrics. A somewhat systematic one is outlined in the field of hazard analysis. Hazard analysis is a qualitative method used in risk analyses to identify components deserving detailed review. It often takes the form of a checklist evaluation completed by industry experts. Andrews and Moss define hazard analysis as a process used for "identifying events which lead to materialization of a hazard, analysis of mechanisms by which these events occur, and estimation of the likelihood and extent of harmful effects" (Andrews and Moss, 2002, pp.59-60). It provides a formulaic method to prioritize metrics to include in the assessment given limited time. Metrics can be selected that best capture events and mechanisms deemed most likely to produce harmful effects. Less formal methods can be used as well. These include literature reviews, interviews with experts, and group discussions.

4. Specify Hydrogen Energy Systems to Evaluate

The metrics developed in the previous step are used to assess the reliability of hydrogen pathways. The pathways should be detailed to the extent possible to allow accurate and consistent reliability ratings. Descriptions should include demand scenarios, primary energy supply systems, hydrogen production processes, and hydrogen transport processes. End use – including energy use associated with compression or liquefaction, required purity and pressure, and risks at the refueling station – also affects reliability, but is beyond the scope of this study. This analysis only considers hydrogen reliability upstream from the consumer.

An important aspect of reliability is the demand scenario under which the hydrogen systems operate. It should be defined over the entire time frame established in the reliability definition. If the pathways are expected to operate under different demand scenarios, each needs to be clearly specified. Items to consider when defining the demand scenario include:

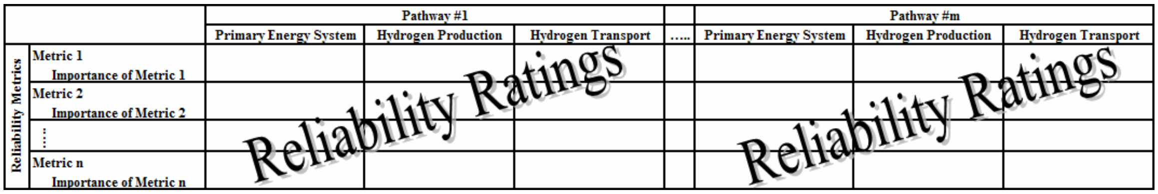
- Total volume demanded
- Demand profiles (variation of demand with time and season)
- Geographical distribution of demand
- Geographical distribution of supply sources and systems
- End use (not considered here)

The primary energy supply system must also be clearly defined. Hydrogen is similar to electricity and gasoline in that it does not exist by itself, and must be created from another energy resource. The primary energy supply system encompasses the entire system used to deliver an energy product to the point of hydrogen production. It includes the primary energy feedstocks, their extraction and transport processes, and the production, transportation, and/or refining of the final energy product. Primary energy feedstocks include any naturally occurring fossil or renewable energy resource. If electricity is used as the primary energy supply system, it also has a primary energy supply system which must be defined in this step. That is, the feedstocks used to create the electricity (and the systems used to extract, transport, and produce those feedstocks) should be specified along with the systems used to generate and transport it to the hydrogen production facility.

Similar considerations apply for defining the hydrogen production and transport processes. The technologies used, the size and geographical extent of the processes, and other details should be specified. Greater detail allows more accuracy and consistency in the ratings.

5. Develop Evaluation Matrix

The metrics selected in *step 3* can be related to the pathways defined in *step 4* in a matrix. The matrix displays the ratings for each metric for each component of each pathway. The structure of the matrix is depicted in Figure 17.

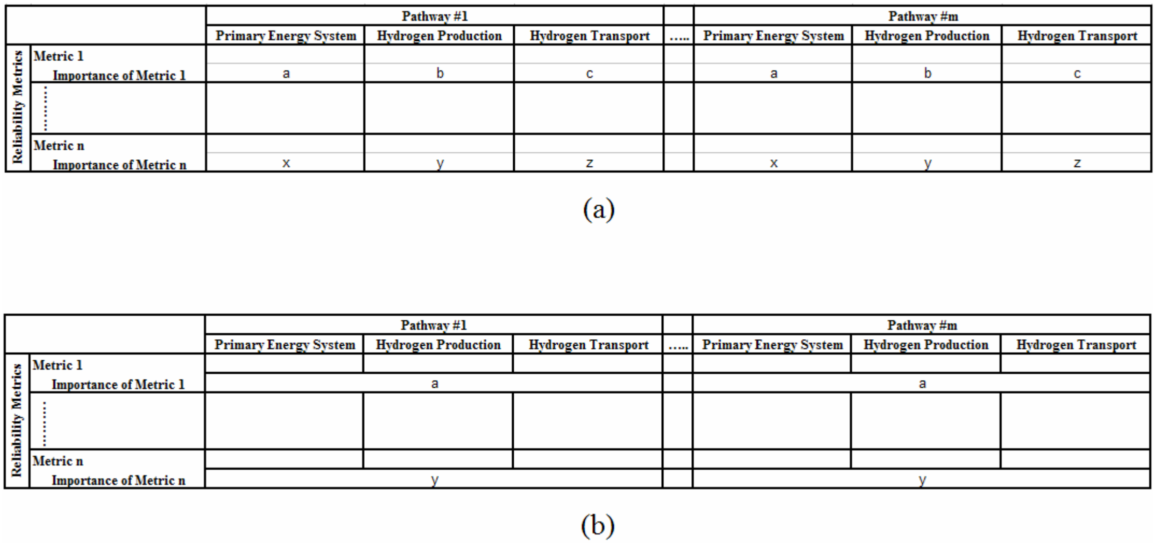


		Pathway #1			…..	Pathway #m		
		Primary Energy System	Hydrogen Production	Hydrogen Transport	…..	Primary Energy System	Hydrogen Production	Hydrogen Transport
Reliability Metrics	Metric 1 Importance of Metric 1							
	Metric 2 Importance of Metric 2							
	⋮							
	Metric n Importance of Metric n							

Figure 17. Structure of hydrogen reliability evaluation matrix.

Associated with each metric is an importance rating. It allows the expert to evaluate the degree to which he or she perceives the metric to contribute to the reliable operation of the system. These ratings are used to weight the reliability ratings during aggregation. The idea is similar to the use of saliency weights in consumer behavior research (Day, 1973, p.310). They weight consumer beliefs about a product and represent the degree to which the item being rated relates to another item or concept, such as preference for the product (Fishbein, 1967, p.489). The importance ratings should be independent of the reliability rating for each element of the matrix. One way to think of the difference between the two ratings is to consider the reliability rating as the likelihood that the element will perform with a certain level of reliability, and the importance rating as the consequence that unreliable performance of that element would have on the system.

The importance metrics should be the same across pathways, but can vary between components. That is, *Metric 1* can be given an importance rating of *a* for the primary energy system, an importance rating of *b* for the hydrogen production process, and an importance rating of *c* for the hydrogen transport process. But across pathways, the same *a, b, c* ratings apply (see Figure 18a). Varying the importance ratings across pathway components adds detail to the assessment and conveys the notion that the importance of a metric depends on the component of the system being considered. But it also increases the burden on the experts, and is sometimes difficult to distinguish the importance of a metric among pathway components. These drawbacks were made apparent in the trial application of the methodology, discussed in later sections. The alternative is to rate the importance of the metric only once, to the entire pathway (see Figure 18b). The selection of the technique depends on the level of information desired from the experts and the time available for the study.



		Pathway #1				Pathway #m		
		Primary Energy System	Hydrogen Production	Hydrogen Transport	…..	Primary Energy System	Hydrogen Production	Hydrogen Transport
Reliability Metrics	Metric 1							
	Importance of Metric 1	a	b	c		a	b	c
	⋮							
	Metric n							
	Importance of Metric n	x	y	z		x	y	z

(a)

		Pathway #1				Pathway #m		
		Primary Energy System	Hydrogen Production	Hydrogen Transport	…..	Primary Energy System	Hydrogen Production	Hydrogen Transport
Reliability Metrics	Metric 1							
	Importance of Metric 1	a				a		
	⋮							
	Metric n							
	Importance of Metric n	y				y		

(b)

Figure 18. Sample importance ratings: a) different importance ratings for each pathway component, b) same importance ratings for each pathway component.

6. Develop Rating Scales and Rating Criteria

After forming the evaluation matrix, rating scales and criteria to evaluate its elements are developed. Rating scales for both the reliability ratings and importance ratings should be specified, though they can be the same. If more are desired, such as different scales for different metrics, then more can be incorporated into the evaluation. While it adds complexity and may make the evaluation more confusing for the experts, various scales could be beneficial in some cases, such as when some metrics can be evaluated quantitatively, and others qualitatively.

The scale used should accurately capture the degree to which the system operates reliably according to the definition established in *step 1*. Several scales exist to capture different types of measurements. The primary difference between scales is the level of information that can be inferred from the rating. Behavioral researchers identify four scales conveying increasing levels of information (e.g., Summers, 1970, p.11). Nominal measurements are the simplest. They are categorical and simply distinguish between responses. They are not appropriate for this study, and are not considered here. Ordinal measures are the next most powerful and simply convey a ranking of elements. That is, a *1* comes before a *2*, comes before a *3*, and so on. Interval measures include an extra degree of information – the interval between numerical ratings is meaningful. That is, the difference between a *2* and a *3* is the same as the difference between a *3* and a *4*. The last, and most powerful, is the ratio measure. This scale includes an absolute origin, so all mathematical operations, including multiplication and division, can be performed on the ratings. That is, a rating of *2* implies twice as much as a rating of *1*. The literature covers the advantages, disadvantages, and semantics of each scale in depth. Here, it suffices to say that care should be taken when developing a rating scale, to properly capture the desired information contained in the expert opinions.

Criteria for rating the elements must also be clearly specified. This allows for consistent ratings and reduces the subjectivity of expert opinion. The criteria may be qualitative, quantitative, or a mixture of both. The selection of the criteria depends on the level of knowledge among the experts and the quantity and quality of data available regarding the metric. Quantitative criteria are often desirable to remove ambiguities that may emerge in subjective ratings. But for somewhat abstract metrics or for those on which little data exists, qualitative criteria may be needed. The type of criterion selected does not necessarily depend on the type of rating scale selected. For example, although a qualitative rating scale of *good*, *fair*, and *poor* might be applied to a metric *weather*, supporting criteria could be quantitative. *Good* might correspond to a mid-day temperature above 85°F, *fair* to temperatures between 60°F and 85°F, and *poor* to those below 60°F.

7. Collect Expert Reliability and Importance Ratings

With all inputs and procedures defined and selected, the method proceeds to the experts. They rate the reliability of each metric as it pertains to the components of each pathway, and the importance of each. Their ratings are based on the scales previously established. If the experts have not been involved in the process until this point, the method and their task should be clearly described to them. This includes clearly defining the metrics, pathways, scales, and criteria involved in the assessment. If multiple experts are involved, the methodology should be similarly described to each.

The shape of future hydrogen energy systems remains unknown and little data exists publicly on their reliability. Thus, expert opinions rely heavily on subjective assumptions about future systems, taking the form of cognitive beliefs. Specific definitions of cognitive belief vary in the literature,[15] but here it is defined to encompass what an expert thinks, knows, or believes about each metric.

Cognitive beliefs can be ascertained through the use of attitudinal surveys. Attitudinal surveys gauge feelings, intentions, and opinions towards concepts, objects, or persons (Mokhtarian, 2003). The process by which the survey is administered is up to the organization, and depends on the scope of the study, the desired results, and the time and resources available. The organization may want to bring the experts together to

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[15] Some examples can be found in Sudman and Bradburn (1982, p.123) and Dillman (1978, pp.80-86).

encourage discussion and consensus, or have the experts conduct the evaluations separately if anonymity is desired. Formal surveys, informal surveys, group discussion, facilitated exercises, or personal interviews can all be used, each suited for different situations.

8. Aggregate Expert Ratings to Determine Reliability Scores

After expert ratings are collected, they are statistically aggregated to develop broad scores for the reliability of each pathway. Specific ratings – of which there could be hundreds or thousands from each expert – are combined to generate general scores applicable to the original definition that can be easily compared across pathways.

The method used to aggregate the scores depends on the scope and intention of the study and the definition of reliability. Two possible techniques are described here, though any number of others could be substantiated as well. One is to take a weighted average of each expert's responses. The idea is to capture the *importance-weighted average perception* of each respondent, using the following formula:

$$\textit{Importance-weighted average perception} = \frac{\sum_{i=1}^{n}\left(R_i \times I_i\right)}{\sum_{i=1}^{n} I_i},$$

where: R_i= Reliability rating of metric i,

I_i = Importance rating of metric i,

n = Number of metrics included in the aggregation.

The other method is to establish a "utility" function to capture each expert's overall evaluation of reliability. Day discusses this method in terms of consumer attitudes and purchasing behavior (Day, 1973, p.312). He defines consumer attitudes toward an object as the product of a belief score multiplied by an importance rating. The belief score represents the degree to which the consumer feels that the object possesses a specific quality. The importance rating is the degree to which the consumer feels that the specific quality is important to an overall purchasing decision. These products are summed across the several attributes important to the object. The nomenclature of his model can be adapted to apply to expert opinions on reliability:

$$Utility = \sum_{i=1}^{n} \left(R_i \times I_i \right).$$

The additive model proposed by Day is conceptually elegant, but poses problems when comparing pathways in which not all metrics apply. If some metrics apply to one pathway but not another, then the first pathway is bound to receive a greater score than the next pathway. If a high score corresponds to poor reliability, the argument could be made that this does not pose a significant problem. One could contend that because not all of the metrics apply, there are fewer opportunities for a loss of reliability and such a pathway deserves a lower score. This claim could be true in many cases. But to argue that the *utility* model properly captures the degree to which reliability improves relies on the dangerous assumption that the metrics encompass reliability perfectly. In cases where a low score corresponds to poor reliability, then the additive model makes little sense. The pathway with fewer applicable metrics would likely appear less reliable than a pathway where more metrics apply.

This problem arose between the pathways assessed in the next section. Many of the metrics were thought to apply to one pathway but not the other. To alleviate this problem, and put the *utility* model on a similar scale as the *importance-weighted average perception* model for comparison purposes, the *utility* model can be scaled by the number of metrics and the maximum reliability rating:

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

where: m = Maximum reliability rating.

The difference between the models is subtle, but noteworthy. Let us assume that a scale of 1-5 is used for both the reliability and importance ratings, where *5* corresponds to high importance and low reliability, and *1* corresponds to low importance and high reliability. Comparatively, both models show identical differences among pathway options. The percentage difference between reliability scores for different pathways is the same under both models. Also, the percentage of the maximum possible reliability score allowed by each model is the same. But the maximum possible aggregated score differs between the two models. Under the *importance-weighted average perception* model, the maximum score is *5*, but maximum score for the *scaled utility* model depends on the importance ratings. It is equal to the score obtained for a given set of importance ratings if all of the reliability ratings are *5*. That is:

$$\textit{Maximum possible aggregated score (scaled utility)} = \frac{\sum_{i=1}^{n}\left(5\times I_i\right)}{m\times n}.$$

The difference appears on an absolute scale, where the scores using the *scaled utility* method will always be lower (unless every metric received an importance rating of 5).

The similarities and differences between the two scales are depicted in Table 6. Using the reliability and importance ratings listed in Table 5, reliability scores are aggregated in Table 6 using both techniques. It can be seen that the maximum score possible using the *scaled utility* model is only *2.8*, but in both methods Pathway #2 scores 1.79 times higher than Pathway #1. The scores obtained using the *scaled utility* model are lower than those using the *importance-weighted average perception* model, but both aggregation techniques yield scores that are 47% of the maximum possible score for Pathway #1, and 76% of the maximum possible in Pathway #2. Figure 19 illustrates the similarities between the methods if both are plotted in terms of their maximum possible score.

Table 5. Reliability and importance ratings for two hypothetical pathways.

	Pathway #1		**Pathway #2**	
	R_i	I_i	R_i	I_i
Metric 1	1	5	3	5
Metric 2	2	4	5	4
Metric 3	4	2	5	2
Metric 4	2	1	2	1
Metric 5	5	2	3	2

Table 6. Reliability scores for two hypothetical hydrogen pathways using two aggregation methods.

	Importance-weighted Average Perception			Scaled Utility			
	Reliability Score	Max Score	$\frac{\text{Reliability Score}}{\text{Max Score}}$	Reliability Score	Max Score	$\frac{\text{Reliability Score}}{\text{Max Score}}$	$\frac{\text{IWAP}}{\text{SU}}$
Pathway #1	2.36	5	0.47	1.32	2.8	0.47	1.79
Pathway #2	3.79	5	0.76	2.12	2.8	0.76	1.79

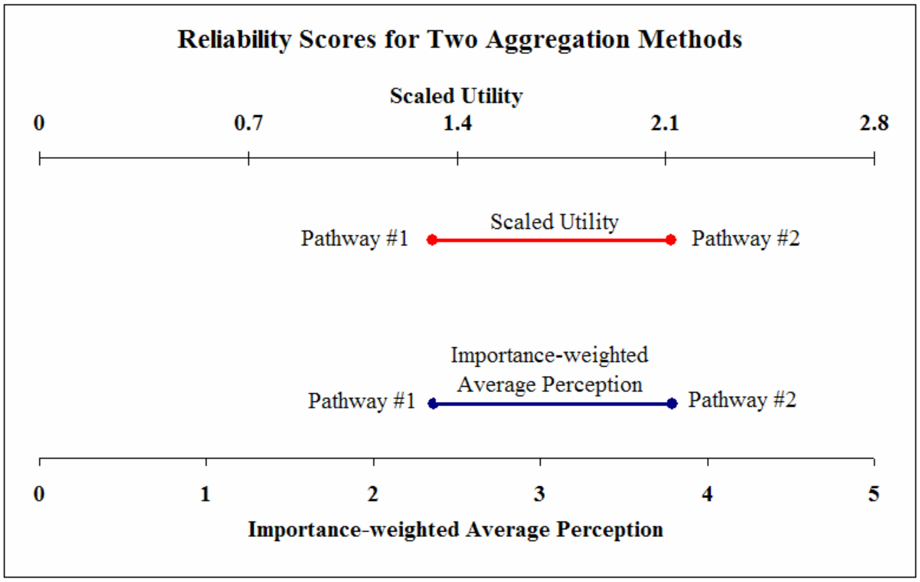

Figure 19. Comparison of reliability scores for two hypothetical hydrogen pathways using the two aggregation methods.

The difference between the techniques stems from the fact that metrics of low importance serve to improve the reliability score under the *scaled utility* model, but in the *importance-weighted average perception* model, they are scaled down and influence reliability to a lesser extent. In the *scaled utility* model, the reliability of a component is determined equally by its reliability rating and its importance to the overall system. That is, a component with an importance rating of *1* and a reliability rating of *5* contributes the same to reliability as a component with an importance rating of *5* and a reliability rating of *1*. The *importance-weighted average perception* model determines component reliability only by its reliability ratings. Under this model, importance ratings serve to weight the reliability ratings in terms of their effect on reliability of the system. The reliability score for the pathway can only be improved by improving the reliability rating of the component.

The differences in the models may be negligible if the assessment looks only to compare pathway options, since both produce the same percentage difference between pathways. But if the reliability scores are to be put on an absolute scale, the differences are no longer negligible. Careful consideration should be taken when selecting the aggregation method, to assure the results are portrayed accurately.

9. Compare Reliability Scores across Pathways

Finally, the aggregated reliability scores are compared across pathways to determine reliable or unreliable aspects. This can be done graphically, numerically, or statistically.

APPLYING THE METHODOLOGY

The methodology was tested using a group of hydrogen researchers from the Institute of Transportation Studies at the University of California, Davis (ITS-Davis) as the expert panel. The primary objective was to refine the methodology and identify opportunities for improvement.

The scope of the assessment and the participation of the panel were limited by time and logistical constraints. First, only three hours were allotted for the study. In practice, vulnerability or risk assessments involving an expert panel often last multiple days at workshops.[16] Due to time limitations, the definition of hydrogen reliability, the metrics to value it, and the specification of pathways were established prior to meeting with the panel. The role of the expert panel was to rate the reliability metrics and provide feedback on the method. Second, although ITS-Davis arguably boasts one of the largest and most diverse groups of hydrogen infrastructure researchers in the world, many are not completely familiar with reliability. An ideal panel would include reliability experts from all relevant sectors, not just hydrogen. Despite these limitations, the test application did serve its purpose. It further developed the methodology and brought to light particular strengths and weaknesses.

Inputs provided to the panel in this assessment were purposefully vague. Certainly, when considering real systems, the panel should be provided with as much information as possible to allow an accurate assessment. But due to the limited time during which the panel was available, descriptions and definitions of reliability, the scope of study, and the supply and demand scenarios were not specified to the degree desired for an assessment of real systems.[17] For the developmental purposes of this application and the hypothetical scenarios considered, specific details were not required. In fact, they would likely not have supplied the experts with extra useful information, and could have biased the results. Many of the researchers comprising the panel do not have a background in reliability studies, and may have not been able to translate specific details about a system

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[16] For example, the U.S. DOE routinely hosts workshops of natural gas industry experts to identify issues with infrastructure reliability and R&D opportunities to address those issues (e.g., U.S. DOE and NETL [2002] and SCNG [2000]).

[17] The inputs that were provided to the panel are discussed in the sections that follow, and the written materials provided to the experts appear in Appendix C.

into accurate reliability ratings. Consider the example of LNG as a primary energy system and the metric *utilization*. If the level of utilization at the LNG import terminal had been specified, many panel members could have had difficulty translating the additional information into a reliability rating. It may have not been too difficult had we specified the degree of utilization to be especially high or low, but doing so could have biased the results to make LNG look particularly attractive or unattractive. Some respondents expressed difficulty in rating some metrics without more information, but providing more would likely not have changed the results significantly. Despite the vague descriptions provided to the panel, the results from this application provide general insights into the reliability of the two hydrogen pathways, which might be the most we can take from the hypothetical scenarios, anyway.

The author assessed the pathways as well, independently from the expert panel. These are not included in the aggregated results presented here, but are given in Appendix D. A description is provided for each rating which intends to bring to light reliability issues that go unnoticed from a simple examination of the ratings and reliability scores.

1. Define Scope of Study and Select Participants

The scope of the study as described to the panel spanned a network of hydrogen refueling stations in Sacramento (CA), and their upstream supply systems. Participants were 11 graduate students, staff, and faculty researchers within the Hydrogen Pathways Program at ITS-Davis who volunteered to participate. The process followed Contadini's first model. A single modeler (the author) defined reliability, selected metrics to value it, and pathways to consider. The role of the experts was limited to rating the elements, as a consequence of time limitations.

2. Define Reliability in Hydrogen Energy Systems

The definition of reliability in hydrogen energy systems is adapted from the definition appearing in literature specific to the electricity sector. There, reliability is defined generally as the ability to meet consumer requirements, and comprises two concepts: adequacy and security. Adequacy refers to the ability of system throughput to meet demand. Security relates to the level of resiliency against disruption. The definitions cited earlier were slightly modified in this step to yield formal definitions for reliability in hydrogen systems:

> 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 (adapted from the NERC's definition of reliability, as cited in: Kirby and Hirst, 2002, p.9).

> Adequacy – The ability of the system to supply the requirements of customers at all times, taking into account reasonably expected outages in the system (adapted from: NERC, 2002, p.7).

Security – The ability of the system to minimize and withstand unexpected interruptions (adapted from: NERC, 2002, p.7).

These terms do not incorporate all of the elements required in a traditional reliability definition as described earlier. Specifically, no time frame is given. In many situations, the specified time frame will influence the assessment significantly. That was not the case in this application. The metrics described below do not value reliability in a traditional, statistical sense. Rather, they aim to capture the relative public benefits between system configurations. If a time frame had been specified, the experts might be inclined to think in terms of the likelihood of hydrogen systems lasting so long, and the concepts captured by the metrics could have been obscured.

3. Select Metrics to Value Reliability in Hydrogen Energy Systems

Metrics to value hydrogen reliability were developed by further dissecting the definition from the concepts of adequacy and security into tangible elements that can be measured. The metrics used here are broad, and value hydrogen reliability from a societal perspective (see Figure 20). They do not aim to quantify reliability in a traditional sense, in terms of the expected performance and lifetime of system components. Rather, they include wide-ranging concepts pertaining to the availability of hydrogen and the consequences that could stem from the use of a particular system.

The relationship between the metrics and the adequacy and security categories is shown in Figure 20. Each element in the figure is discussed below, and defined in Appendix C.

The 20 metrics on the right in the figure are the most rudimentary elements of reliability considered in this study. Many were selected from the literature review detailed earlier. The sub-categorization could continue, and each could be dissected further. This was not done for practical reasons, but various aspects of each metric are discussed with the author's ratings in the Appendix.

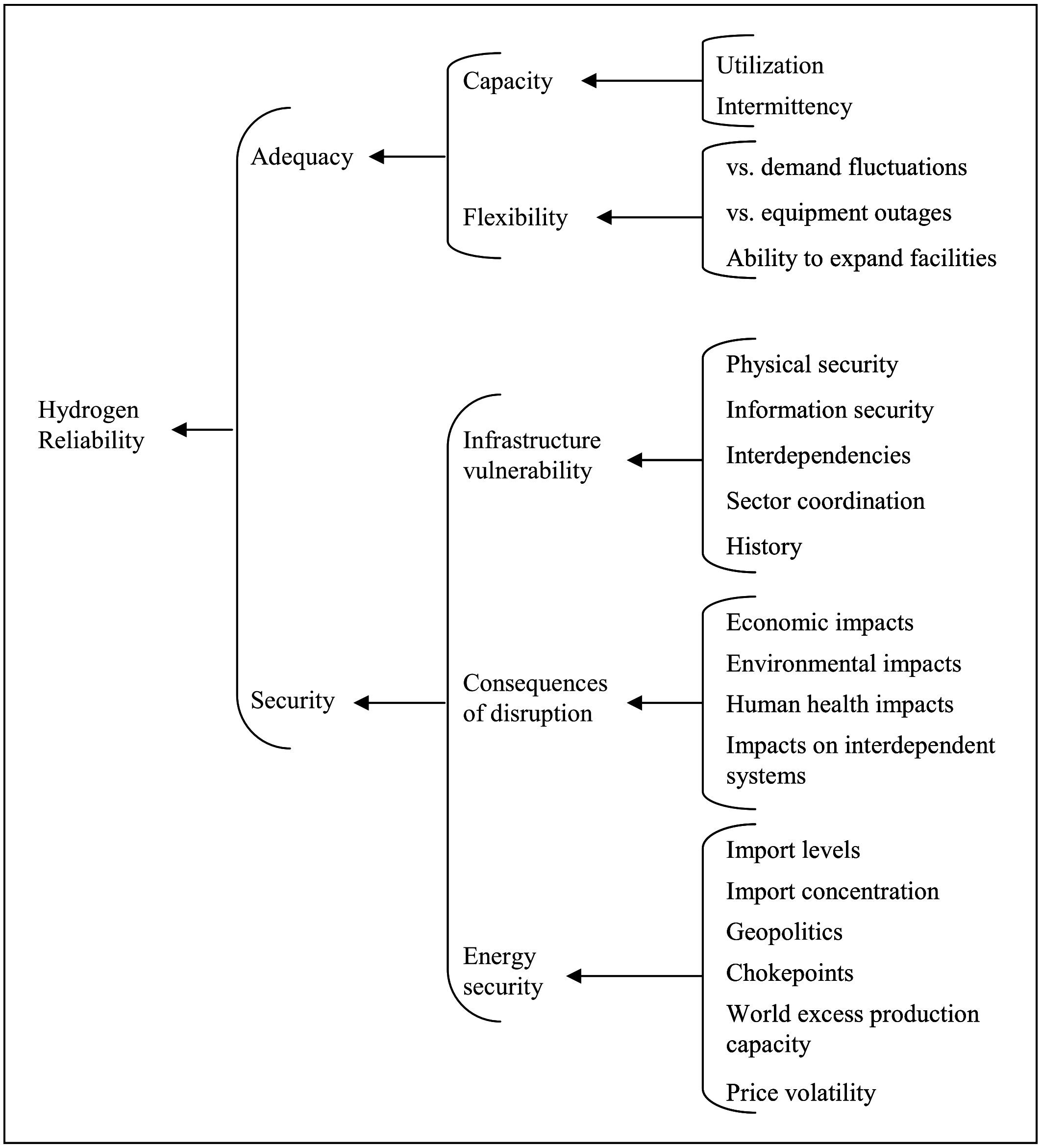


Figure 20. Hydrogen reliability metrics considered in this study.

Adequacy

The definition of adequacy captures two ideas – *capacity* and *flexibility*. *Capacity* refers to the ability of the system to produce and transport sufficient quantities of hydrogen to supply end user demands. It is assigned two metrics:

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

Flexibility speaks to the second portion of the definition, and refers to the degree to which the system can adapt to changing conditions. This concept 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.

Security

Security covers concepts of risk management and supply security of energy resources. It is valued here by three measures. Risk is typically defined as the product of the probability of a failure and the consequence of the failure. These concepts are captured with the measures *infrastructure vulnerability* and *consequences of infrastructure disruption*, respectively. *Energy security* constitutes the third component of 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 infrastructures 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 U.S.
- *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 energy resources to the U.S.
- *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. Specify Hydrogen Energy Systems to Evaluate

The demand scenario under which the pathways operate was defined as “a network of hydrogen refueling stations” in Sacramento (see Appendix C). No parameter regarding demand volume, demand profile, or geographical distribution of the refueling stations was specified. Some information regarding end use and time frame was implied in the description, but no details were given. Transportation applications are suggested as the end use, but no consideration was given to the requirements of the end user or reliability at the refueling stations. Also, the experts were asked to evaluate reliability in terms of their knowledge of the systems and environmental, political, and social conditions today. This suggests a near-term time frame, though again, none was specified.

Two pathways were assessed. *Pathway #1* relies on hydrogen produced centrally via steam reformation of imported LNG and distribution of hydrogen by pipeline. LNG supplies come primarily from Trinidad and Tobago, but also from Alaska, Australia, Indonesia, Malaysia, and trace amounts from the Middle Eastern states of Qatar and the United Arab Emirates. In *Pathway #2*, hydrogen is produced at its point of end use via electrolysis of water using electricity produced independently from the electric grid from locally available renewable energy resources. No transport of hydrogen from offsite is needed in this pathway.

The pathways were defined vaguely, and selected to capture general reliability concerns surrounding two apparently disparate hydrogen supply options. The intention was to learn generally about comparative advantages and disadvantages between primary energy feedstocks, and between centralized and distributed systems.

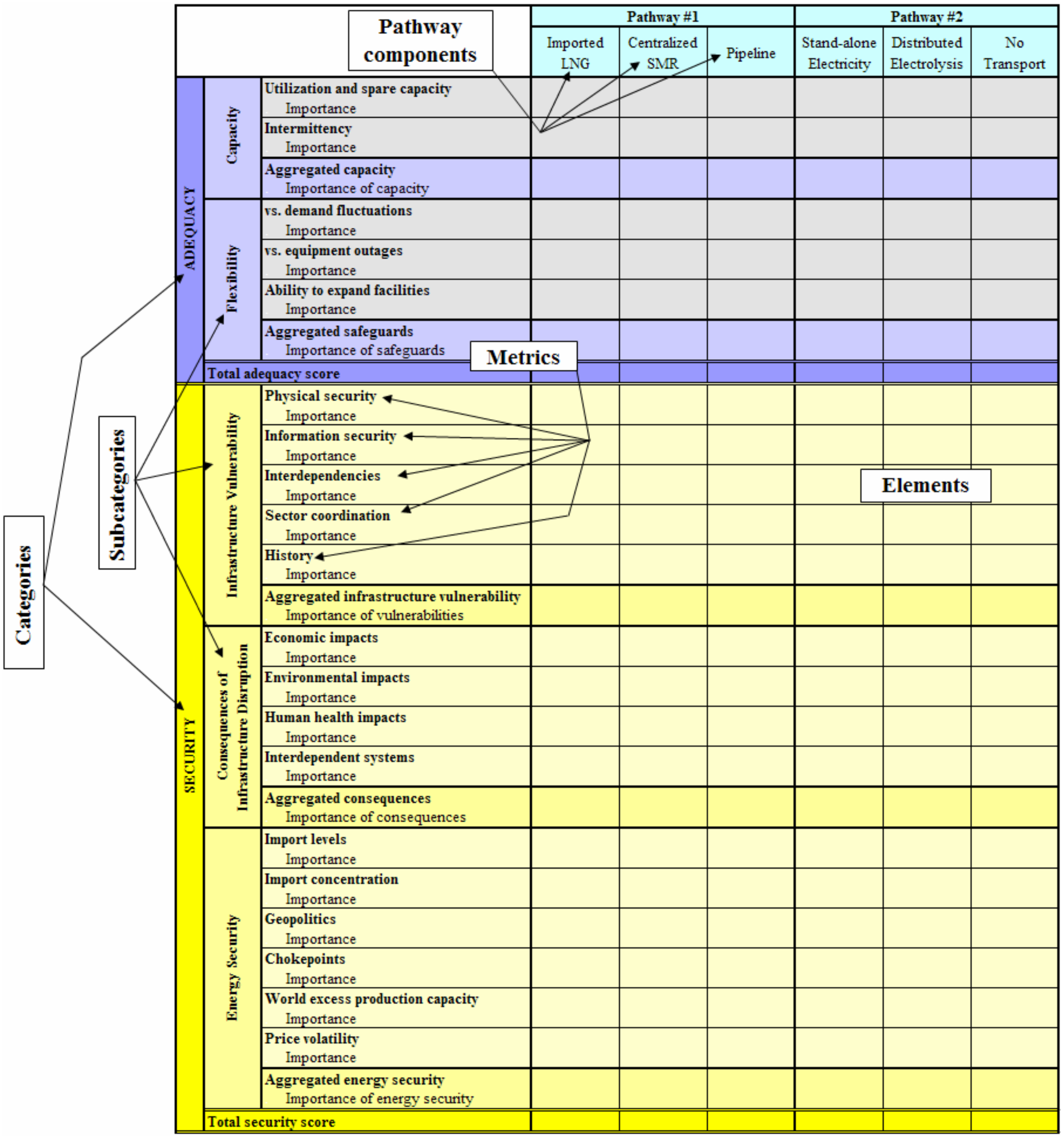
5. Develop Evaluation Matrix

The evaluation matrix summarizes all of the information obtained in the study, and relates the metrics selected and their importance to the pathways defined. The evaluation matrix used here is shown in Figure 21. The pathway components are listed across the top of the matrix, and the metrics are listed down the side. The metrics are separated according to the two subcategories of *adequacy,* and the three subcategories of *security.* The evaluation matrix provides a useful visual to compare reliability ratings across pathway components. The aggregated reliability scores are also depicted, in the darkly shaded regions.

It is fitting here to introduce nomenclature that will be used in the remainder of this discussion. Although words such as "component" and "element" have been used somewhat loosely before, they now take on more concrete meanings:

- *Category.* The two aspects of hydrogen reliability – *adequacy* and *security*.
- *Subcategory.* The five aspects of *adequacy* and *security –capacity*, *flexibility*, *infrastructure vulnerability*, *consequence of infrastructure disruption*, and *energy security*.
- *Metric.* The aspects of the subcategories which are rated.

- *Pathway component*. The three aspects of each pathway which are rated – *primary energy supply system*, *hydrogen production*, and *hydrogen transport*.
- *Element*. The boxes in the evaluation matrix which correspond to a specific metric and pathway component.



			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
ADEQUACY	Capacity	**Utilization and spare capacity** Importance						
		Intermittency Importance						
		Aggregated capacity Importance of capacity						
	Flexibility	**vs. demand fluctuations** Importance						
		vs. equipment outages Importance						
		Ability to expand facilities Importance						
		Aggregated safeguards Importance of safeguards						
	Total adequacy score							
SECURITY	Infrastructure Vulnerability	**Physical security** Importance						
		Information security Importance						
		Interdependencies Importance						
		Sector coordination Importance						
		History Importance						
		Aggregated infrastructure vulnerability Importance of vulnerabilities						
	Consequences of Infrastructure Disruption	**Economic impacts** Importance						
		Environmental impacts Importance						
		Human health impacts Importance						
		Interdependent systems Importance						
		Aggregated consequences Importance of consequences						
	Energy Security	**Import levels** Importance						
		Import concentration Importance						
		Geopolitics Importance						
		Chokepoints Importance						
		World excess production capacity Importance						
		Price volatility Importance						
		Aggregated energy security Importance of energy security						
	Total security score							

Figure 21. Evaluation Matrix for Pathway #1 and Pathway #2 used in this study.

6. Develop Rating Scales and Rating Criteria

The scale developed to rate the reliability ratings is a variation of a five-point Likert scale. Rensis Likert introduced a rating scale widely used today to capture attitudes by assigning a value of one to five to each position in a five-point qualitative rating scale [Likert, 1932]. Here, an integer value of one to five is assigned to positions regarding reliability in terms of each metric. A general description of the scale is shown in Table 7. The ratings measure the degree to which the expert feels that reliability of the metric threatens reliability of the entire pathway. High ratings suggest that the metric presents a high level of threat to the reliable performance of the system. This scale holds for each metric. That is, a *5* always represents poor reliability, and a *1* always represents high reliability.[18] This convention was a point of confusion for some members of the expert panel, as it sometimes counters intuition. For example, although a higher rating for *capacity* intuitively seems good, according to this scale it indicates a lack of capacity. Some experts suggested that it would have been easier to make metrics defying intuition grammatically negative. That is, rather than calling the metric *capacity,* name it *lack of capacity*, or something similar. The rating scale and sometimes counterintuitive standard were adopted to simplify analysis and allow the same rating scale to be used for each metric. But in retrospect, it may have been clearer for the ratings to be descriptive positions, rather than using the Likert scale.

The rating scale also includes two other options, *0* and *?*. A *0* corresponds to an attitude that reliability of the metric could not possibly have any repercussions for reliability of

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[18] Attributing a numerical value to the qualitative ratings was somewhat arbitrary. Low scores were set to correspond to high reliability to take advantage of the rating *0* in the analysis. But the scale could have been inverted so that high ratings corresponded to high reliability and low ratings to low reliability.

the overall system. The question mark can mean two things – that the respondent does not know how to rate the reliability of the matrix element, or that the respondent feels that the metric does not apply to the pathway component being considered. The experts were asked to note why they selected *?* in any instances where they did. The primary motivation for including the two additional ratings was to capture expert opinion regarding non-applicable metrics. A metric might actually strengthen (or potentially, weaken) pathway reliability by not applying to a particular component. For example, by not having a hydrogen transport process in Pathway #2, many of the metrics are seemingly rendered inapplicable. In these cases, the experts could give ratings of *0* to suggest the pathway is made more reliable by not having hydrogen transport, or ratings of *?* to suggest that the metric does not apply and should not be included in the aggregation.

Table 7. Scale used to rate the reliability of each metric as it applies to each pathway component.

Degree to which the element threatens the reliability of the subcategory						
?	**0**	**1**	**2**	**3**	**4**	**5**
Unknown, or metric does not apply	None	Low	Moderately-Low	Moderate	Moderately-High	High

The same scale was used for the importance ratings. Table 8 describes the importance ratings used in this study. A rating of *5* always corresponds to a high level of importance, while a *1* always signifies low importance. A *0* means that the element has absolutely no influence on reliability, and a *?* indicates that the respondent does not know, or feels that the metric does not apply to the pathway component.

Table 8. Scale used to rate the importance of the metrics to reliability of the pathway component.

Level of importance of element to overall reliability						
?	**0**	**1**	**2**	**3**	**4**	**5**
Unknown, or metric does not apply	None	Low	Moderately-Low	Moderate	Moderately-High	High

Rating criteria were devised for each metric, and provided to the expert panel. Criteria were outlined for ratings of *0*, *1*, *3*, and *5*. The experts were left to interpolate ratings of *2* and *4* from the criteria. The criteria correspond to the rating scale just described, and intend to guide the experts and provide a uniform basis for their ratings. An example of the criteria for rating the metric *intermittency* is given in Table 9. The criteria suggest that a component should be given a *5* if output is completely unpredictable, a *3* if output is somewhat intermittent but predictable, and a *1* if output is usually constant. A rating of *0* suggests that the system will never operate intermittently. The criteria for rating all of the metrics appear in Appendix C.

Table 9. 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

7. Collect Expert Reliability and Importance Ratings

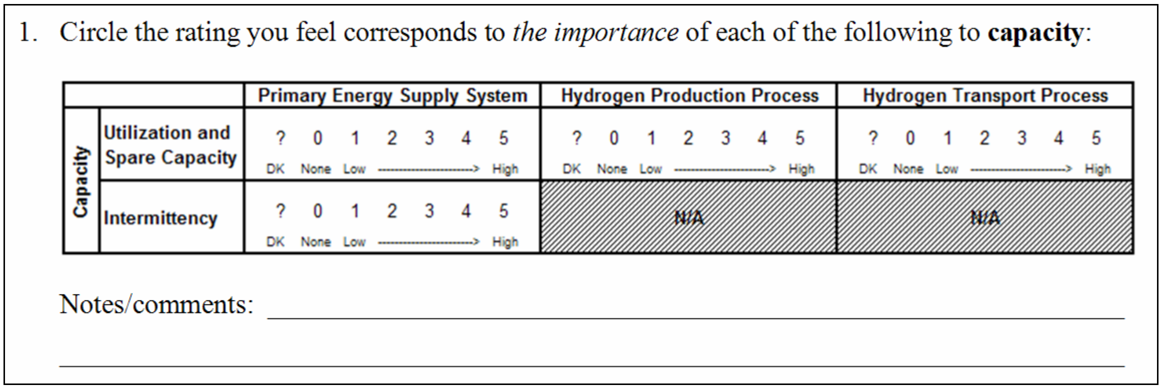
Expert opinions were elicited as part of a facilitated exercise through an informal survey. The entire survey, as well as the instructions and all of the supporting materials, is included in Appendix C. The expert panel convened in an informal atmosphere encouraging questions and discussion. A brief overview of the research and the methodology was given. The panel was incrementally walked through the rating procedure using an unrelated example – milk supply pathways – and was asked to rate the elements in turn. The example incorporated the same subcategories, metrics and pathway components as the hydrogen case. Cows constituted the primary supply system, milk processing at the dairy was the production process, and delivery via trucks served as the milk transport process.

The exercise was divided into two sections to reduce the stress on the experts and keep the objectives and considerations discussed in the example fresh in their minds. First, the experts were walked through the importance ratings for the milk supply pathway, and asked for importance ratings for the two hydrogen pathways. The same was done for the reliability ratings. Since the importance ratings are to be uniform across all pathways, they were ascertained first. This was done to prevent consideration of the reliability of specific pathways from influencing the ratings for the importance of the metrics to hydrogen reliability generally. To this end, the importance ratings were considered only in terms of the general pathway sub-processes: primary energy system, hydrogen production process, and hydrogen transport process. Specific components of Pathways #1 and #2 (e.g., hydrogen pipelines vs. onsite utilization) were introduced after the panel had rated importance.

The experts were asked to rate the importance of two relationships in the matrix. First, they rated the importance of each metric as it applied to reliability of its subcategory. For example, the importance of *utilization and spare capacity* and *intermittency* was rated as it pertains to the reliability of the subcategory *capacity.* Next, the experts rated the importance of each subcategory to overall reliability. These ratings were to be completely independent of the former ratings. Thus, it is possible for an expert to rate every metric under a particular subcategory very low, while rating the importance of the subcategory very high (this would suggest that the metrics were poorly chosen, however). This dichotomous scheme was adopted in order to allow the inclusion of less important metrics in subcategories of high importance to overall reliability. If the experts only rated the importance of the metrics, those thought to be less important to reliability of the subcategory might artificially lower the perceived importance of the subcategory to overall reliability.

The importance of the metrics was ascertained prior to that of the subcategories to prevent thoughts about the subcategory from influencing the importance ratings of the metrics. In the end, pathway reliability is ultimately determined by the reliability of the subcategories. The metrics serve to determine reliability of the subcategories. The importance ratings have no reach beyond weighting the influence of the various metrics on reliability of the subcategory, and should not be skewed by thoughts regarding the importance of the subcategory to overall reliability.

The importance rating portion of the survey contained six questions. The first five asked for the importance of the metrics pertaining to the five subcategories. The last question asked for the importance of the subcategories to overall reliability. The importance of each metric was rated for each pathway component, as depicted in Figure 18a. A sample question excerpted from the survey is shown in Figure 22. The question asks the expert to rate the reliability of the two metrics comprising the subcategory *capacity*. The pathway components appear across the top in general form – no specific components are given. Two of the boxes are blocked out and marked as "not applicable." This was done to save time and reduce the burden on the experts in cases where it was felt that the metrics did not apply. There was also room for comments from the panel after every question, and feedback was strongly encouraged.



1. Circle the rating you feel corresponds to *the importance* of each of the following to **capacity**:

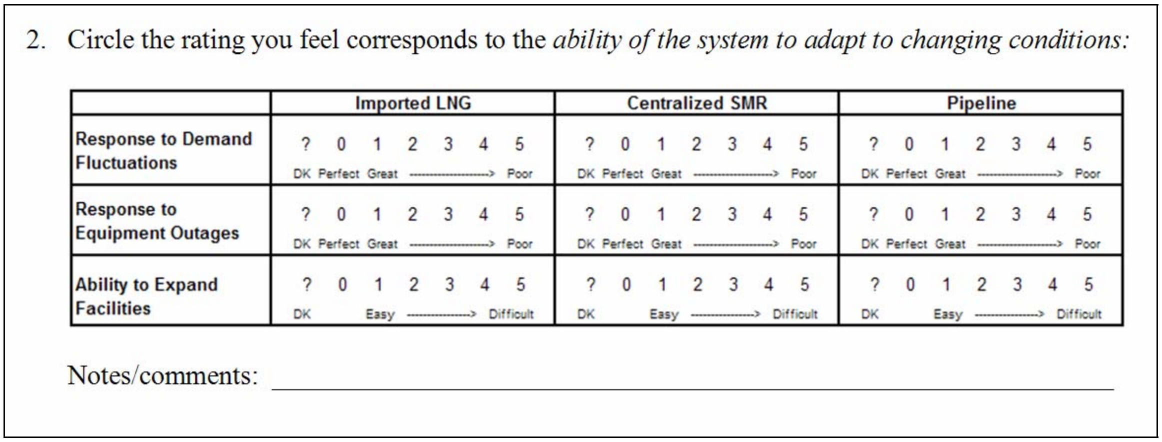
		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Capacity	**Utilization and Spare Capacity**	? 0 1 2 3 4 5 DK None Low -------------------> High	? 0 1 2 3 4 5 DK None Low -------------------> High	? 0 1 2 3 4 5 DK None Low -------------------> High
	Intermittency	? 0 1 2 3 4 5 DK None Low -------------------> High	N/A	N/A

Notes/comments: ____

____

Figure 22. Sample question excerpted from survey, ascertaining expert opinions on the importance of two metrics to the subcategory *capacity*.

After the importance ratings, the experts were walked through the reliability ratings for the milk supply example, and asked to rate the reliability of each element for both pathways. To keep from introducing a systematic bias, half of the panel was given Pathway #1 first, and half was given Pathway #2 first. An example question from the reliability rating portion of the survey for Pathway #1 is shown in Figure 23. The format is similar to that in Figure 22. The pathway components appear across the top, now specific to each pathway. The only difference between the portions of the survey for Pathway #1 and Pathway #2 is these pathway components. Descriptions are given under the numerical values of each metric. These vary according to the intuition evoked by the name of the metric, and were provided in an effort to reduce some of the confusion surrounding counterintuitive ratings. Nevertheless, as mentioned above, the scale served as a point of confusion for some members of the panel.



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 23. Sample question excerpted from survey, ascertaining expert opinions on the reliability of three metrics corresponding to the subcategory *flexibility* in Pathway #1.

8. Aggregate Expert Ratings to Determine Reliability Scores

The expert ratings were aggregated according to the *scaled utility* model. This method was used because it reflected a consensus among the panel that the importance ratings and reliability ratings equally influenced reliability. The model was scaled by the maximum reliability rating (five) and the number of components (n) being aggregated, to maintain the 0-5 scale between subcategories. The equation is repeated below:

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

where: R_i = Reliability rating of metric i,

I_i = Importance rating of metric i,

n = Number of metrics included in the aggregation.

Three aggregation steps were used to determine various pathway adequacy and security scores, each based on the *scaled utility* model. These are depicted in terms of adequacy in Figure 24. The same procedures apply for determining security scores. Step 1 aggregates metrics within each subcategory along each pathway component. This develops aggregated subcategory scores for each pathway component (depicted by ① in the figure). Second, these subcategory scores are aggregated to determine an adequacy score for each pathway component (the two ① for each pathway component are combined using the *scaled utility* model to get ② for the component). The scores found here provide insight into the perceived adequacy of each pathway component, but are not used in subsequent aggregations. Third, the subcategory scores are aggregated across all pathway components to determine one adequacy score for the entire pathway (the six ① are combined using the *scaled utility* model to get ③ for the entire pathway). Scores from step 1 were combined in step 3 because the importance ratings were allowed to vary across pathway components (see Figure 18a). If the importance ratings had been fixed across pathway components (as in Figure 18b), each pathway would be weighted equally and the three scores found in step 2 could be averaged to determine pathway adequacy.

The experts' ratings were input into separate evaluation matrices and aggregated independently. The average and standard deviation of the aggregated scores from each expert was used to determine overall pathway reliability. The average and standard deviation of each rating and aggregated score is shown in Table 10. The table allows the elements which most influence adequacy and security to be identified. For example, Pathway #2 received an average pathway adequacy score of 1.54. The component contributing the highest *scaled utility* score to pathway adequacy was the aggregated capacity of the stand-alone electricity system. It received the highest average reliability score (2.80) of the six contributing subcategories, and the second highest average importance rating (4.36). The metric providing the highest *utility* rating to this subcategory was *utilization and spare capacity*. Correlating the ratings and scores in this manner suggests that the perceived adequacy of Pathway #2 could be improved by adding to the capacity of its primary energy supply system (stand-alone electricity).

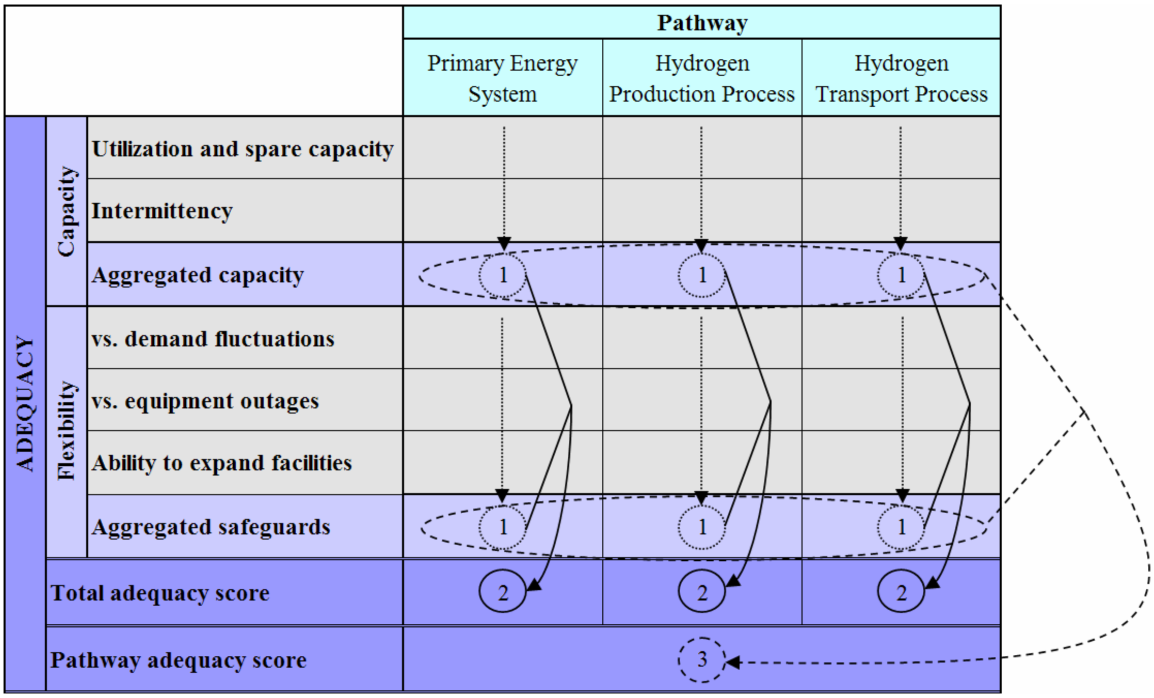
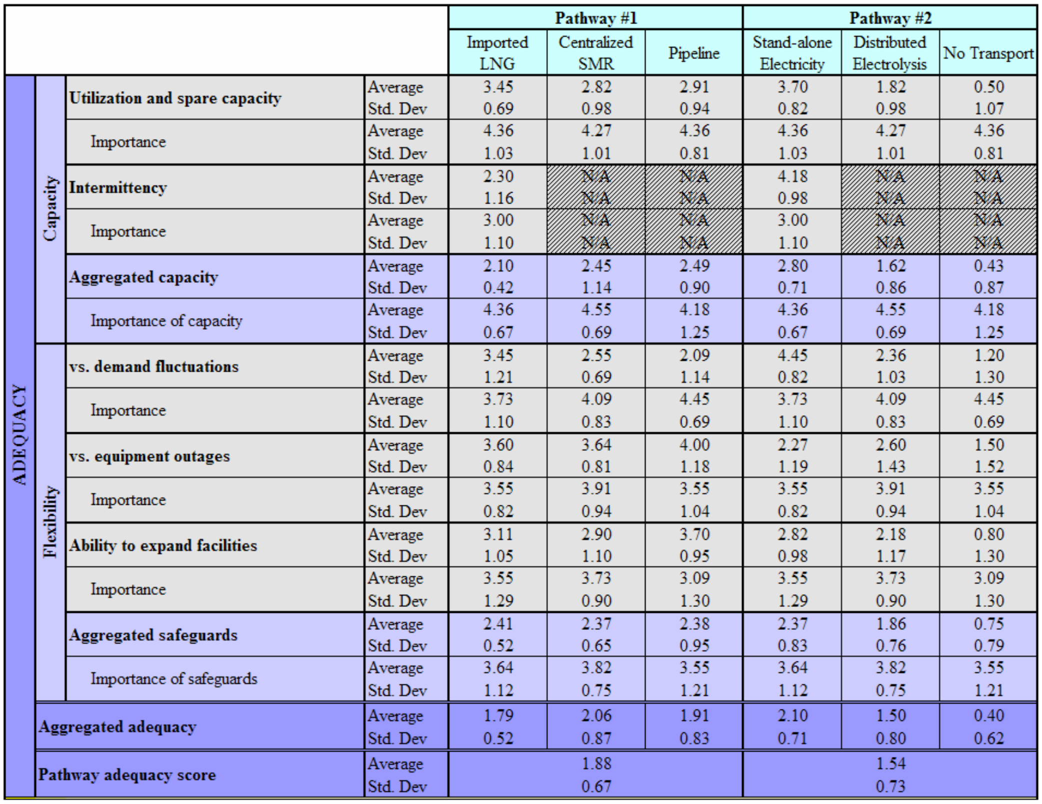


Figure 24. Aggregation steps used to determine aggregated adequacy scores.

Examining the standard deviations in Table 10 can provide insight into possible issues of confusion or conflict surrounding the method, and demonstrate confidence in the results. Many reliability scores associated with the hydrogen transport process (no transport) in Pathway #2 received high standard deviations. This was partly the result of many experts perceiving it as *not applicable*, leaving fewer ratings from which to average. But the consistently high standard deviations throughout the pathway component also suggest that the panel may have had difficulty here. Indeed, during the rating process, many panel members expressed confusion. They were unsure of how to rate metrics which they felt did not apply. This suggests there may have been a lack of clarity in describing the rating procedures of that section, or some confusion with the rating scale. Future applications of the methodology to this or similar pathways should be modified to reduce this confusion. The standard deviations in Table 10 also indicate the level of consensus among panel members, which parallels the degree of confidence in the results. Small standard deviations suggest consensus, and provide confidence in the results. Large standard deviations suggest a lack of consensus and may leave the results open to dispute.

Table 10. Average and standard deviation of experts' reliability ratings.



				Pathway #1			Pathway #2		
				Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
ADEQUACY	Capacity	**Utilization and spare capacity**	Average	3.45	2.82	2.91	3.70	1.82	0.50
			Std. Dev	0.69	0.98	0.94	0.82	0.98	1.07
		Importance	Average	4.36	4.27	4.36	4.36	4.27	4.36
			Std. Dev	1.03	1.01	0.81	1.03	1.01	0.81
		Intermittency	Average	2.30	N/A	N/A	4.18	N/A	N/A
			Std. Dev	1.16	N/A	N/A	0.98	N/A	N/A
		Importance	Average	3.00	N/A	N/A	3.00	N/A	N/A
			Std. Dev	1.10	N/A	N/A	1.10	N/A	N/A
		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
		Importance of capacity	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
	Flexibility	**vs. demand fluctuations**	Average	3.45	2.55	2.09	4.45	2.36	1.20
			Std. Dev	1.21	0.69	1.14	0.82	1.03	1.30
		Importance	Average	3.73	4.09	4.45	3.73	4.09	4.45
			Std. Dev	1.10	0.83	0.69	1.10	0.83	0.69
		vs. equipment outages	Average	3.60	3.64	4.00	2.27	2.60	1.50
			Std. Dev	0.84	0.81	1.18	1.19	1.43	1.52
		Importance	Average	3.55	3.91	3.55	3.55	3.91	3.55
			Std. Dev	0.82	0.94	1.04	0.82	0.94	1.04
		Ability to expand facilities	Average	3.11	2.90	3.70	2.82	2.18	0.80
			Std. Dev	1.05	1.10	0.95	0.98	1.17	1.30
		Importance	Average	3.55	3.73	3.09	3.55	3.73	3.09
			Std. Dev	1.29	0.90	1.30	1.29	0.90	1.30
		Aggregated safeguards	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
		Importance of safeguards	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	Infrastructure Vulnerability	**Physical security**	Average	3.55	3.09	4.18	1.64	1.36	1.33
			Std. Dev	1.04	1.04	0.75	0.67	0.67	1.75
		Importance	Average	4.18	3.90	3.70	4.18	3.90	3.70
			Std. Dev	0.87	0.99	1.06	0.87	0.99	1.06
		Information security	Average	2.75	2.50	2.40	2.09	1.50	0.75
			Std. Dev	0.71	1.08	0.84	1.04	0.97	0.96
		Importance	Average	3.73	4.09	3.64	3.73	4.09	3.64
			Std. Dev	1.49	1.04	0.81	1.49	1.04	0.81
		Interdependencies	Average	3.18	3.18	2.09	1.27	1.75	0.50
			Std. Dev	0.87	0.98	0.70	0.79	1.49	0.58
		Importance	Average	3.36	3.91	3.64	3.36	3.91	3.64
			Std. Dev	1.12	0.94	0.81	1.12	0.94	0.81
		Sector coordination	Average	3.44	2.50	2.50	1.88	2.14	1.20
			Std. Dev	0.88	0.76	0.93	0.99	1.35	1.30
		Importance	Average	3.40	3.20	2.90	3.40	3.20	2.90
			Std. Dev	0.84	0.79	1.10	0.84	0.79	1.10
		History	Average	2.33	1.57	2.56	2.25	2.25	1.25
			Std. Dev	1.22	0.79	1.24	1.28	1.28	1.50
		Importance	Average	3.27	2.18	2.18	3.27	2.18	2.18
			Std. Dev	0.90	0.75	1.25	0.90	0.75	1.25
		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
		Importance of vulnerabilities	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
	Consequences of Infrastructure Disruption	**Economic impacts**	Average	4.00	3.82	3.73	2.36	2.36	1.14
			Std. Dev	0.89	1.17	0.90	1.21	1.29	1.46
		Importance	Average	4.27	3.73	3.00	4.27	3.73	3.00
			Std. Dev	0.79	0.79	0.89	0.79	0.79	0.89
		Environmental impacts	Average	2.70	2.27	2.45	1.18	1.18	0.57
			Std. Dev	1.34	1.42	1.29	0.98	0.87	0.79
		Importance	Average	3.55	3.27	3.00	3.55	3.27	3.00
			Std. Dev	1.04	1.35	0.89	1.04	1.35	0.89
		Human health impacts	Average	2.10	2.27	2.55	0.82	1.18	0.71
			Std. Dev	1.52	1.49	1.37	0.60	0.98	1.11
		Importance	Average	4.18	3.55	3.55	4.18	3.55	3.55
			Std. Dev	1.08	1.37	1.37	1.08	1.37	1.37
		Interdependent systems	Average	3.82	3.18	3.27	2.36	1.90	0.83
			Std. Dev	1.08	1.17	1.19	1.50	1.37	1.17
		Importance	Average	4.00	3.55	3.09	4.00	3.55	3.09
			Std. Dev	1.00	1.21	1.04	1.00	1.21	1.04
		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
		Importance of consequences	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
	Energy Security	**Import levels**	Average	4.00	N/A	N/A	0.36	N/A	N/A
			Std. Dev	0.94	N/A	N/A	0.50	N/A	N/A
		Importance	Average	4.00	N/A	N/A	4.00	N/A	N/A
			Std. Dev	0.89	N/A	N/A	0.89	N/A	N/A
		Import concentration	Average	3.90	N/A	N/A	0.64	N/A	N/A
			Std. Dev	0.88	N/A	N/A	1.21	N/A	N/A
		Importance	Average	4.55	N/A	N/A	4.55	N/A	N/A
			Std. Dev	0.52	N/A	N/A	0.52	N/A	N/A
		Geopolitics	Average	2.90	N/A	N/A	0.55	N/A	N/A
			Std. Dev	0.74	N/A	N/A	0.52	N/A	N/A
		Importance	Average	4.27	N/A	N/A	4.27	N/A	N/A
			Std. Dev	0.90	N/A	N/A	0.90	N/A	N/A
		Chokepoints	Average	3.80	N/A	N/A	1.18	N/A	N/A
			Std. Dev	1.03	N/A	N/A	1.72	N/A	N/A
		Importance	Average	3.64	N/A	N/A	3.64	N/A	N/A
			Std. Dev	0.81	N/A	N/A	0.81	N/A	N/A
		World excess production capacity	Average	2.80	N/A	N/A	0.89	N/A	N/A
			Std. Dev	0.92	N/A	N/A	0.78	N/A	N/A
		Importance	Average	3.91	N/A	N/A	3.91	N/A	N/A
			Std. Dev	1.04	N/A	N/A	1.04	N/A	N/A
		Price volatility	Average	2.90	N/A	N/A	2.20	N/A	N/A
			Std. Dev	1.29	N/A	N/A	1.55	N/A	N/A
		Importance	Average	3.73	N/A	N/A	3.73	N/A	N/A
			Std. Dev	1.10	N/A	N/A	1.10	N/A	N/A
		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
		Importance of energy security	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		

9. Compare Reliability Scores across Pathways

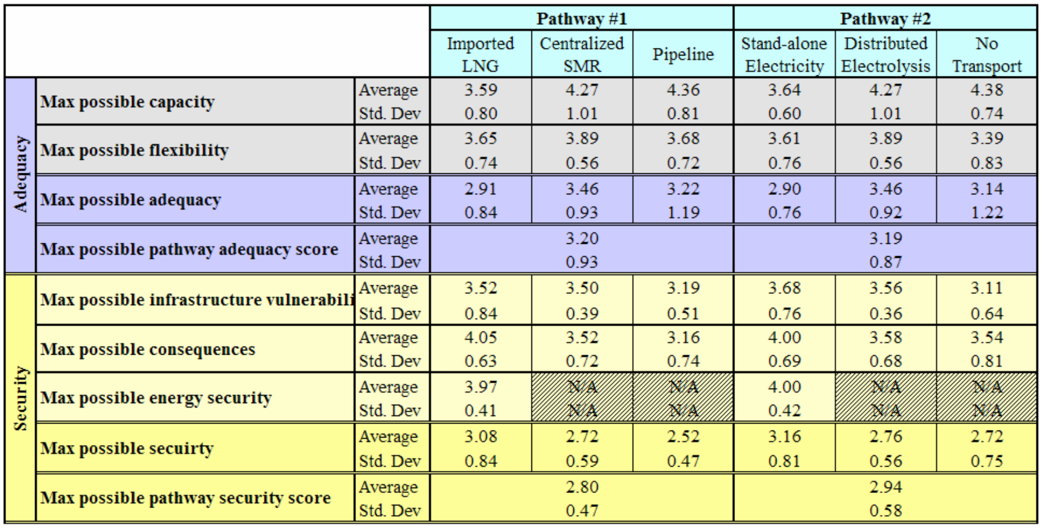
The expert panel found Pathway #2 to be more reliable than Pathway #1. The aggregated reliability scores for the pathways are compared in Table 11. According to the aggregation technique used here, Pathway #1 received an adequacy score of 1.88 and a security score of 1.74. Pathway #2 received a score of 1.54 for adequacy and 0.86 for security. Although the panel felt that LNG provided more adequate primary energy than stand-alone electricity (LNG received a lower aggregated adequacy score than stand-alone electricity, 1.79 versus 2.10), the distributed method of hydrogen production and the lack of hydrogen transport caused Pathway #2 to receive a more favorable adequacy score than Pathway #1. In terms of security, each component of Pathway #2 received more favorable reliability scores than those for Pathway #1.

Table 11. Average and standard deviation of experts' aggregated reliability scores.

			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		

As discussed previously, the maximum possible reliability scores using the *scaled utility* model will be less than *5* unless all of the importance ratings are *5*. The average and standard deviation of the maximum reliability scores from each expert are given in Table 12. On average, the maximum possible adequacy score is about 3.20.[19] The average maximum security score is 2.80 for Pathway #1, and 2.94 for Pathway #2. Although the importance ratings are the same for both pathways, the maximum possible scores vary somewhat because some metrics were thought to not apply to some pathway components. The average reliability scores are juxtaposed with the average maximum possible reliability scores in Table 13, along with their percentage of the maximum. Judging in terms of the percentage of the maximum possible score, the reliability scores appear much less reliable than they do on a scale with a maximum score of *5*.[20]

Table 12. Average and standard deviation of experts' maximum possible aggregated scores.



			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone Electricity	Distributed Electrolysis	No Transport
Adequacy	**Max possible capacity**	Average	3.59	4.27	4.36	3.64	4.27	4.38
		Std. Dev	0.80	1.01	0.81	0.60	1.01	0.74
	Max possible flexibility	Average	3.65	3.89	3.68	3.61	3.89	3.39
		Std. Dev	0.74	0.56	0.72	0.76	0.56	0.83
	Max possible adequacy	Average	2.91	3.46	3.22	2.90	3.46	3.14
		Std. Dev	0.84	0.93	1.19	0.76	0.92	1.22
	Max possible pathway adequacy score	Average	3.20			3.19		
		Std. Dev	0.93			0.87		
Security	**Max possible infrastructure vulnerabili**	Average	3.52	3.50	3.19	3.68	3.56	3.11
		Std. Dev	0.84	0.39	0.51	0.76	0.36	0.64
	Max possible consequences	Average	4.05	3.52	3.16	4.00	3.58	3.54
		Std. Dev	0.63	0.72	0.74	0.69	0.68	0.81
	Max possible energy security	Average	3.97	N/A	N/A	4.00	N/A	N/A
		Std. Dev	0.41	N/A	N/A	0.42	N/A	N/A
	Max possible secuirty	Average	3.08	2.72	2.52	3.16	2.76	2.72
		Std. Dev	0.84	0.59	0.47	0.81	0.56	0.75
	Max possible pathway security score	Average	2.80			2.94		
		Std. Dev	0.47			0.58		

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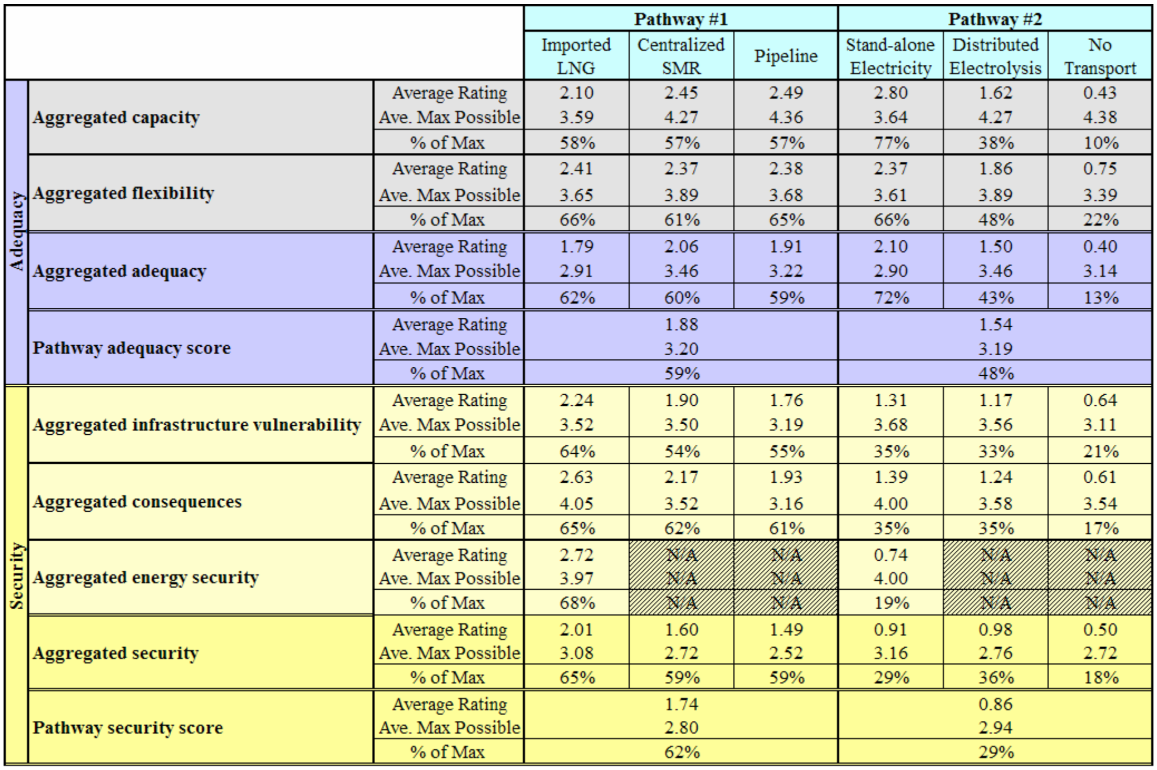
[19] Recall, the maximum possible score under the *scaled utility* model can be determined by setting each reliability rating to *5* in the aggregation.

[20] Recall that high reliability scores correspond to poor reliability, and low scores correspond to high reliability. When comparing the aggregated scores to the maximum that they can take on given importance ratings less than *5*, they appear less reliable (i.e., a higher percentage of the maximum) than they do when the maximum possible score is assumed to be *5*.

Table 13. Aggregated reliability scores showing percentage of maximum score possible.



			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 reliability of the two pathways is compared graphically in Figure 25. The maximum possible adequacy and security scores are shown by the vertical and horizontal lines, respectively.[21] The bars emanating from the reliability points represent the standard deviation of the expert responses. It can be seen that there is a relatively small standard deviation for security in Pathway #2. That signifies a general consensus among the expert panel on the level of security provided by Pathway #2.

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[21] The horizontal line in Figure 4.6 is the average of the two maximum possible security scores (i.e., 2.87).

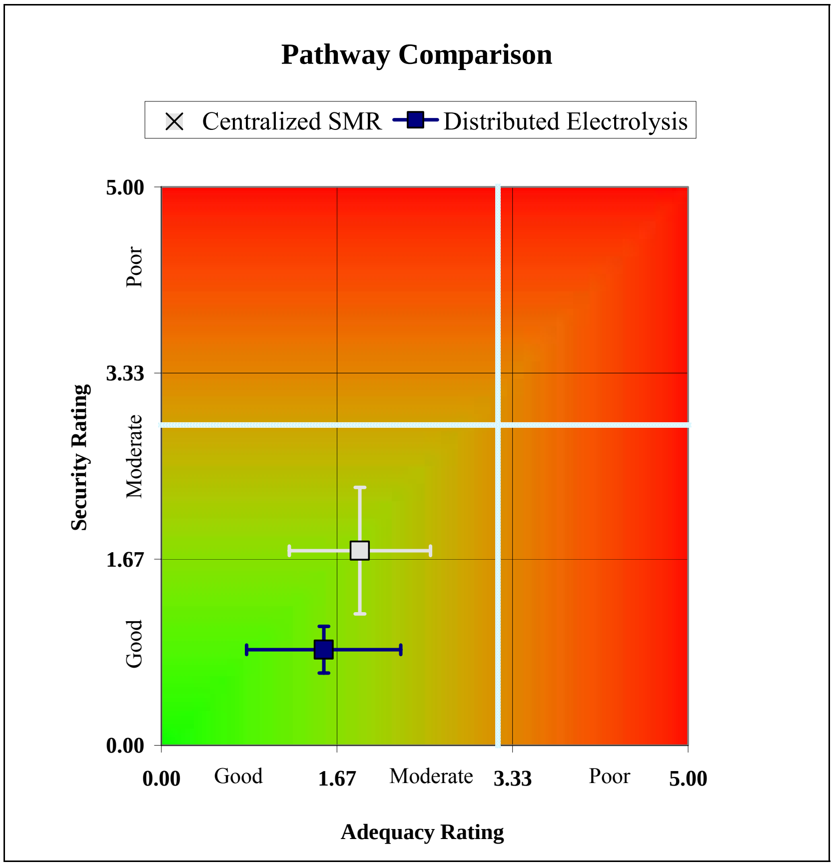

Figure 25. Comparison of adequacy and security scores for Pathways #1 and #2 (unscaled).

Both pathways appear quite reliable in Figure 25. If the scales are divided into thirds to represent qualitative reliability descriptions of *good*, *moderate*, and *poor*, the adequacy and security of both pathways appear to be *good* or *moderately-good*. But if the adequacy and security scales are adjusted in terms of their maximum possible scores, a different representation emerges. The reliability of the two pathways is compared graphically again in Figure 26. This figure may be more indicative of the reliability of each pathway on an absolute scale. Here, the previous figure has been cropped at the lines for the maximum possible adequacy and security scores, and the qualitative descriptions have been adjusted accordingly. The reliability of both pathways appears worse than in Figure 25. The adequacy of both pathways is now *moderate*, and security is *moderately-poor* in Pathway #1, and only *moderately-good* in Pathway #2.

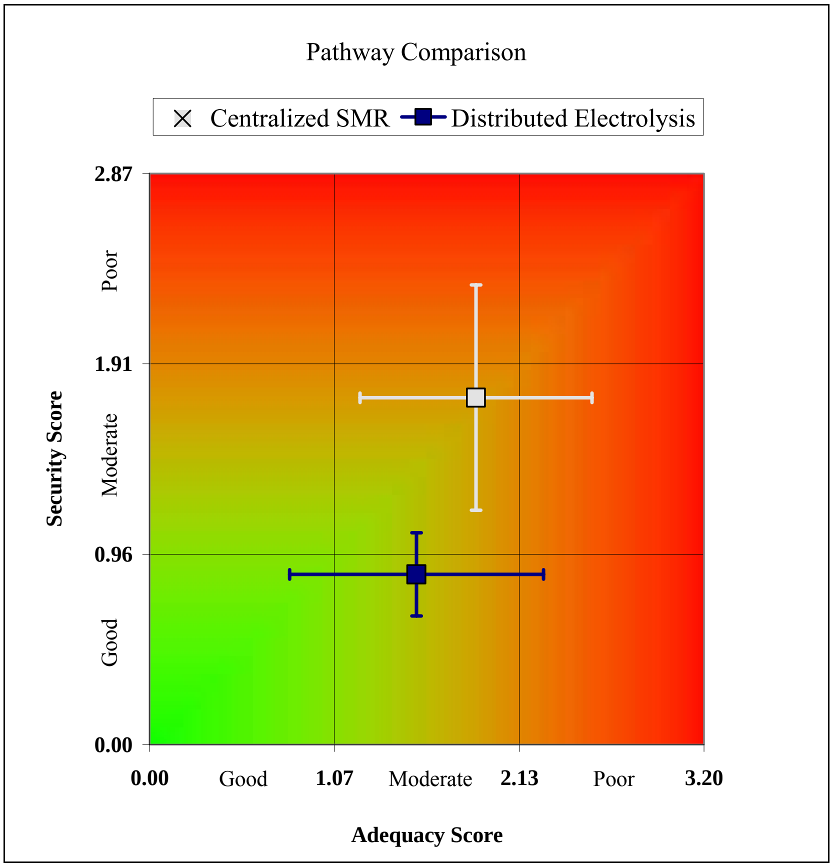

Figure 26. Comparison of adequacy and security scores for Pathways #1 and #2 (scaled according to maximum possible reliability scores).

Although uncertainty surrounds the placement of the pathways on an absolute scale, conclusions can still be made on a comparative basis. The scores here suggest reliability gains to be had in hydrogen energy systems by moving to distributed production and limiting hydrogen transport. These attributes of Pathway #2 appear more reliable than the hydrogen production and transport schemes used in Pathway #1, both in terms of adequacy and security. LNG appears to be a more reliable primary energy supply system in terms of adequacy than stand-alone electricity systems. But, the stand-alone electricity system was determined to be much more secure than the LNG system.

The results and conclusions from this preliminary application are not definitive. They are included to demonstrate the methodology and the information that might be gleaned from its application. Certainly, results from the assessment are interesting and indicative of perceived reliability, but their significance should not be overstated, nor the primary motivation of this test application be obfuscated.

CONCLUSIONS

This research describes a method to compare the reliability of hydrogen supply options for use in transportation applications. The methodology was tried using two distinct hydrogen pathways: one considering large, centralized processes and relying on imported energy resources, the other using small, distributed processes and locally available energy resources. A panel of 11 hydrogen researchers from ITS-Davis rated the reliability of the two pathways in terms of several metrics. The ratings were combined to determine broad reliability scores that were compared across the two pathways. The aggregated scores suggest that distributed production and onsite utilization are more reliable – both in terms of adequacy and security – than centralized production and pipeline transport. Grid-independent electricity was determined to be a much more secure primary energy supply system than imported LNG, but was found to be somewhat less reliable in terms of adequacy, mostly due to potential intermittency in the system.

The application described here was primarily intended to test the methodology. Limited resources were available for the assessment, and the results are only preliminary. If the pathways were assessed again – perhaps using a larger panel composed of experts from diverse backgrounds, and allowing the panel more time and involvement in the process – different findings might surface.

Lessons Learned from Trial Application

The trial run of the methodology revealed points of confusion and opportunities to improve the method. Some noteworthy lessons learned include:

- The three hours allotted for the study were not enough to fully describe the methodology and involve the expert panel to the degree desired. As it was, the panel had just enough time to rate the reliability and importance of the 20 metrics for both pathways. If more discussion or input from the panel was desired, or more pathways or metrics considered, much more time would be needed. Also, to rate more than 200 items in three hours places a toll on the panel which might lead its members to rush through the rating process. Additional time might allow more relaxed and thoughtful consideration of each rating.

- Some panel members expressed difficulty delineating the importance of the metrics between pathway components. Many suggested it would have been easier to only rate the importance once for each metric, as illustrated in Figure 18b. Presumably, experts with perfect knowledge would not have this problem, and this complaint might reflect a lack of expertise (although not necessarily). Whether the case or not, future applications of the methodology should give greater consideration to the importance ratings. The value of the extra degree of specificity should be weighed against the added burden placed on the experts and the difficulty in distinguishing the importance in terms of the pathway components. The selection of the technique might ultimately depend on the composition and knowledge of the panel.

- It was suggested that metrics within the subcategory *consequences of infrastructure disruption* related to importance, rather than reliability. In retrospect, this appears true, and this subcategory should not be included in future applications as is. It may be desirable to capture the four dimensions of consequence described by the metrics, but this should be done in the importance ratings associated with *infrastructure vulnerabilities*, rather than with the reliability metrics.

- Many panel members expressed difficulty rating the reliability of the elements without more information. As discussed previously, the amount of information to provide to the panel was considered prior to administering the survey. Many specific details were omitted due to time constraints and the cursory nature of this preliminary application. But when assessing real systems, all relevant information known about the system and end user requirements should certainly be provided.

- The rating scale used was confusing, and should probably be modified in subsequent applications of the methodology. Some panel members expressed difficulty in distinguishing between ratings on a five-point scale, and suggested only using three points. Many panelists also had difficulty understanding that a high score (e.g., a *5*) always corresponded to poor reliability. They indicated that it would have been clearer to make the confusing metrics grammatically negative. For example, if metrics such as *utilization and spare capacity* or *physical security* – where a high score intuitively seems good – were titled *lack of spare capacity* or *lack of physical security*, there may have been less confusion. But rating a *lack* of something seems confusing as well. The panel also expressed confusion with the double meaning of the rating *?,* and the difference between ratings of zero and not applicable. It was suggested that all be lumped into one rating of *0* or *N/A*. Delineating between *0* and *N/A* was initially thought desirable to account for conditions under which reliability was improved by a metric not applying (e.g., a pathway using no imported energy is seemingly made more reliable than one that does, even if the metric *imports* is thought not to apply). But judging from the standard deviations in the ratings of elements where such differentiations might occur, and from the confusion expressed by the panel, the benefits of such a scale may not be worth the added uncertainty. Perhaps it would least confusing to replace the 1-5 scale with qualitative descriptions (e.g., *high reliability, moderately-high reliability, moderate reliability, moderately-low reliability,* and *low reliability*) and offer an additional rating of *N/A*. Regardless, the selection and naming of the metrics should be carefully considered in terms of the rating scale.

- The rating criteria were not uniform across rows. That is, if a metric received a rating of *2* for one pathway component and *3* for another, it cannot be concluded that the latter is less reliable. This is a consequence of the qualitative nature of the rating criteria, and might not be possible to resolve. The metrics would each have to be judged similarly (e.g., in dollar figures), which might constrain the assessment.

- It might be beneficial to add confidence ratings to the assessment process. They would reflect the degree to which the experts are confident in their ratings of each metric (or element). It could be especially valuable with a diverse expert panel. The ratings of experts with better knowledge about a particular element would be weighted more heavily, possibly generating more accurate results. But confidence ratings add more time and complexity to the rating process, and increase the burden on the expert panel.

- The methodology is limited by understanding of the supply systems and demand scenarios. Experts can rate reliability more accurately if specific details regarding the pathways and metrics are known. Although some metrics apply in existing energy systems and are relatively well understood, it is difficult to rate others in these essentially non-existent systems without additional information.

Opportunities for Future Research

This work represents the first systematic investigation of hydrogen reliability. The methodology provides an effective way to consider reliability in hydrogen energy systems, and an opportunity to compare reliability across energy sectors. Although this research effectively introduces many issues and methods to evaluate them, it only touches the surface of this enormous subject. Ultimately, the goal is to compare the reliability of hydrogen systems to existing gasoline systems, but a great deal of work is needed before we fully understand hydrogen reliability and can make those comparisons. Among the many research opportunities that emerged from this discussion are:

- The methodology should be continually tested and applied under different situations. Several aspects can be varied to further the methodology and advance understanding of reliability in hydrogen systems. These include the metrics and pathways being assessed, the composition and role of the expert panel, and the aggregation techniques used to determine final pathway reliability. A broad selection of stakeholders representing diverse viewpoints should be consulted and their thoughts and suggestions incorporated.

- A fourth pathway component for end use can be incorporated into the analysis. End use considerations include: compression and liquefaction, pressure, purity, and vulnerabilities and consequences at refueling stations. Whether or not reliability at hydrogen refueling stations will differ from gasoline stations deserves investigation.

- Further research is needed regarding the rating scales and criteria. The development of an absolute scale to allow comparisons to be made between pathway components and general conclusions to be drawn from the reliability scores on a fixed basis (rather than just comparative conclusions between pathways) is desirable. But such a scale might require quantification of the rating criteria, which is difficult in this developmental stage of the technology and could limit the selection of the metrics.

- Aggregation techniques should be studied in greater quantity and detail. The aggregation method has profound implications for the final reliability scores, and should not be overlooked. New techniques should be investigated, and a greater understanding of the applicability of various techniques to different scenarios should be developed.

- Interdependencies between hydrogen and other critical infrastructures can be investigated. This could be of huge interest to the homeland security community, and is not well understood for any infrastructure, let alone hydrogen.

- The methodology could be applied to other energy sectors, and reliability compared across energy systems. As developed here, the method only considers hydrogen systems. But it is broad enough that it could easily be applied to other energy sectors as well. As the future extent of hydrogen remains uncertain, a comparison of hydrogen to gasoline and other energy systems would be immensely valuable in guiding its possible development. Presumably, the same metrics could be used to evaluate multiple energy systems, if they are broad enough. Perhaps it would be beneficial to use the same panel of experts to assess each energy system, as well. This would add consistency between the assessments, but should be weighed against the possible loss of expertise. Regardless of the methods used in evaluating different energy systems, the validity of such comparisons should be investigated.

- Other considerations such as cost or environmental impact could be added to the analysis as well, to rate the overall *societal benefit* of different hydrogen pathways or energy systems. Output from this analysis could be conveyed in a graph similar to that shown in Figures 25 and 26, but with third and higher dimensions relating to other measures of interest.

This research set out to promote the fair consideration of reliability issues in hydrogen discourse. The method works effectively towards that goal, but much work remains before fully understanding the issues. Political, social, and economic climates today make energy reliability issues such as risk, energy security, and energy availability urgent. Recent and past events have demonstrated the consequences of unreliability in the energy sector, and warned of worse. As we anticipate possibly creating an entirely new energy system, we are awarded the opportunity to proactively design reliability into the system, rather than rely on reactive fixes. We can little afford to disregard this unique opportunity, and should embrace it with great mind.

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APPENDIX A: GEOPOLITICAL OVERVIEW OF OPEC MEMBER STATES

Algeria

<u>Production (January 2004)</u>: 1,645 Mbbl/day
<u>Net Exports (2001)</u>: 1,383.3 Mbbl/day
<u>Reserves (January 2003)</u>: 9,200 MMbbl
<u>Freedom House Rating (1-7)</u>:[22] Not Free (5.5)

<u>Geopolitical Concerns</u>:

Algeria is a significant oil exporter, especially to Western Europe, and may become an even more important oil producer in the future. Resources in the country are considered under-explored, and it is expected that with added investment in the future, production capacity and reserve estimates could be greatly expanded. In an effort to realize this expansion, Algeria is considering law changes to restructure the state oil company and attract private investment (EIA, 2004a).

Algeria's economy is currently booming, spurred by increased oil and natural gas revenues since 1999. GDP grew an estimated 7.4% in 2003, and is expected to grow 6.4% in 2004. But Algeria continues to face significant economic, social, and political difficulties. The most significant problem facing the economy may be the high unemployment rates, which are at least 30%. In addition, a large black market exists in Algeria, possibly as large as 20% of GDP, and the non-oil economy lags.

Since the military nullified a national election won by the Islamic Salvation Front (FIS) in 1992, Algeria has been engaged in civil war. Up to 150,000 people have died since the turmoil began, and although violence has lessened, it continues to erupt periodically. The FIS has threatened to rescind all contracts between the government and foreign oil

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[22] Freedom House is a nonprofit organization that rates the level of freedom throughout the world (Freedom House 2004).

companies since 1992 if it comes back into power (EIA, 2003a). President Abdelaziz Bouteflika has attempted to reconcile opposing parties but seemingly with little success. He won reelection to another five-year term in April 2004, amid claims from his opposition that the election was a "sham."

Indonesia

<u>Production (January 2004)</u>: 1,130 Mbbl/day
<u>Net Exports (2001)</u>: 307.9 Mbbl/day
<u>Reserves (January 2003)</u>: 5,000 MMbbl
<u>Freedom House Rating (1-7)</u>: Partly Free (3.5)

<u>Geopolitical Concerns</u>:

Indonesia's oil production and reserves are declining, but as an OPEC member and the world's largest exporter of LNG, it remains an important player in the world energy market. Its petroleum sector is vulnerable to the economic and political turbulence the country has recently faced. The economy continues to struggle since its collapse in 1998, following which the International Monetary Fund (IMF) provided Indonesia with $43 billion in emergency debt relief. The IMF has continued to provide disbursements to the country in exchange for economic reforms. Reforms include privatization of some sectors of the economy, but have been slow to take hold. As of April 2003, about 75% of Indonesian businesses remained in technical bankruptcy (EIA, 2003b).

Groups in oil-rich provinces have demanded greater revenues from oil and gas developments. The Timor Gap Treaty, which had divided revenues from the oil and gas development in the Timor Gap between Indonesia and Australia, was revoked as East Timor moved for independence. East Timor did gain independence, on May 20, 2002, and established the "Timor Sea Agreement" with Australia to divide oil and gas revenues. Additionally, Indonesia faces separatist movements in its four most oil-rich provinces of Aceh, East Kalimantan, Irian Jaya, and Riau. Aceh lies on the Strait of Malacca, a vulnerable "chokepoint" through which a significant portion of the world's global oil trade travels (see discussion on chokepoints in Appendix B for further details). Tensions threaten the oil and gas supplies in the region, and perhaps trade through the Strait. In June 2003, Indonesia closed waters around Aceh to prevent weapons from reaching the separatists. Indonesia declared martial law in May 2003 and dispatched 40,000 troops to the region. A smaller insurgency persists in Irian Jaya that hinders plans for an LNG facility in Tangguh (EIA, 2003a).

Iran

<u>Production (January 2004)</u>: 3,950 Mbbl/day
<u>Net Exports (2001)</u>: 2,420.7 Mbbl/day
<u>Reserves (January 2003)</u>: 89,700 MMbbl
<u>Freedom House Rating (1-7)</u>: Not Free (6.0)

<u>Geopolitical Concerns</u>:

As OPEC's second largest producer and holder of about 7% of the world's proven reserves, Iran will be a significant player in the global oil market for years to come. Major oil discoveries have been made in Iran recently which could further increase reserve totals. One was the Azadegan field, the largest oil discovery in the last 30 years. Also, it is thought that Iran could significantly increase capacity in coming years. Iranian production has been continuously increasing over the last 20 years. But at about 4 MMbbl/day currently, production is still much lower than the 6 MMbbl/day it was producing prior to the Iranian Revolution in 1979 (EIA, 2003c).

Since the Iran hostage crisis of 1979-80, the U.S. has had no diplomatic ties with Iran, and several points of contention continue between the nations, including (EIA, 2003a):

- U.S. claims that Iran is pursuing nuclear capabilities
- U.S. claims that Iran supports terrorism
- Iran's opposition to the U.S. vision of the Middle East peace process
- Iran's purchases of military equipment from North Korea and Russia
- U.S.-imposed sanctions on Iran that extend to foreign oil and gas companies investing in projects in Iran
- Iran's claim over three islands disputed by the United Arab Emirates in the strategic Strait of Hormuz (another "chokepoint")

Iran's economy is heavily dependent on oil export revenues, which supply about 40% to 50% of total government earnings, and about 10% to 20% of GDP. Oil price increases over the last few years has the economy improving, with GDP growing by about 5.9% in 2002, and an estimated 4.5% in 2003. But Iran still faces serious economic problems, including significant external debt, a growing young population, high rates of unemployment and poverty, and international isolation and sanctions. The economy remains heavily dependent on oil revenues, but the government has begun investing in other areas to improve economic stability (EIA, 2003c).

Iraq

<u>Production (January 2004)</u>: 2,103 Mbbl/day
<u>Net Exports (2001)</u>: 1,907.8 Mbbl/day
<u>Reserves (January 2003)</u>: 112,500 MMbbl
<u>Freedom House Rating (1-7)</u>: Not Free (7.0)

<u>Geopolitical Concerns</u>:

Iraq is considered an incredibly attractive oil prospect, and should be a significant player in the world oil market for some time. It has the third most proven oil reserves in the world, only behind Saudi Arabia and Canada, and remains largely unexplored. Only about 10% of the country has been explored, and some analysts estimate that 50 billion-100 billion barrels, or more, remain to be discovered. Only 17 of the 80 discovered fields have been developed, and development and production prices in Iraq are among the lowest in the world. Considering these factors, it is not unlikely that Iraq could increase production by several million barrels per day in the future, if major technical and infrastructure problems are first addressed (EIA, 2004b).

Iraq presents substantial vulnerability to the global market as well, as it has been at the center of regional and international conflict. Major wars over the last few decades – including the Iran-Iraq war from 1980-88, the Kuwait war of 1990-91, and the 2003 war against the U.S.-led coalition – and more than ten years of economic sanctions have left the economy, infrastructure, and all social systems in disarray. The economy has shown signs of improving since the 2003 war that ended with Saddam Hussein’s ouster, with sanctions having being lifted and Iraq’s new currency, the New Iraqi Dinar, gaining value. Nevertheless, the status and future of Iraq’s social, political, and economic systems remains uncertain amid the current turmoil (EIA, 2004b).

Kuwait

Production (January 2004): 2,300 Mbbl/day
Net Exports (2001): 1,839.0 Mbbl/day
Reserves (January 2003): 96,500 MMbbl
Freedom House Rating (1-7): Partly Free (4.5)

Geopolitical Concerns:

Kuwait’s economy depends heavily on revenue from oil exports. Oil revenues account for about 90%-95% of total exports, and about 40% of GDP. High oil prices in 2003-04 produced huge surges in revenue for Kuwait, and an expected record budget surplus. Kuwait invests 10% of its oil revenues into the “Future Generations Fund,” a fund worth about $65 billion for use when oil income runs out (EIA, 2004c).

A major task facing the Kuwaiti government is creating jobs for its young citizens. Approximately 65% of the population is under 25 years old, and 90% of all private sector employees are foreigners (80% of the entire labor force is foreign). Kuwait is currently in the process of privatizing several sectors, but the transfer is complicated by trying to protect Kuwaiti jobs. Approximately 93% of Kuwaiti citizens are employed through the government, and state-operated sectors. Kuwait maintains close relations with Western countries, and was considered a key ally by the U.S. State Department in the 2003 war against Iraq (EIA, 2004c).

Libya

Production (January 2004): 1,450 Mbbl/day
Net Exports (2001): 1,197.8 Mbbl/day
Reserves (January 2003): 29,500 MMbbl
Freedom House Rating (1-7): Not Free (7.0)

Geopolitical Concerns:

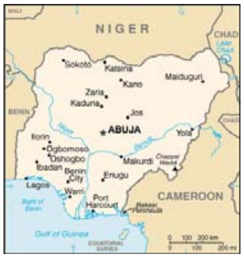
Libya stands to become a larger supplier, and perhaps a more influential player in the oil market. The country remains unexplored and has a good potential for more discoveries. Libya also has a well-developed infrastructure, and can produce oil inexpensively (for as little as $1/barrel at some fields), making it attractive to foreign investors. Libya is looking for as much as $30 billion in foreign investment to increase production to 2 MMbbl/day by 2010 (EIA, 2004d).

Increased foreign investment will be enabled by the recent lifting of international sanctions against Libya. Following the extradition on April 5, 1999 of two men suspected in the bombing of Pan Am flight 103, the U.N. suspended sanctions against Libya that had been in place since 1992. Since then, various countries have restored diplomatic relations with Libya, and oil and gas companies have reentered the country and are set to expand operations. President Bush renewed sanctions against the country in January 2004, despite Libya's announcement on December 19, 2003 that it would abandon efforts to acquire weapons of mass destruction. But relations between the countries have improved, and in April 2004, the U.S. announced it would ease sanctions against Libya. The move allows most commercial activities between the countries to resume, and enables companies in the U.S. to buy and invest in the development of

Libyan oil. Libya does remain on the U.S. State Department's list of states sponsoring terrorism, however (BBC news, 2004).

The Libyan economy relies on oil export revenues for about 75% of government receipts. Recent increases in oil prices have created significant economic surpluses. Libya is attempting to diversify the economy, especially in agriculture, and is moving towards economic reforms that would reduce the influence of the state in the economy. In October 2003, Libya announced that 361 firms in various sectors will be privatized in 2004 (EIA, 2004d).

Nigeria



Production (January 2004): 2,530 Mbbl/day
Net Exports (2001): 1,955.7 Mbbl/day
Reserves (January 2003): 24,000 MMbbl
Freedom House Rating (1-7): Partly Free (4.5)

Geopolitical Concerns:

Nigeria faces continuing ethnic and political conflicts, high rates of crime, and large income disparities. Over 10,000 Nigerians have died from social unrest since 2000. The ongoing violence threatens Nigerian oil supply. In March 2003, ethnic clashes between the Ijaw and Itsekiri peoples in the Niger Delta caused ChevronTexaco and Shell to suspend production in the region. At the peak, about a total of 817,500 bbl/day was shut down, about one-third of Nigeria's total production.

A thriving black market for oil poses another problem for Nigeria's petroleum sector. Siphoning of fuel from pipelines has caused a number to explode, at least five over the two-year span from 2002 to 2003. The worst explosion occurred in October 1998, where over 1,000 people died. In addition to fuel siphoning, the Nigerian government projects that up to 300,000 bbl/day of crude oil is illegally freighted out of the country. In response, the Nigerian government has ordered satellite equipment to monitor oil facilities, has authorized the navy to sink any ship carrying crude oil that cannot be accounted for, and has reinstated the death penalty for vandalism of pipelines and electricity infrastructure (EIA, 2003a).

Qatar

Production (January 2004): 785 Mbbl/day
Net Exports (2001): 761.2 Mbbl/day
Reserves (January 2003): 15,207 MMbbl
Freedom House Rating: Not Free (6.0)

Geopolitics:

Qatar is more influential in the natural gas market than the oil market. Oil production capacity is relatively modest, currently 850,000 bbl/day and expected to increase to 1.05 MMbbl/day by 2006. Similar to other OPEC members, Qatar suffers from economic dependence on oil revenue, but has avoided many of the troubles of other major oil suppliers due to its investment in LNG and petrochemicals, and its small population. Since coming to power in a coup in 1995, Qatar has been ruled by Sheikh Hamad bin Khalifa al-Thani, who has implemented several policy changes and reforms, including the creation of an elected council and extending the right to vote to women (EIA, 2003d).

Saudi Arabia

Production (January 2004): 8,700 Mbbl/day
Net Exports (2001): 7,361.3 Mbbl/day
Reserves (January 2003): 261,800 MMbbl
Freedom House Rating (1-7): Not Free (7.0)

Geopolitics:

As the world's dominant oil supplier, geopolitics in Saudi Arabia carry more significance than any other supplying state. If Saudi Arabia's 7.4 MMbbl/day in exports were disrupted, not even the excess capacity of the entire world could replace the lost supplies (see Figure 13 for global excess production capacity). Saudi Arabia's 261.8 billion barrels of proven reserves amount to more than a quarter of the world's total, and ultimately recoverable oil may be as much as 1 trillion barrels. It maintains a crude production capacity of about 10.0-10.5 MMbbl/day, and in 2003, supplied the U.S. with an average of 1.8 MMbbl/day (EIA, 2003e).

Saudi Arabia's economy is dependent on oil revenue, and the recent price increase is likely to create budget surpluses. But the country remains in significant debt, has high rates of unemployment, is experiencing rapid increases in population, and has seen per capita income plummet, from $28,600 in 1981 to $6,800 in 2001 (Baer, 2003). A large, rapidly expanding extended ruling family receives large stipends that stress the treasury. Half the population is under 18, placing an enormous strain on the economy. Saudi Arabia is one of the world's largest welfare states, providing free health care and education, interest-free home and business loans, and providing airfare, gasoline, electricity, and telephone service at far below cost (Baer, 2003). Reforms to reduce these subsidies and move towards privatization have been slow to take effect (EIA, 2003e).

United Arab Emirates

Production (January 2004): 2,400 Mbbl/day
Net Exports (2001): 2,153.8 Mbbl/day
Reserves (January 2003): 97,800 MMbbl
Freedom House Rating (1-7): Not Free (5.5)

Geopolitics:

United Arab Emirates (UAE) has significant reserves, and should be a major world oil supplier for years to come. Proven reserves are currently 98 billion barrels, nearly 10% of the world's total. Also, the country is currently is engaged in a $1.5 billion effort to increase production capacity to 3 MMbbl/day by the end of 2006.

United Arab Emirates is a federation of seven emirates – Abu Dhabi, Dubai, Sharjah, Ajman, Fujairah, Ras al-Khaimah, and Umm al-Qaiwain. Abu Dhabi controls the majority of UAE's resource, and together with Dubai, provides nearly 80% of UAE's total income. Political power rests in this emirate as well. The economy depends heavily on oil exports, which make up about 30% of GDP, but is somewhat diversified to include several other industries. The UAE is a member of the World Trade Organization, and Dubai has become a central hub for trade in the Middle East. The country has one of the most open economies in the Middle East (EIA, 2004e).

Territorial disputes between UAE and Iran regarding the three islands of Abu Mesa, Greater Tunb and Lesser Tunb in the Strait of Hormuz have persisted. The islands are strategically located in the Strait (see Appendix B). Iran has claimed them "an inseparable part of Iran" and occupied the islands with military forces in 1992. The conflict is a concern, but UAE and Iran remain close trading partners (EIA, 2004e).

Venezuela

<u>Production (January 2004)</u>: 2,490 Mbbl/day
<u>Net Exports (2001)</u>: 2,666.0 Mbbl/day
<u>Reserves (January 2003)</u>: 77,800 MMbbl
A) <u>Freedom House Rating (1-7)</u>: Partly Free (3.5)

<u>Geopolitics</u>:

Venezuela has the largest oil reserves in the Western Hemisphere, and has been a favorite exporter of the U.S. as a nearby, and supposedly more secure, alternative to Persian Gulf suppliers. But like most of the world's oil exporters, Venezuela is experiencing economic, political, and social troubles. Any disruption to oil supply could drastically affect Venezuela's economy, as it relies heavily on oil revenues. Oil constitutes about half of government revenues, and one-third of GDP. General strikes are frequent in the country, and often affect the petroleum sector. On April 12, 2002 after three days of general strikes, President Hugo Chávez was overthrown by the military. He regained power, but in December 2002 more strikes were organized in opposition to the President's rule. These strikes shut down much of the nation's oil infrastructure and drastically reduced output, to one-third of levels from the month before (EIA).[23] The President remains unpopular, and faces a potential recall election. The National Electoral Council (NEC) is expected to rule in May 2004 on whether opposing parties have gathered enough signatures to force the election.

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[23] Average monthly crude oil production in Venezuela was 2,972 Mbbl/d in November 2002, and 1,020 Mbbl/d in December 2002 (EIA, Table 1.1a).

APPENDIX B: DESCRIPTION OF INTERNATIONAL OIL TRANSPORT CHOKEPOINTS

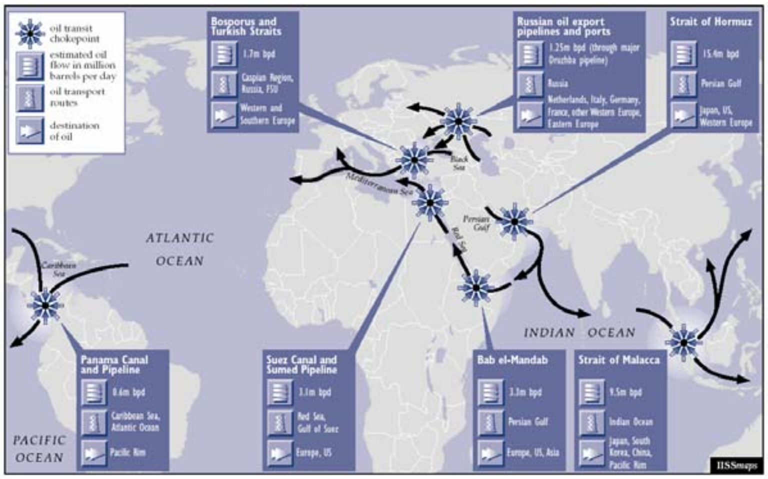

Figure 27. Chokepoints for international petroleum transport (International Institute for Strategic Studies, 2001).

Bab el-Mandab

Bab el-Mandab separates Africa and Yemen, connecting the Red Sea with the Gulf of Aden and the Arabian Sea. Oil traveling west from the Persian Gulf destined for the Suez Canal or the Sumed Pipeline must travel through Bab el-Mandab. Oil flows through Bab el-Mandab were an estimated 3.3 MMbbl/day in 2000. A disruption could significantly increase transit time, and tie up spare capacity. Northbound traffic could bypass the route using the 5.0 MMbbl/day East-West Pipeline across Saudi Arabia, but no alternatives exist to the south. Tankers headed for the Suez Canal or Sumed Pipeline from the Persian Gulf would be diverted around the Cape of Good Hope (EIA [2002] and Adams [2003, pp.60-61]).

Bosporus Straits

The Bosporus Straits cut through Istanbul, Turkey and connect the Black Sea with the Sea of Marmara. The Straits carry an estimated 1.7-2.0 MMbbl/day mostly to Western and Southern Europe. Bosporus is the world’s busiest waterway, carrying about 50,000 vessels annually, 5,500 of which are oil tankers (EIA, 2002). It is also one of the most difficult waterways to navigate. The straits stretch 17 miles and have maximum and minimum widths of 2 miles and 700 yards, respectively. Navigation requires 12 course changes, many of which are at 45°. Over the past decade, 350 accidents have occurred, an astonishingly high rate. The Straits serve as an "energy bridge" between the resource-rich Caspian Sea and Middle East regions, and provide several high profile targets in a region with much unrest (Adams, 2003, pp.61-63). Projected increases in production from the Caspian Sea could further increase demands on the Straits.

Panama Canal and Pipeline

The Panama Canal cuts through Panama, connecting the Pacific Ocean with the Caribbean Sea and Atlantic Ocean. The Canal carries an estimated 613,000 bbl/day, mostly westward to islands in the Pacific. Political unrest threatens the region, especially in bordering Columbia. The absence of a military in Panama adds vulnerability (Adams, 2003, p.71). A disruption in the canal could be bypassed by the 860,000 bbl/day Panama Pipeline, which was closed in 1996 after Alaskan oil shipments to the Gulf of Mexico declined (EIA, 2002).

Strait of Hormuz

The Strait of Hormuz is by far the world's most significant chokepoint. It is located between Oman and Iran, and connects the Persian Gulf with the Gulf of Oman and the Arabian Sea. It is the world's largest oil transit lane, carrying an estimated 13-15 MMbbl/day, and the only exit from the Persian Gulf. Exports through the Strait are destined for Japan, the U.S., and Western Europe. The Strait has a 2-mile-wide inbound and outbound lane, separated by a 2-mile-wide buffer. Iran and the UAE dispute control over the Strait, specifically the three islands of Greater Tunb, Lesser Tunb, and Abu Musa. Militarization of the islands would provide the capability to close the Strait. A few pipelines provide alternative routes, but not sufficient capacity to handle daily flows through Hormuz. The East-West Pipeline is one, and currently has about 3.0 MMbbl/day of spare capacity (Adams, 2003, pp.72-73). The 290,000 bbl/day Abqaiq-Yanbu natural gas liquids pipeline and the 1.65 MMbbl/day Iraqi Pipeline also cross Saudi Arabia and could be used to some extent (EIA, 2002).

Strait of Malacca

The Strait of Malacca separates Malaysia and Indonesia, and connects the Indian Ocean with the South China Sea and the Pacific Ocean. About 10 million barrels of oil from the Middle East destined for China, Japan, South Korea, and other Pacific Rim countries travel through the Strait daily. The Strait is 500 miles long, but only 10-70 meters deep (Adams, 2003, p.69), and is 1.5 miles wide at its narrowest point (EIA, 2002). It is the key chokepoint in Asia, and the second busiest shipping route behind the Bosporus Straits. Half of all sea shipments of oil bound for East Asia passes through the Strait, and two-thirds of the world's LNG (IAGS, 2003c). The Lombok Strait provides an alternative route, at a cost of about 1000 extra miles, or three extra days (Adams, 2003, p.70). Another potential route in the future is a canal through Thailand, a project that China is pursuing to avoid the Strait as its oil demand rapidly increases (EIA, 2002).

Suez Canal

The Suez Canal is located in Egypt and connects the Red Sea and the Gulf of Suez with the Mediterranean. The Suez carries about 1.3 MMbbl/day destined for Europe and the U.S. The Canal is 100 miles long, with a minimum width of 195 ft. Loss of the canal would be significant, but not devastating. Shipments through the Canal would have to be rerouted around the Cape of Good Hope (Adams, 2003, p.73).

Sumed Pipeline

The Sumed Pipeline also connects the Gulf of Suez and the Red Sea through Egypt with the Mediterranean. It carries an estimated 2.2-2.5 MMbbl/day northbound destined to the U.S. and Europe, mostly from Saudi Arabia. It is vulnerable like any pipeline.

APPENDIX C: MATERIALS PROVIDED TO THE EXPERT PANEL

HYDROGEN RELIABILITY EVALUATION EXERCISE

Institute of Transportation Studies
University of California, Davis

Friday, September 10, 2004

OVERVIEW

Reliability[*] in the energy sector is defined in terms of two categories: **adequacy** and **security.** **Adequacy** refers to the extent to which the system has sufficient throughput to satisfactorily supply demand. **Security** refers to the ability of the system to minimize and withstand unexpected interruptions. These categories encompass five subcategories. **Adequacy** includes two: **capacity** and **flexibility**. **Security** includes three: **infrastructure vulnerability**, **consequence of infrastructure disruption**, and **energy security**.

In this exercise, you will be asked to rate several aspects of those subcategories and their importance to reliability for two hydrogen pathways. Your ratings will be weighted according to the importance scores you give them, and aggregated to develop reliability ratings for the five subcategories. These scores will then be weighted and aggregated again to develop a score for the **adequacy** and **security** categories.

The category and subcategory scores highlight portions of the pathways that are particularly reliable or capricious. Comparing these scores across pathways can reveal reliable options for hydrogen infrastructure network designs.

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[*] All items that appear in **bold** are defined in the glossary

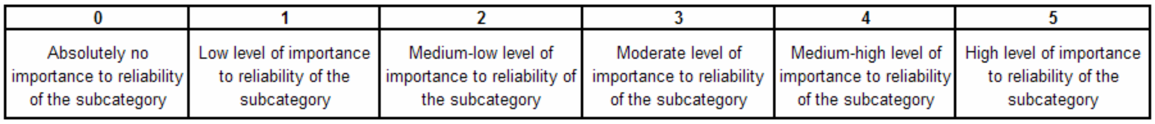
IMPORTANCE RATINGS

OVERVIEW

In this portion of the exercise, you are asked to rate the **importance** of several aspects of reliability. The importance ratings will be used to weight the reliability ratings that you will later develop. The weighted scores will then be aggregated to develop scores for each subcategory and for **adequacy** and **security**.

INSTRUCTIONS

In this section, you will be asked to rate the **importance** of several components of reliability. First, you will rate the importance of several aspects of the five subcategories. Rate the importance of these components *as you feel they influence the reliability of the subcategory*. Use the following scale:



0	1	2	3	4	5
Absolutely no importance to reliability of the subcategory	Low level of importance to reliability of the subcategory	Medium-low level of importance to reliability of the subcategory	Moderate level of importance to reliability of the subcategory	Medium-high level of importance to reliability of the subcategory	High level of importance to reliability of the subcategory

Note that these are *ratings,* not *rankings.* You are rating components independently, as they pertain to the subcategory, rather than ranking components relative to each other. If you feel that none of the components strongly influence the reliability of the subcategory, rate them all low. Similarly, if you feel that all are very important, you may rate them all very high.

Next, you will be asked to rate the importance of each of the five subcategories to overall reliability. *These should be independent of the ratings you gave the components of the subcategories.* That is, although you may have rated every aspect of one subcategory quite low, if you feel that the subcategory itself is important to overall reliability, that subcategory should receive a high importance rating nonetheless. The scale used for these ratings is the same as the scale described above.

1. Circle the rating you feel corresponds to *the importance* of each of the following to **capacity**:

		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Capacity	Utilization and Spare Capacity	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
	Intermittency	? 0 1 2 3 4 5 DK None Low ---------------------> High	N/A	N/A

Notes/comments:

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2. Circle the rating you feel corresponds to *the importance* of each of the following to **flexibility**:

		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Flexibility	Response to Demand Fluctuations	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
	Response to Equipment Outages	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
	Ability to Expand Facilities	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High

Notes/comments:

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3. Circle the rating you feel corresponds to *the importance* of each of the following to **infrastructure vulnerability**:

		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Infrastructure Vulnerability	**Physical Security**	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Information Security	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Interdependencies	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Sector Coordination	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	History	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High

Notes/comments:

4. Circle the rating you feel corresponds to *the importance* of each of the following to the **consequence of an infrastructure disruption**:

		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Consequences of Infrastructure Disruption	**Economic Consequences**	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Environmental Consequences	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Human Health Impacts	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High
	Impacts on Interdependent Systems	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High	? 0 1 2 3 4 5 DK None Low -----------------------> High

Notes/comments:

5. Circle the rating you feel corresponds to *the importance* of each of the following to **energy security**:

		Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Energy Security	**Import Levels**	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A
	Import Concentration	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A
	Geopolitics	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A
	Chokepoints	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A
	World Excess Production Capacity	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A
	Price Volatility	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A

Notes/comments:

6. Circle the rating you feel corresponds to *the importance* of each of the following to overall hydrogen system **reliability**. These ratings should be independent of your ratings above.

	Primary Energy Supply System	Hydrogen Production Process	Hydrogen Transport Process
Capacity	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High
Flexibility	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High
Infrastructure Vulnerability	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High
Consequences of Infrastructure Disruption	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High	? 0 1 2 3 4 5 DK None Low ----------------> High
Energy Security	? 0 1 2 3 4 5 DK None Low ----------------> High	N/A	N/A

Notes/comments:

PATHWAY RELIABILITY RATINGS

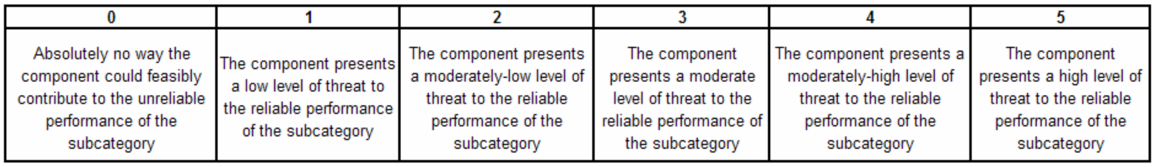
OVERVIEW

The city of Sacramento is planning to install a network of hydrogen refueling stations to meet the city's burgeoning demand for hydrogen fuel. City officials are considering two pathways to supply the city's needs, justly named *Pathway #1* and *Pathway #2*. The city has conducted economic and environmental analyses of the two pathway alternatives, but before proceeding in its selection process, wants to better understand the reliability implications of each. To this end, the city is conducting a survey of hydrogen experts to assess reliability implications surrounding both pathways.

INSTRUCTIONS

You are asked to rate *how aspects of each subcategory contribute to the reliability of that subcategory*, for two pathways. Similar to the importance ratings, try to rate these independently of each other, and independent of your thinking about the overall reliability of the subcategory.

A general scale for rating the reliability of the various components is given below. Rating scales specific to each subcategory are included in a separate handout. Note that *a 5 always represents a lack of reliability, and a 1 always represents a high level of reliability.* For example, although a higher rating for **capacity** intuitively seems good, it actually indicates a lack of capacity. *The higher ratings always represent a greater threat to reliability.* A good score in the capacity case would actually be a low one. In rating components low, however, keep in mind that *a rating of 0 should only be given if you feel that there is no possible way that the aspect would ever threaten reliability* of the subcategory.



0	1	2	3	4	5
Absolutely no way the component could feasibly contribute to the unreliable performance of the subcategory	The component presents a low level of threat to the reliable performance of the subcategory	The component presents a moderately-low level of threat to the reliable performance of the subcategory	The component presents a moderate level of threat to the reliable performance of the subcategory	The component presents a moderately-high level of threat to the reliable performance of the subcategory	The component presents a high level of threat to the reliable performance of the subcategory

If you feel that an aspect of reliability does not apply to a particular pathway component, or if you just don't know how to rate it, circle the question mark (?). In the space for notes below each question, please explain your reasoning for circling the question mark, and make any other comments about the section that you wish.

Name: _______________________

PATHWAY #1 DESCRIPTION

Pathway #1 would bring hydrogen via pipeline from a central production facility located in Richmond to each refueling station in the Sacramento network. The central production plant has the ability to produce more than 1,000,000 kg H_2/day via steam reformation of natural gas. Natural gas is supplied to the facility directly from the controversial new **liquefied natural gas (LNG)** import terminal that was recently constructed in the Richmond area. Trinidad and Tobago is the primary supplier of **LNG** into the port, and shipments come via the Panama Canal. But supplies also come from Alaska, Australia, Indonesia, Malaysia, and trace amounts from the Middle Eastern states of Qatar and the United Arab Emirates.

1. Circle the rating you feel corresponds to the *degree to which the system is constrained by capacity:*

	Imported LNG	Centralized SMR	Pipeline
Utilization and Spare Capacity	? 0 1 2 3 4 5 DK No threat ----------------> High threat	? 0 1 2 3 4 5 DK No threat ----------------> High threat	? 0 1 2 3 4 5 DK No threat ----------------> High threat
Intermittency	? 0 1 2 3 4 5 DK None Low ----------------------> High	N/A	N/A

Notes/comments:

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:

3. Circle the rating you feel corresponds to the *level of* ***vulnerability*** that exists in the pathway:

	Imported LNG	Centralized SMR	Pipeline
Physical Security	? 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
Information Security	? 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
Interdependencies	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
Sector Coordination	? 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
History	? 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

Notes/comments:

4. Circle the rating you feel corresponds to the *feasible* ***consequence of an infrastructure disruption*** for the pathway:

	Imported LNG	Centralized SMR	Pipeline
Economic Consequences	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
Environmental Consequences	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
Human Health Impacts	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High
Impacts on Interdependent Systems	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High	? 0 1 2 3 4 5 DK None Low ---------------------> High

Notes/comments:

5. Circle the rating you feel corresponds to the *level of* ***energy security*** in the pathway:

	Imported LNG	**Centralized SMR**	**Pipeline**
Import Levels	? 0 1 2 3 4 5 DK None Low ----------------------> High	N/A	N/A
Import Concentration	? 0 1 2 3 4 5 DK None Low ----------------------> High	N/A	N/A
Geopolitics	? 0 1 2 3 4 5 DK Perfect Stable ---------------> Unstable	N/A	N/A
Chokepoints	? 0 1 2 3 4 5 DK None Safe ------------------> Unsafe	N/A	N/A
World Excess Production Capacity	? 0 1 2 3 4 5 DK Perfect High --------------------> Low	N/A	N/A
Price Volatility	? 0 1 2 3 4 5 DK None Low ----------------------> High	N/A	N/A

Notes/comments:

Name: ______________________

PATHWAY #2 DESCRIPTION

In accordance with recommendations from experts in the field regarding the development of California's Hydrogen Highway, the city is also considering an alternative pathway that would utilize renewable energy. The mayor is considering issuing an Executive Order that would require all hydrogen sold in the city to be produced from renewable resources. City officials have developed an alternative pathway to supply the city's hydrogen demand, which they call *Pathway #2*. Under the Pathway #2 proposal, each refueling station would produce hydrogen onsite from electricity produced locally from renewable resources.

1. Circle the rating you feel corresponds to the *degree to which the system is constrained by capacity:*

	Stand-Alone Wind Electricity	Distributed Electrolysis	No Transport (Onsite Utilization)
Utilization and Spare Capacity	? 0 1 2 3 4 5 DK No threat ---------------> High threat	? 0 1 2 3 4 5 DK No threat ---------------> High threat	? 0 1 2 3 4 5 DK No threat ---------------> High threat
Intermittency	? 0 1 2 3 4 5 DK None Low ---------------------> High	N/A	N/A

Notes/comments:

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

	Stand-Alone Wind Electricity	Distributed Electrolysis	No Transport (Onsite Utilization)
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:

3. Circle the rating you feel corresponds to the *level of* ***vulnerability*** that exists in the pathway:

	Stand-Alone Wind Electricity	Distributed Electrolysis	No Transport (Onsite Utilization)
Physical Security	? 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
Information Security	? 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
Interdependencies	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High
Sector Coordination	? 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
History	? 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

Notes/comments:

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4. Circle the rating you feel corresponds to the *feasible* ***consequence of an infrastructure disruption*** for the pathway:

	Stand-Alone Wind Electricity	Distributed Electrolysis	No Transport (Onsite Utilization)
Economic Consequences	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High
Environmental Consequences	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High
Human Health Impacts	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High
Impacts on Interdependent Systems	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High	? 0 1 2 3 4 5 DK None Low ----------------------> High

Notes/comments:

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5. Circle the rating you feel corresponds to the *level of* ***energy security*** in the pathway:

	Stand-Alone Wind Electricity	**Distributed Electrolysis**	**No Transport (Onsite Utilization)**
Import Levels	? 0 1 2 3 4 5 DK None Low ---------------------> High	N/A	N/A
Import Concentration	? 0 1 2 3 4 5 DK None Low ---------------------> High	N/A	N/A
Geopolitics	? 0 1 2 3 4 5 DK Perfect Stable --------------> Unstable	N/A	N/A
Chokepoints	? 0 1 2 3 4 5 DK None Safe -----------------> Unsafe	N/A	N/A
World Excess Production Capacity	? 0 1 2 3 4 5 DK Perfect High ------------------> Low	N/A	N/A
Price Volatility	? 0 1 2 3 4 5 DK None Low ---------------------> High	N/A	N/A

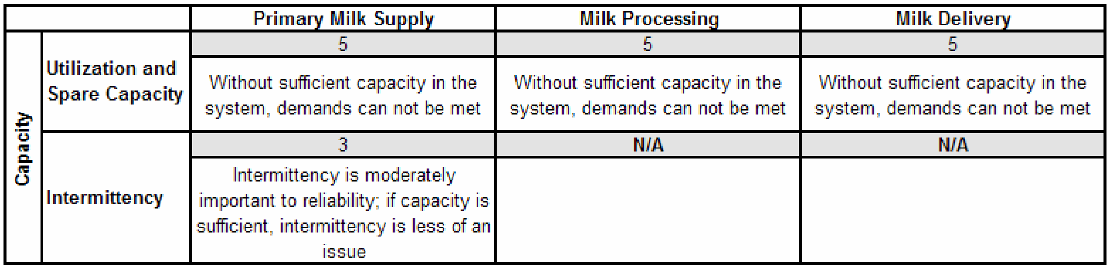
Notes/comments:

MILK SUPPLY EXAMPLE

Pathway: Milk is supplied throughout the Dallas/Fort Worth metro area from a dairy in the small town of Lactose, TX. 10,000 head of cattle supply the dairy, where the milk is processed and bottled before being distributed by a fleet of 150 milk delivery trucks.

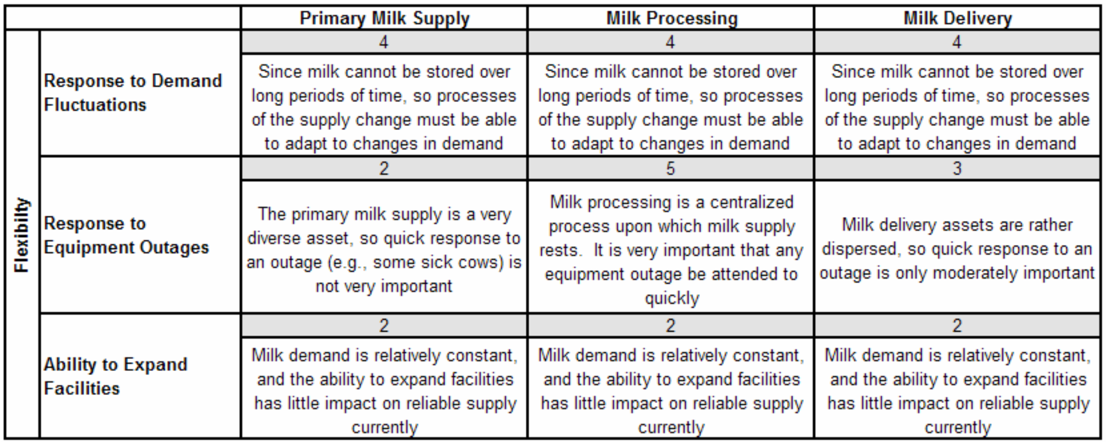
IMPORTANCE RATINGS

1. Circle the rating you feel corresponds to *the importance* of each of the following to **capacity**:



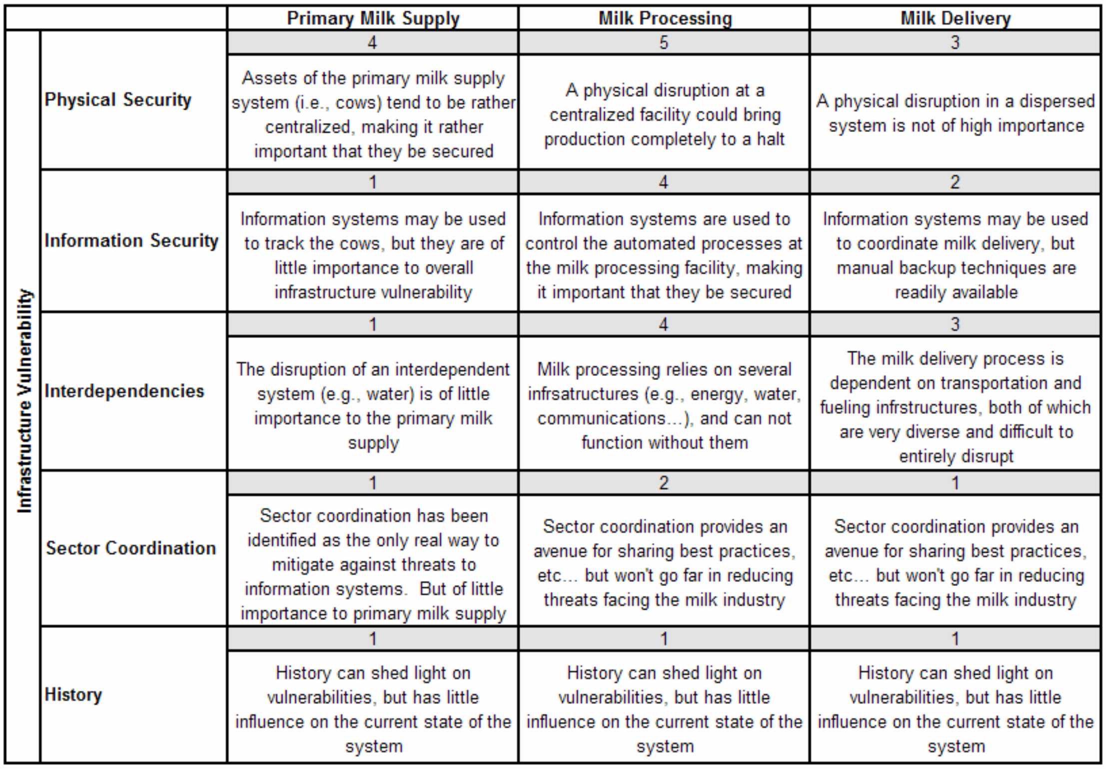
		Primary Milk Supply	Milk Processing	Milk Delivery
Capacity	Utilization and Spare Capacity	5	5	5
		Without sufficient capacity in the system, demands can not be met	Without sufficient capacity in the system, demands can not be met	Without sufficient capacity in the system, demands can not be met
	Intermittency	3	N/A	N/A
		Intermittency is moderately important to reliability; if capacity is sufficient, intermittency is less of an issue		

2. Circle the rating you feel corresponds to *the importance* of each of the following to **flexibility**:



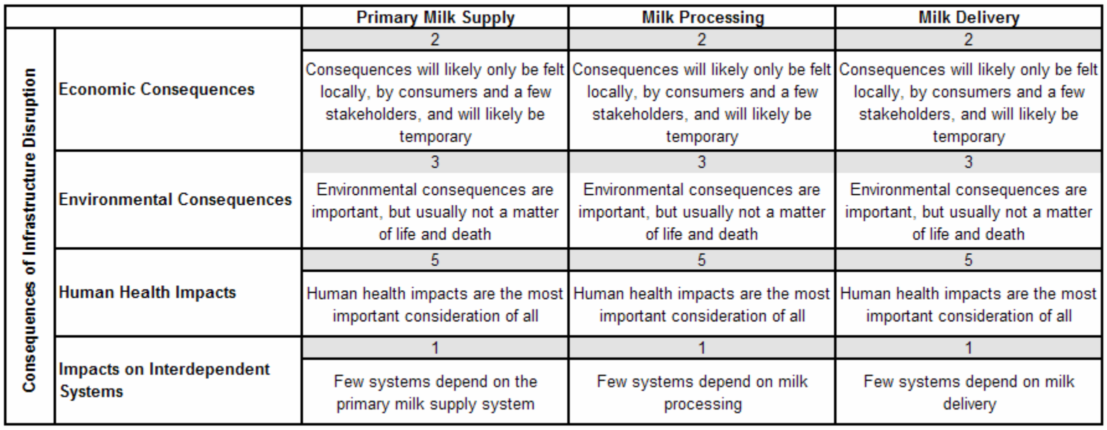
		Primary Milk Supply	Milk Processing	Milk Delivery
Flexibility	Response to Demand Fluctuations	4	4	4
		Since milk cannot be stored over long periods of time, so processes of the supply change must be able to adapt to changes in demand	Since milk cannot be stored over long periods of time, so processes of the supply change must be able to adapt to changes in demand	Since milk cannot be stored over long periods of time, so processes of the supply change must be able to adapt to changes in demand
	Response to Equipment Outages	2	5	3
		The primary milk supply is a very diverse asset, so quick response to an outage (e.g., some sick cows) is not very important	Milk processing is a centralized process upon which milk supply rests. It is very important that any equipment outage be attended to quickly	Milk delivery assets are rather dispersed, so quick response to an outage is only moderately important
	Ability to Expand Facilities	2	2	2
		Milk demand is relatively constant, and the ability to expand facilities has little impact on reliable supply currently	Milk demand is relatively constant, and the ability to expand facilities has little impact on reliable supply currently	Milk demand is relatively constant, and the ability to expand facilities has little impact on reliable supply currently

3. Circle the rating you feel corresponds to *the importance* of each of the following to **infrastructure vulnerability**:



		Primary Milk Supply	Milk Processing	Milk Delivery
Infrastructure Vulnerability	**Physical Security**	4	5	3
		Assets of the primary milk supply system (i.e., cows) tend to be rather centralized, making it rather important that they be secured	A physical disruption at a centralized facility could bring production completely to a halt	A physical disruption in a dispersed system is not of high importance
	Information Security	1	4	2
		Information systems may be used to track the cows, but they are of little importance to overall infrastructure vulnerability	Information systems are used to control the automated processes at the milk processing facility, making it important that they be secured	Information systems may be used to coordinate milk delivery, but manual backup techniques are readily available
	Interdependencies	1	4	3
		The disruption of an interdependent system (e.g., water) is of little importance to the primary milk supply	Milk processing relies on several infrsatructures (e.g., energy, water, communications…), and can not function without them	The milk delivery process is dependent on transportation and fueling infrstructures, both of which are very diverse and difficult to entirely disrupt
	Sector Coordination	1	2	1
		Sector coordination has been identified as the only real way to mitigate against threats to information systems. But of little importance to primary milk supply	Sector coordination provides an avenue for sharing best practices, etc… but won't go far in reducing threats facing the milk industry	Sector coordination provides an avenue for sharing best practices, etc… but won't go far in reducing threats facing the milk industry
	History	1	1	1
		History can shed light on vulnerabilities, but has little influence on the current state of the system	History can shed light on vulnerabilities, but has little influence on the current state of the system	History can shed light on vulnerabilities, but has little influence on the current state of the system

4. Circle the rating you feel corresponds to *the importance* of each of the following to the **consequence of an infrastructure disruption**:



		Primary Milk Supply	Milk Processing	Milk Delivery
Consequences of Infrastructure Disruption	**Economic Consequences**	2	2	2
		Consequences will likely only be felt locally, by consumers and a few stakeholders, and will likely be temporary	Consequences will likely only be felt locally, by consumers and a few stakeholders, and will likely be temporary	Consequences will likely only be felt locally, by consumers and a few stakeholders, and will likely be temporary
	Environmental Consequences	3	3	3
		Environmental consequences are important, but usually not a matter of life and death	Environmental consequences are important, but usually not a matter of life and death	Environmental consequences are important, but usually not a matter of life and death
	Human Health Impacts	5	5	5
		Human health impacts are the most important consideration of all	Human health impacts are the most important consideration of all	Human health impacts are the most important consideration of all
	Impacts on Interdependent Systems	1	1	1
		Few systems depend on the primary milk supply system	Few systems depend on milk processing	Few systems depend on milk delivery

5. Circle the rating you feel corresponds to *the importance* of each of the following to **energy security**:

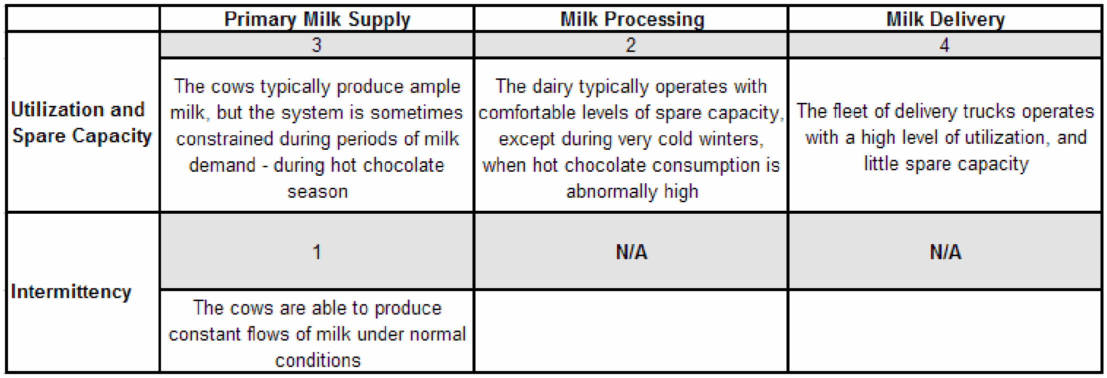
		Primary Milk Supply	Milk Processing	Milk Delivery
Energy Security	**Import Levels**	5	N/A	N/A
		Imports are the primary component of supply security ("milk independence")		
	Import Concentration	4	N/A	N/A
		Vulnerability from imports largely determined by level of import concentration, but only a factor to degree that imports are		
	Geopolitics	3	N/A	N/A
		Vulnerability from import concentration largely shaped by geopolitics, but only a factor to degree that import concentration is		
	Chokepoints	3	N/A	N/A
		Chokepoints pose a threat to all world trade, but only of moderate importance		
	World Excess Production Capacity	2	N/A	N/A
		Excess supply capacity not too important while demand low		
	Price Volatility	5	N/A	N/A
		Price volatility is a primary gauge of reliability in the milk industry		

6. Circle the rating you feel corresponds to *the importance* of each of the following to overall hydrogen system **reliability**. These ratings should be independent of your ratings above.

	Primary Milk Supply	Milk Processing	Milk Delivery
Capacity	5	5	5
	Without enough capacity (i.e. available milk), there can not be adequate supply	Without sufficient processing capacity, there can not be adequate supply	Without sufficient delivery capacity, there can not be adequate supply
Flexibility	4	4	4
	Being able to adapt to changing conditions imperative, but only applies to the extent that capacity is sufficient to allow it	Being able to adapt to changing conditions imperative, but only applies to the extent that capacity is sufficient to allow it	Being able to adapt to changing conditions imperative, but only applies to the extent that capacity is sufficient to allow it
Infrastructure Vulnerability	3	4	3
	Vulnerabilities such as disease and adequate food supplies are important, but the diverse nature of the asset lessens the importance of any single vulnerability	High importance, because assets are concentrated at a common site	Moderate importance because of diverse nature of the asset, and some backup options exist
Consequences of Infrastructure Disruption	5	5	5
	Consequences are very important; they are why we care about reliability at all	Consequences are very important; they are why we care about reliability at all	Consequences are very important; they are why we care about reliability at all
Milk Supply Security	4	N/A	N/A
	Supply security is essentially part of vulnerability; but important because it is a hot issue in the government and media		

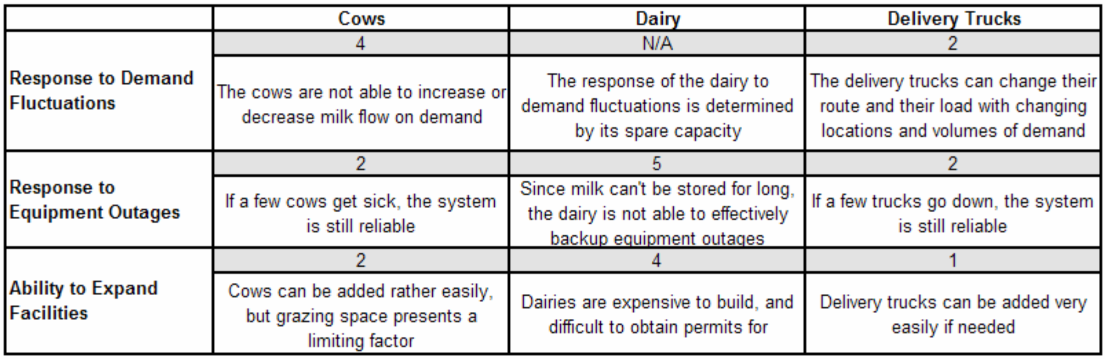
PATHWAY RELIABILITY RATINGS

1. Circle the rating you feel corresponds to the *degree to which the system is constrained by capacity*:



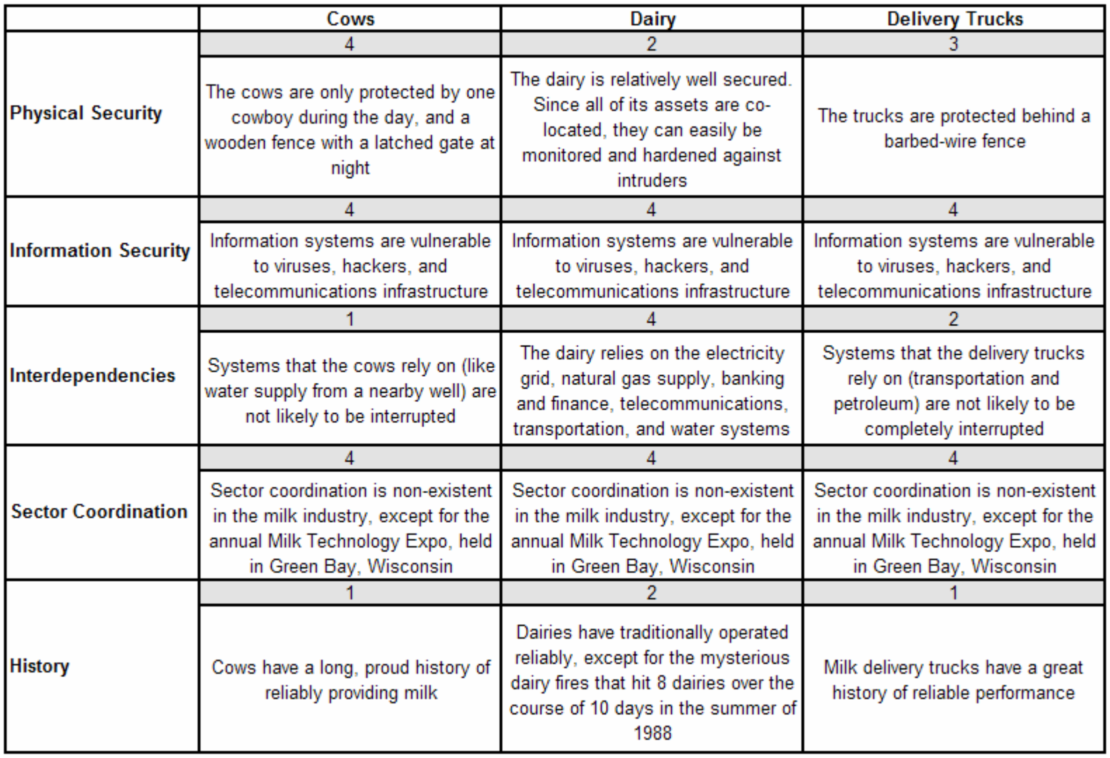
	Primary Milk Supply	**Milk Processing**	**Milk Delivery**
Utilization and Spare Capacity	3	2	4
	The cows typically produce ample milk, but the system is sometimes constrained during periods of milk demand - during hot chocolate season	The dairy typically operates with comfortable levels of spare capacity, except during very cold winters, when hot chocolate consumption is abnormally high	The fleet of delivery trucks operates with a high level of utilization, and little spare capacity
Intermittency	1	**N/A**	**N/A**
	The cows are able to produce constant flows of milk under normal conditions		

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



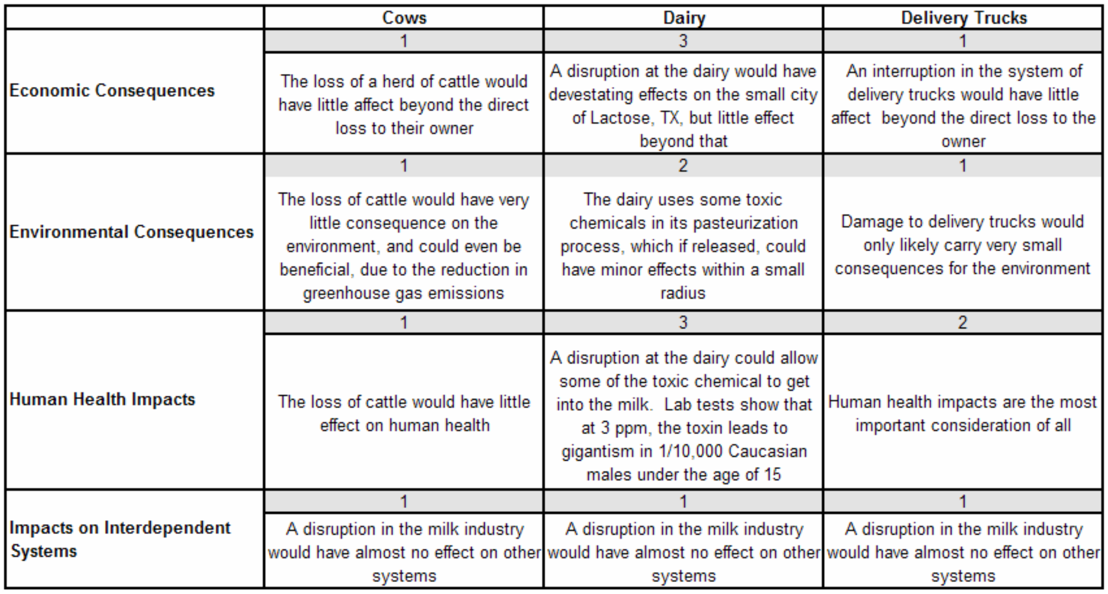
	Cows	**Dairy**	**Delivery Trucks**
Response to Demand Fluctuations	4	N/A	2
	The cows are not able to increase or decrease milk flow on demand	The response of the dairy to demand fluctuations is determined by its spare capacity	The delivery trucks can change their route and their load with changing locations and volumes of demand
Response to Equipment Outages	2	5	2
	If a few cows get sick, the system is still reliable	Since milk can't be stored for long, the dairy is not able to effectively backup equipment outages	If a few trucks go down, the system is still reliable
Ability to Expand Facilities	2	4	1
	Cows can be added rather easily, but grazing space presents a limiting factor	Dairies are expensive to build, and difficult to obtain permits for	Delivery trucks can be added very easily if needed

3. Circle the rating you feel corresponds to the *level of* ***vulnerability*** that exists in the pathway:



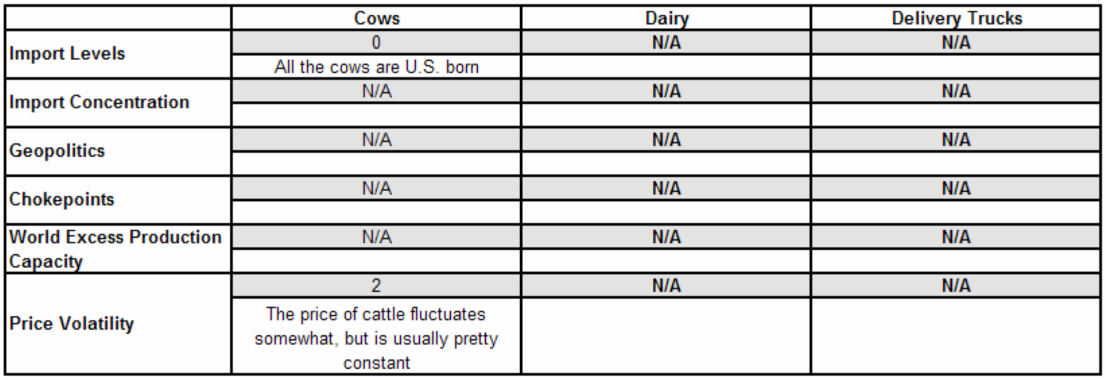
	Cows	Dairy	Delivery Trucks
Physical Security	4	2	3
	The cows are only protected by one cowboy during the day, and a wooden fence with a latched gate at night	The dairy is relatively well secured. Since all of its assets are co-located, they can easily be monitored and hardened against intruders	The trucks are protected behind a barbed-wire fence
Information Security	4	4	4
	Information systems are vulnerable to viruses, hackers, and telecommunications infrastructure	Information systems are vulnerable to viruses, hackers, and telecommunications infrastructure	Information systems are vulnerable to viruses, hackers, and telecommunications infrastructure
Interdependencies	1	4	2
	Systems that the cows rely on (like water supply from a nearby well) are not likely to be interrupted	The dairy relies on the electricity grid, natural gas supply, banking and finance, telecommunications, transportation, and water systems	Systems that the delivery trucks rely on (transportation and petroleum) are not likely to be completely interrupted
Sector Coordination	4	4	4
	Sector coordination is non-existent in the milk industry, except for the annual Milk Technology Expo, held in Green Bay, Wisconsin	Sector coordination is non-existent in the milk industry, except for the annual Milk Technology Expo, held in Green Bay, Wisconsin	Sector coordination is non-existent in the milk industry, except for the annual Milk Technology Expo, held in Green Bay, Wisconsin
History	1	2	1
	Cows have a long, proud history of reliably providing milk	Dairies have traditionally operated reliably, except for the mysterious dairy fires that hit 8 dairies over the course of 10 days in the summer of 1988	Milk delivery trucks have a great history of reliable performance

4. Circle the rating you feel corresponds to the *feasible* ***consequence of an infrastructure disruption*** for the pathway:



	Cows	Dairy	Delivery Trucks
Economic Consequences	1	3	1
	The loss of a herd of cattle would have little affect beyond the direct loss to their owner	A disruption at the dairy would have devestating effects on the small city of Lactose, TX, but little effect beyond that	An interruption in the system of delivery trucks would have little affect beyond the direct loss to the owner
Environmental Consequences	1	2	1
	The loss of cattle would have very little consequence on the environment, and could even be beneficial, due to the reduction in greenhouse gas emissions	The dairy uses some toxic chemicals in its pasteurization process, which if released, could have minor effects within a small radius	Damage to delivery trucks would only likely carry very small consequences for the environment
Human Health Impacts	1	3	2
	The loss of cattle would have little effect on human health	A disruption at the dairy could allow some of the toxic chemical to get into the milk. Lab tests show that at 3 ppm, the toxin leads to gigantism in 1/10,000 Caucasian males under the age of 15	Human health impacts are the most important consideration of all
Impacts on Interdependent Systems	1	1	1
	A disruption in the milk industry would have almost no effect on other systems	A disruption in the milk industry would have almost no effect on other systems	A disruption in the milk industry would have almost no effect on other systems

5. Circle the rating you feel corresponds to the *level of* ***energy security*** in the pathway:



	Cows	Dairy	Delivery Trucks
Import Levels	0	N/A	N/A
	All the cows are U.S. born		
Import Concentration	N/A	N/A	N/A
Geopolitics	N/A	N/A	N/A
Chokepoints	N/A	N/A	N/A
World Excess Production Capacity	N/A	N/A	N/A
Price Volatility	2	N/A	N/A
	The price of cattle fluctuates somewhat, but is usually pretty constant		

GLOSSARY

Terms listed here are defined as they are meant to be considered in this study. The definitions presented here may not apply universally outside of this study.

Ability to expand facilities: The degree to which portions of the system or subsystem can be easily and cost-effectively expanded

Adequacy: The ability of the system or subsystem to provide hydrogen within consumer accepted standards to supply total demand, including expected outages within the system

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

Centralized production: A large hydrogen production facility supplying a wide region

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

Consequences of Infrastructure Disruption: The degree to which a disruption in the system or subsystem causes harm

Distributed production: A small hydrogen production facility producing hydrogen to be used onsite

Economic impacts: The degree to which a disruption in the system or subsystem causes economic damage to industry stakeholders, the government, or the public

Electrolysis: Electricity passes through an electrolyte and breaks water into its fundamental components, producing hydrogen and oxygen:

$$2H_2O \rightarrow 2H_2 + O_2$$

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

Environmental impacts: The degree to which a disruption in the system or subsystem causes environment damage

Flexibility: The degree to which the system or subsystem is able to adapt to changing conditions

Geopolitics: The degree to which the political and social conditions in primary-energy-exporting countries threaten their supply to the U.S.

History: The degree to which the system or subsystem has been prone to disruption in the past

Human health impacts: The degree to which a disruption in the system or subsystem harms the health of employees and/or the public

Impacts on interdependent systems: The degree to which a disruption in the system or subsystem causes damage to interdependent systems

Importance: The degree to which an aspect of reliability weighs on the reliability of the hydrogen pathway

Imported liquefied natural gas (LNG): Natural gas supplies imported as a liquid

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

Import levels: The degree to which the primary energy supply relies on resources originating outside of the U.S.

Information security: The degree to which information assets in the system or subsystem are secure against threats

Interdependencies: The degree to which the system or subsystem relies on other infrastructures for its reliable operation, and is vulnerable to their disruption

Intermittency: The degree to which the productivity of the system or subsystem is not constant

Physical security: The degree to which assets in the system or subsystem are secure against physical threats

Pipeline: Hydrogen transported through a pipe, often buried underground

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

Primary energy supply system: The upstream system(s) providing the energy from which hydrogen is derived (e.g., natural gas, electricity, or renewable supply infrastructure)

Response to demand fluctuations: The degree to which the system or subsystem is able to adapt to varying demand levels and locations

Response to equipment outages: The degree to which the system or subsystem is able to continue reliable operation in the event of equipment downtime

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

Security: The ability of the system or subsystem to mitigate risk and withstand unexpected interruptions

Steam methane reformation (SMR): A thermochemical process by which methane (CH_4) – the primary component of natural gas – is converted into hydrogen. The reaction occurs in two steps:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \text{(Steam reforming)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \text{(Water-gas shift reaction)}$$

The overall reaction is given by:

$$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$$

Utilization and spare capacity: The degree to which the capacity of the system or subsystem is being used

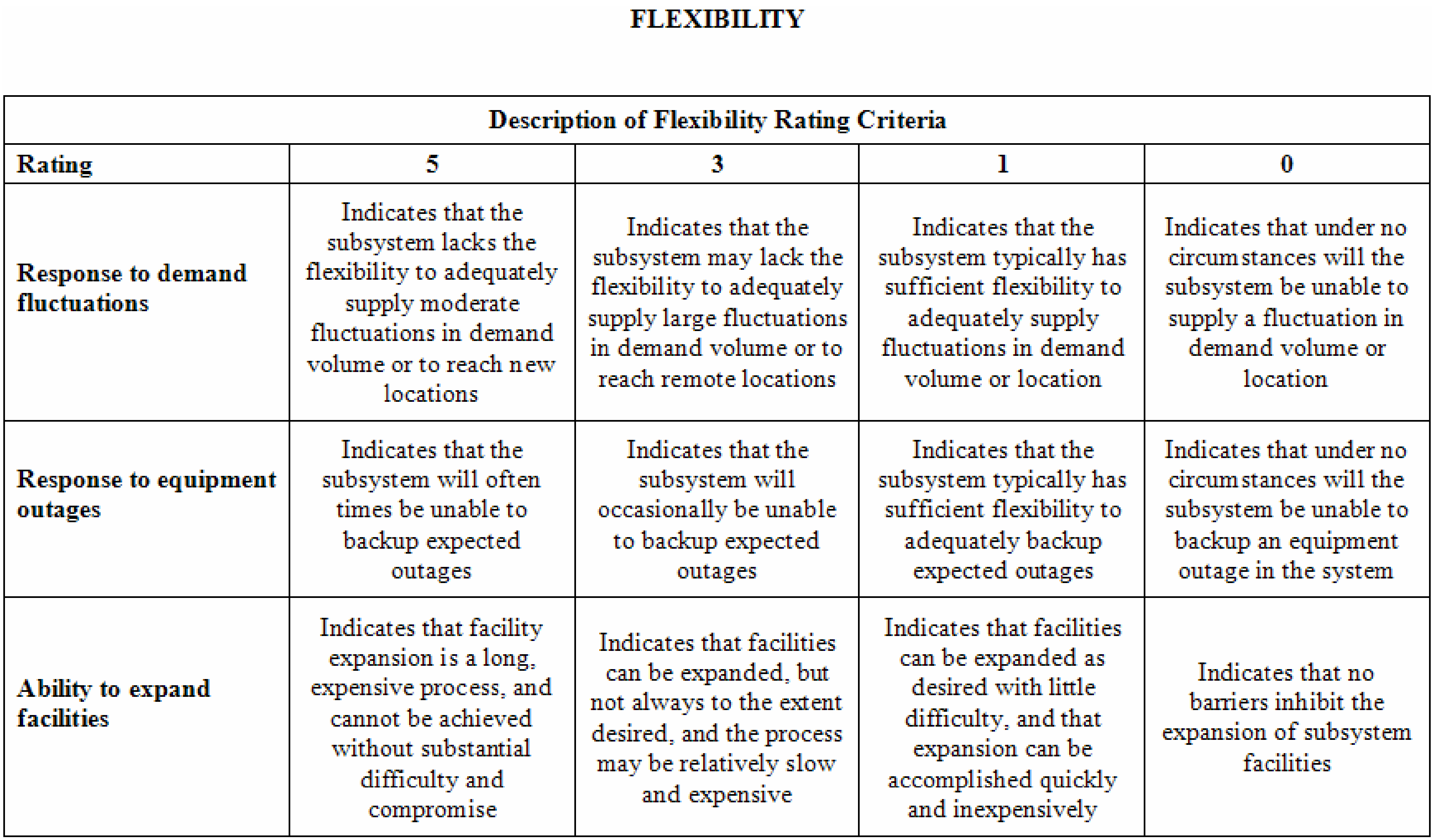
Vulnerability: The degree to which the system or subsystem is susceptible to disruption

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

RATING CRITERIA

CAPACITY

Description of Capacity Rating Criteria				
Rating	**5**	**3**	**1**	**0**
Utilization & Spare Capacity	Indicates that the subsystem typically operates with little or no spare capacity, and even small changes in demand could overstress the system	Indicates that the subsystem can be expected to operate at or near maximum utilization occasionally, during yearly peak demands	Indicates that the subsystem typically operates with sufficient spare capacity, and would only approach maximum utilization under rare conditions	Indicates that under no circumstances will the subsystem ever approach maximum utilization
Intermittency	Indicates that, given sufficient inputs, the subsystem will operate with high levels of unpredictable intermittency	Indicates that, given sufficient inputs, the subsystem will operate with relatively high levels of predictable intermittency	Indicates that, given sufficient inputs, the subsystem will operate with low levels of predictable intermittency	Indicates that under no circumstances will the subsystem operate intermittently



FLEXIBILITY

Description of Flexibility Rating Criteria				
Rating	**5**	**3**	**1**	**0**
Response to demand fluctuations	Indicates that the subsystem lacks the flexibility to adequately supply moderate fluctuations in demand volume or to reach new locations	Indicates that the subsystem may lack the flexibility to adequately supply large fluctuations in demand volume or to reach remote locations	Indicates that the subsystem typically has sufficient flexibility to adequately supply fluctuations in demand volume or location	Indicates that under no circumstances will the subsystem be unable to supply a fluctuation in demand volume or location
Response to equipment outages	Indicates that the subsystem will often times be unable to backup expected outages	Indicates that the subsystem will occasionally be unable to backup expected outages	Indicates that the subsystem typically has sufficient flexibility to adequately backup expected outages	Indicates that under no circumstances will the subsystem be unable to backup an equipment outage in the system
Ability to expand facilities	Indicates that facility expansion is a long, expensive process, and cannot be achieved without substantial difficulty and compromise	Indicates that facilities can be expanded, but not always to the extent desired, and the process may be relatively slow and expensive	Indicates that facilities can be expanded as desired with little difficulty, and that expansion can be accomplished quickly and inexpensively	Indicates that no barriers inhibit the expansion of subsystem facilities

INFRASTRUCTURE VULNERABILITY

Description of Infrastructure Vulnerability Rating Criteria				
Rating	**5**	**3**	**1**	**0**
Physical security	Indicates that physical security is lacking, and many physical components of the system are highly susceptible to disruption	Indicates that security protects some physical assets, but portions of the system are moderately susceptible to disruption	Indicates that effective security systems guard all physical assets, and the likelihood of a disruption is small	Indicates that physical security is so effective that no threat agent would be capable of disrupting physical assets
Information security	Indicates that information security is lacking, and information systems are highly susceptible to disruption	Indicates that security protects some information assets, but portions of the system are moderately susceptible to disruption	Indicates that effective security systems guard information assets, and the likelihood of a disruption is small	Indicates that information security is so effective that no threat agent would be capable of disrupting the information system(s)
Interdependencies	Indicates that the subsystem is critically dependent on other systems, or that a disruption in an interdependent system could halt throughput in the subsystem	Indicates that the subsystem is highly dependent on other systems, or that interdependent systems pose significant threat to disrupt the subsystem	Indicates that the subsystem is mostly independent from other systems, or that interdependent systems pose little threat to disrupt the subsystem	Indicates that the subsystem is completely isolated from other systems, or that an interruption in an interdependent system could not possibly disrupt the subsystem

Sector coordination	Indicates that very little or no coordination exists among stakeholders to share information regarding emerging threats and mitigation strategies	Indicates coordination between stakeholders is generally ineffective in sharing information regarding emerging threats and mitigation strategies	Indicates that coordination between stakeholders is generally effective in sharing information regarding emerging threats and mitigation strategies	Indicates that coordination between stakeholders is completely effective in sharing information regarding emerging threats and mitigation strategies
History	Indicates that there is a vast operating history of the subsystem, and that disruptions occur frequently	Indicates that there is a vast operating history of the subsystem, and that disruptions occur with moderate frequency	Indicates that there is a vast operating history of the subsystem, and disruptions are rare	Indicates that there is a vast operating history of the subsystem, and that there have never been any disruptions

CONSEQUENCE OF INFRASTRUCTURE DISRUPTION

Description of Consequence Rating Criteria				
Rating	**5**	**3**	**1**	**0**
Economic impacts	Indicates that the economic impacts resulting from a feasible disruption could be devastating to stakeholders, and might be felt regionally or nationally	Indicates that the economic impacts resulting from a feasible disruption could be substantial to individual stakeholders, and might be felt on a local basis	Indicates that the economic impacts resulting from a feasible disruption would be small, and isolated to a few stakeholders	Indicates that there would be absolutely no economic impacts resulting from a feasible disruption of the subsystem

Environmental impacts	Indicates that the environmental impacts resulting from a feasible disruption would cause significant, widespread, and potentially irreparable damage to ecosystems	Indicates that the environmental impacts resulting from a feasible disruption would cause moderate, isolated damage or minor, widespread damage to ecosystems	Indicates that the environmental impacts resulting from a feasible disruption would cause minor, relatively isolated damage to ecosystems	Indicates that there would be absolutely no environmental impacts resulting from a feasible disruption
Human health impacts	Indicates that the effects on human health of a feasible disruption could reach the public, and would likely result in loss of life	Indicates that the effects of a feasible disruption could have potentially significant health consequences, including death, on a small human population knowingly exposed to the risk (i.e., employees)	Indicates that the effects of a feasible disruption on human health would be small, and would most likely not result in loss of life	Indicates that there would be absolutely no impacts on human health resulting from a feasible disruption
Impacts on interdependent systems	Indicates that a disruption in the subsystem would cascade to other interdependent systems causing severe consequences across multiple sectors	Indicates that a disruption in the subsystem could noticeably effect interdependent systems, but not to the extent of them becoming non-functional	Indicates that a disruption in the subsystem would have limited effects on interdependent systems, and would not hinder their throughput in a significant way	Indicates that a disruption in the subsystem would have absolutely no negative effects on interdependent systems

ENERGY SECURITY

Description of Energy Security Rating Criteria				
Rating	**5**	**3**	**1**	**0**
Import levels	Indicates that imports constitute essentially all of the primary energy resource supply	Indicates that imports constitute a moderate portion of the primary energy resource supply	Indicates that imports constitute a small portion of the primary energy resource supply	Indicates that there are no imports in the primary energy resource supply
Import concentration	Indicates that imports of primary energy supply resources are highly concentrated from a small group of countries	Indicates that imports of primary energy supply resources are highly concentrated from several (more than five) countries	Indicates that imports of primary energy supply resources are distributed relatively evenly among several supplying countries	Indicates that imports are evenly distributed among all potential supplying countries
Geopolitics	Indicates that most imports come from politically and socially unstable countries, or those who have poor relations with the U.S.	Indicates that at a moderate portion of imports come from politically and socially unstable countries, or those who have poor relations with the U.S.	Indicates that a minor portion of imports come from politically and socially unstable countries	Indicates that all imports come from politically and socially stable countries who have well-developed relations with the U.S.

“Chokepoints”	Indicates that there exists vulnerable transport “chokepoints” along the primary energy supply route whose closure would have devastating effects on world energy trade	Indicates that there exist transport “chokepoints” along the primary energy supply route whose closure would have a noticeable effect on world energy trade	Indicates that there exist low vulnerability transport “chokepoints” along the primary energy supply route whose closure would have a little effect on world energy trade	Indicates that there are no transport “chokepoints” where primary energy supply could be cut off
World excess production capacity	Indicates that world excess export capacity is minimal, and cannot supply an increase in global demand, or an outage in the global supply system, without capacity expansion	Indicates that world excess export capacity is unable to meet projected increases in global demand or a substantial disruption in the global supply system without capacity expansion	Indicates that world excess export capacity is sufficient to meet most feasible increases in global demand or outages in the global supply system	Indicates that world excess export capacity is sufficient to meet any feasible increases in global demand or outage in the supply system
Price volatility	Indicates that the price of the energy product at the outlet of the subsystem is subject to wild, unpredictable variations	Indicates that the price of the energy product at the outlet of the subsystem is subject to large, but predictable, variations corresponding to seasonal fluctuations in demand	Indicates that the price of the energy product at the outlet of the subsystem is subject to small, predictable variations corresponding to seasonal fluctuations in demand	Indicates that the price of the energy product at the outlet of the subsystem is constant over time and not subject to any instability

APPENDIX D: AUTHOR’S RELIABILITY RATINGS

Evaluation Matrix

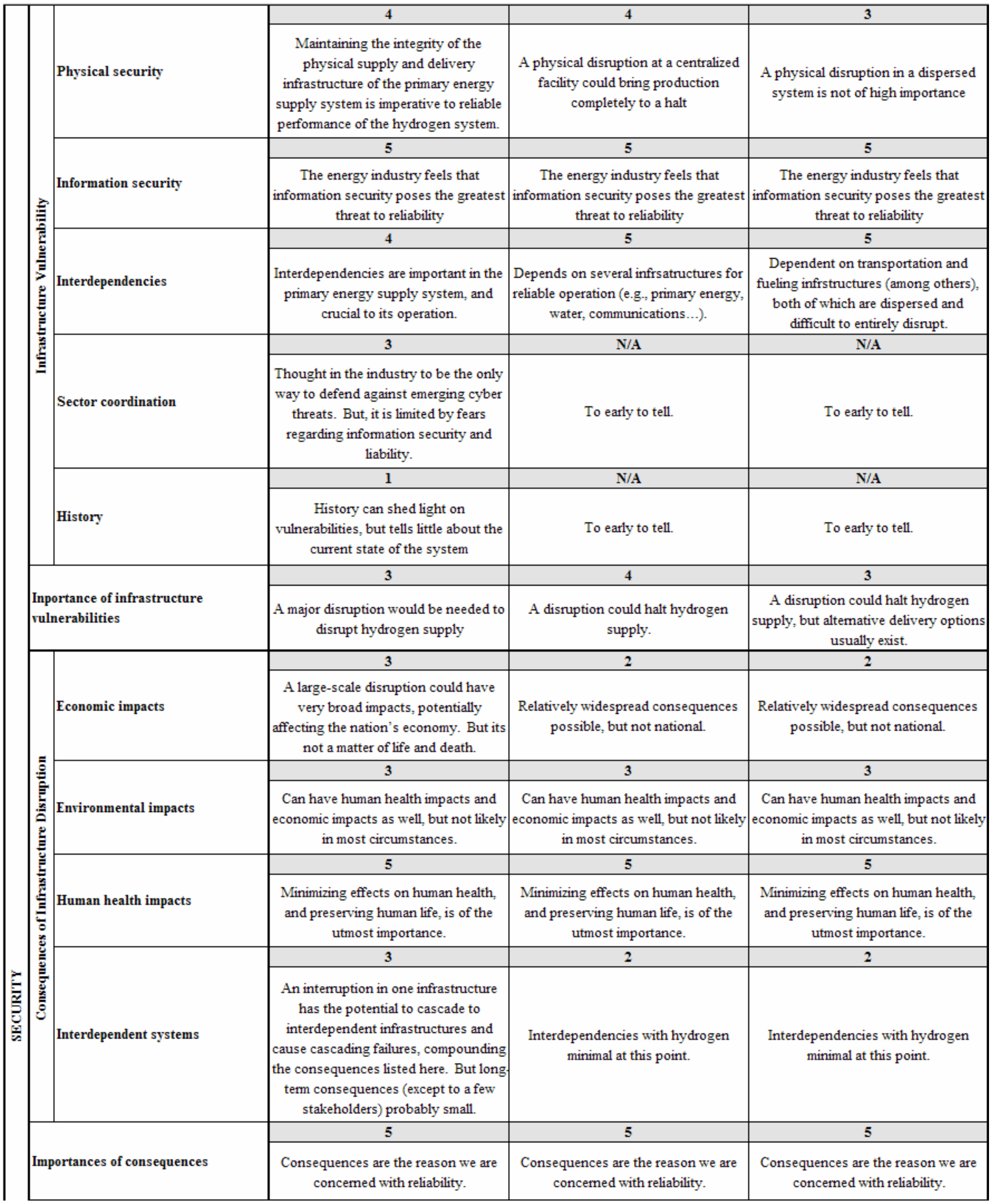
			Pathway #1			Pathway #2		
			Imported LNG	Centralized SMR	Pipeline	Stand-alone electricity	Distributed Electrolysis	No Transport
ADEQUACY	**Capacity**	**Utilization and spare capacity**	3	1	1	4	3	N/A
		Importance	5	5	5	5	5	5
		Intermittency	1	N/A	N/A	3	N/A	N/A
		Importance	2	N/A	N/A	2	N/A	N/A
		Aggregated capacity	1.70	1.00	1.00	2.60	3.00	N/A
		Importance of capacity	3	5	5	3	5	5
	Flexibility	**vs. demand fluctuations**	1	N/A	3	4	N/A	N/A
		Importance	2	N/A	4	2	N/A	4
		vs. equipment outages	3	3	4	4	2	N/A
		Importance	3	4	3	3	4	3
		Ability to expand facilities	5	4	4	2	2	N/A
		Importance	3	4	4	3	4	4
		Aggregated safeguards	1.73	2.80	2.67	1.73	1.60	N/A
		Importance of safeguards	2	4	4	2	4	4
	Total adequacy score		0.86	1.62	1.57	1.13	2.14	N/A
	Pathway adequacy score		1.35			1.63		
SECURITY	**Infrastructure Vulnerability**	**Physical security**	4	4	4	2	2	N/A
		Importance	4	4	3	4	4	3
		Information security	4	4	4	3	3	N/A
		Importance	5	5	5	5	5	5
		Interdependencies	4	5	3	1	3	N/A
		Importance	4	5	5	4	5	5
		Sector coordination	4	N/A	N/A	N/A	N/A	N/A
		Importance	3	N/A	N/A	N/A	N/A	N/A
		History	3	N/A	N/A	N/A	N/A	N/A
		Importance	1	N/A	N/A	N/A	N/A	N/A
		Aggregated infrastructure vulnerability	2.68	4.07	3.13	1.80	2.53	N/A
		Importance of vulnerabilities	3	4	3	3	4	3
	Consequences of Infrastructure Disruption	**Economic impacts**	2	3	3	1	1	N/A
		Importance	3	2	2	3	2	2
		Environmental impacts	3	3	2	1	1	N/A
		Importance	3	3	3	3	3	3
		Human health impacts	5	5	3	2	2	N/A
		Importance	5	5	5	5	5	5
		Interdependent systems	3	3	3	1	1	N/A
		Importance	3	2	2	3	2	2
		Aggregated consequences	2.45	2.30	1.65	0.95	0.85	N/A
		Importance of consequences	5	5	5	5	5	5
	Energy Security	**Import levels**	5	N/A	N/A	0	N/A	N/A
		Importance	5	N/A	N/A	5	N/A	N/A
		Import concentration	4	N/A	N/A	N/A	N/A	N/A
		Importance	4	N/A	N/A	4	N/A	N/A
		Geopolitics	3	N/A	N/A	N/A	N/A	N/A
		Importance	3	N/A	N/A	3	N/A	N/A
		Chokepoints	3	N/A	N/A	N/A	N/A	N/A
		Importance	2	N/A	N/A	2	N/A	N/A
		World excess production capacity	4	N/A	N/A	N/A	N/A	N/A
		Importance	2	N/A	N/A	2	N/A	N/A
		Price volatility	3	N/A	N/A	2	N/A	N/A
		Importance	3	N/A	N/A	3	N/A	N/A
		Aggregated energy security	2.43	N/A	N/A	0.60	N/A	N/A
		Importance of energy security	5	N/A	N/A	5	N/A	N/A
	Total security score		2.16	2.78	1.77	0.88	1.44	N/A
	Pathway security score		2.22			1.10		

Importance Ratings and Descriptions

Adequacy

			Primary Energy Supply System	**Hydrogen Production Process**	**Hydrogen Transport Process**
ADEQUACY	**Capacity**	**Utilization and spare capacity**	**5**	**5**	**5**
			Without sufficient capacity in the system, demands can not be met. Hydrogen provides the ability to load level somewhat, but is unlikely to be stored in significant quantities, and will have to be produced at relatively constant levels year-round, even if NG system fully utilized.	Without sufficient capacity in the system, demands can not be met	Without sufficient capacity in the system, demands can not be met
		Intermittency	**2**	N/A	N/A
			Unpredictable intermittency is dangerous. But if it can be planned for, and if capacity is sufficient, it is less of an issue.		
	Importance of capacity		**3**	**5**	**5**
			Marginal demand from hydrogen will have minimal impact on primary energy system in foreseeable future.	Sufficient capacity imperative to meeting end user demands.	Sufficient capacity imperative to meeting end user demands.
	Flexibility	**vs. demand fluctuations**	**2**	**N/A**	**4**
			Supply must be able to adapt to changes in demand, but hydrogen demand fluctuations will have a negligible impact on primary energy systems in the foreseeable future.	Production facilities are important in safeguarding against demand fluctuations, but do so by increasing output, which is akin to utilization, above.	Hydrogen unlikely to be stored in large quantities, so must be able to adapt to changes in demand
		vs. equipment outages	**3**	**4**	**3**
			Many (but not all) primary energy systems are established, diverse assets that will be uneffected by most equipment outages. Equipment outages which do have a noticeable effect will likely have short-term effects.	Hydrogen unlikely to be stored in large quantities, so must be able to backup outages.	Must be able to backup outages, but various transportation alternatives exist.
		Ability to expand facilities	**3**	**4**	**4**
			To the extent that hydrogen adds marginal demand to the system that was not originally designed for, the ability to expand the primary energy supply system is incredibly important, but in large primary energy systems, is less of an issue.	Ability to expand facilities necessary for reliable supply, especially as demand builds in early stages.	Ability to expand facilities necessary for reliable supply, especially as demand builds in early stages.
	Importance of flexibility		**2**	**4**	**4**
			Generally dispersed, well established systems which will be able to adapt to any changes resulting from near-term hydrogen demand.	Flexibility especially important as hydrogen demand initially develops.	Flexibility especially important as hydrogen demand initially develops.

Security

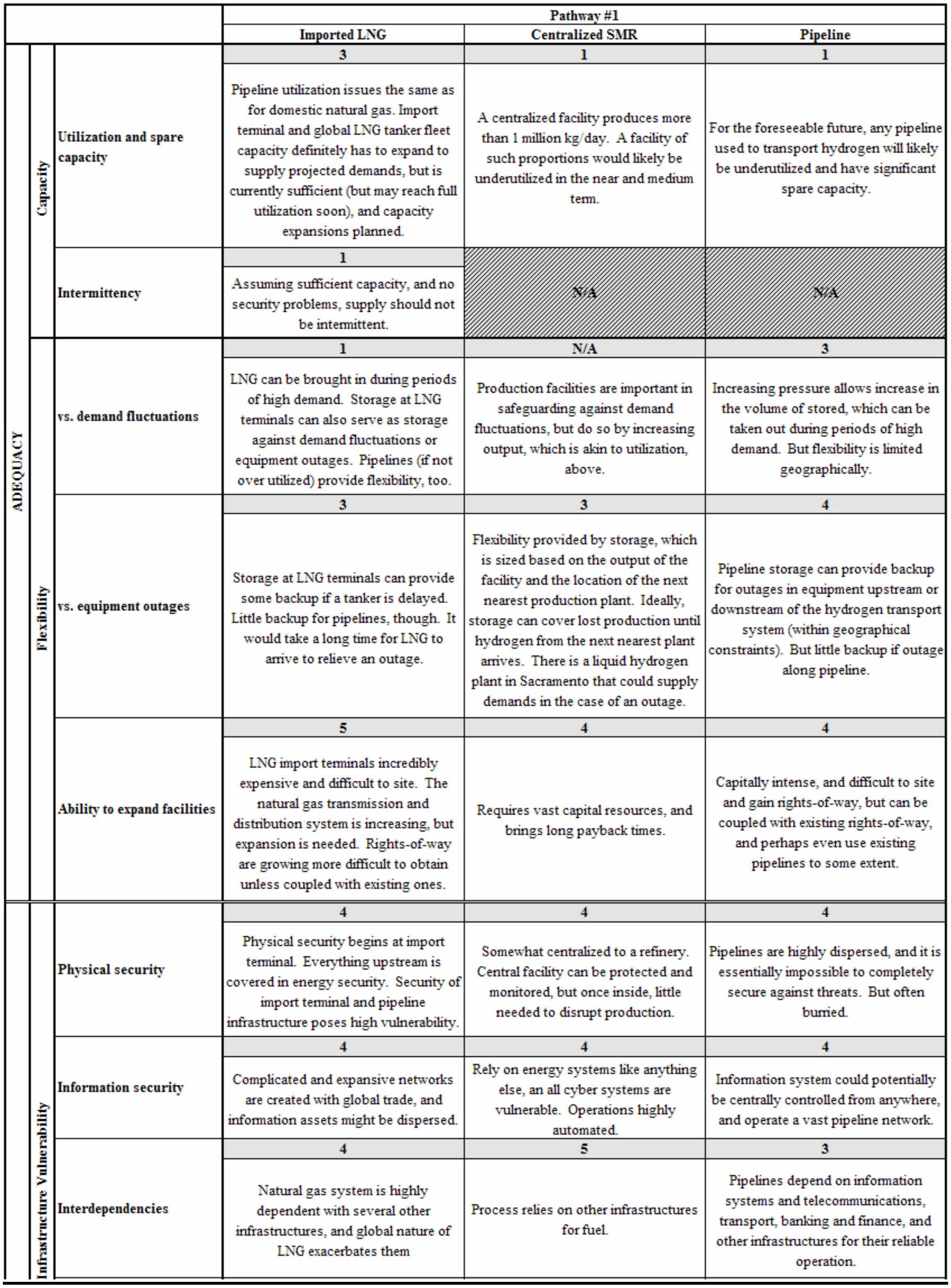


SECURITY	Infrastructure Vulnerability	**Physical security**	**4** Maintaining the integrity of the physical supply and delivery infrastructure of the primary energy supply system is imperative to reliable performance of the hydrogen system.	**4** A physical disruption at a centralized facility could bring production completely to a halt	**3** A physical disruption in a dispersed system is not of high importance
		Information security	**5** The energy industry feels that information security poses the greatest threat to reliability	**5** The energy industry feels that information security poses the greatest threat to reliability	**5** The energy industry feels that information security poses the greatest threat to reliability
		Interdependencies	**4** Interdependencies are important in the primary energy supply system, and crucial to its operation.	**5** Depends on several infrsatructures for reliable operation (e.g., primary energy, water, communications…).	**5** Dependent on transportation and fueling infrstructures (among others), both of which are dispersed and difficult to entirely disrupt.
		Sector coordination	**3** Thought in the industry to be the only way to defend against emerging cyber threats. But, it is limited by fears regarding information security and liability.	**N/A** To early to tell.	**N/A** To early to tell.
		History	**1** History can shed light on vulnerabilities, but tells little about the current state of the system	**N/A** To early to tell.	**N/A** To early to tell.
	Inportance of infrastructure vulnerabilities		**3** A major disruption would be needed to disrupt hydrogen supply	**4** A disruption could halt hydrogen supply.	**3** A disruption could halt hydrogen supply, but alternative delivery options usually exist.
	Consequences of Infrastructure Disruption	**Economic impacts**	**3** A large-scale disruption could have very broad impacts, potentially affecting the nation's economy. But its not a matter of life and death.	**2** Relatively widespread consequences possible, but not national.	**2** Relatively widespread consequences possible, but not national.
		Environmental impacts	**3** Can have human health impacts and economic impacts as well, but not likely in most circumstances.	**3** Can have human health impacts and economic impacts as well, but not likely in most circumstances.	**3** Can have human health impacts and economic impacts as well, but not likely in most circumstances.
		Human health impacts	**5** Minimizing effects on human health, and preserving human life, is of the utmost importance.	**5** Minimizing effects on human health, and preserving human life, is of the utmost importance.	**5** Minimizing effects on human health, and preserving human life, is of the utmost importance.
		Interdependent systems	**3** An interruption in one infrastructure has the potential to cascade to interdependent infrastructures and cause cascading failures, compounding the consequences listed here. But long-term consequences (except to a few stakeholders) probably small.	**2** Interdependencies with hydrogen minimal at this point.	**2** Interdependencies with hydrogen minimal at this point.
	Importances of consequences		**5** Consequences are the reason we are concerned with reliability.	**5** Consequences are the reason we are concerned with reliability.	**5** Consequences are the reason we are concerned with reliability.

Energy Security	**Import levels**	**5** Imports are the most apparent measure of energy security.	N/A	N/A
	Import concentration	**4** May be a more important metric than imports themselves - since imports can improve reliability - but only important to the extent that imports are an important part of energy supply.	N/A	N/A
	Geopolitics	**3** Geopolitics are a primary factor making imports vulnerable, but only a threat to the degree that imports and import concentration are important.	N/A	N/A
	Chokepoints	**2** Major chokepoints have the potential to completely disrupt world energy trade, but large disruptions have not been a problem historically, and only important to degree that imports are. A disruption at a chokepoint could be shorter term than one from geopolitics.	N/A	N/A
	World excess production capacity	**2** Excess production capacity essentially serves as storage vs. demand fluctuations or equipment outages, but only as important as imports are.	N/A	N/A
	Price volatility	**3** Price stability is an essential component of reliability, but instability won't lead directly to a disruption of supply.	N/A	N/A
Importance of energy security		**5** Energy security has vast implications for national and international security.	N/A	N/A

Pathway Reliability Ratings and Descriptions

Pathway #1



			Pathway #1		
			Imported LNG	**Centralized SMR**	**Pipeline**
ADEQUACY	**Capacity**	**Utilization and spare capacity**	**3** Pipeline utilization issues the same as for domestic natural gas. Import terminal and global LNG tanker fleet capacity definitely has to expand to supply projected demands, but is currently sufficient (but may reach full utilization soon), and capacity expansions planned.	**1** A centralized facility produces more than 1 million kg/day. A facility of such proportions would likely be underutilized in the near and medium term.	**1** For the foreseeable future, any pipeline used to transport hydrogen will likely be underutilized and have significant spare capacity.
		Intermittency	**1** Assuming sufficient capacity, and no security problems, supply should not be intermittent.	N/A	N/A
	Flexibility	**vs. demand fluctuations**	**1** LNG can be brought in during periods of high demand. Storage at LNG terminals can also serve as storage against demand fluctuations or equipment outages. Pipelines (if not over utilized) provide flexibility, too.	**N/A** Production facilities are important in safeguarding against demand fluctuations, but do so by increasing output, which is akin to utilization, above.	**3** Increasing pressure allows increase in the volume of stored, which can be taken out during periods of high demand. But flexibility is limited geographically.
		vs. equipment outages	**3** Storage at LNG terminals can provide some backup if a tanker is delayed. Little backup for pipelines, though. It would take a long time for LNG to arrive to relieve an outage.	**3** Flexibility provided by storage, which is sized based on the output of the facility and the location of the next nearest production plant. Ideally, storage can cover lost production until hydrogen from the next nearest plant arrives. There is a liquid hydrogen plant in Sacramento that could supply demands in the case of an outage.	**4** Pipeline storage can provide backup for outages in equipment upstream or downstream of the hydrogen transport system (within geographical constraints). But little backup if outage along pipeline.
		Ability to expand facilities	**5** LNG import terminals incredibly expensive and difficult to site. The natural gas transmission and distribution system is increasing, but expansion is needed. Rights-of-way are growing more difficult to obtain unless coupled with existing ones.	**4** Requires vast capital resources, and brings long payback times.	**4** Capitally intense, and difficult to site and gain rights-of-way, but can be coupled with existing rights-of-way, and perhaps even use existing pipelines to some extent.
	Infrastructure Vulnerability	**Physical security**	**4** Physical security begins at import terminal. Everything upstream is covered in energy security. Security of import terminal and pipeline infrastructure poses high vulnerability.	**4** Somewhat centralized to a refinery. Central facility can be protected and monitored, but once inside, little needed to disrupt production.	**4** Pipelines are highly dispersed, and it is essentially impossible to completely secure against threats. But often burried.
		Information security	**4** Complicated and expansive networks are created with global trade, and information assets might be dispersed.	**4** Rely on energy systems like anything else, an all cyber systems are vulnerable. Operations highly automated.	**4** Information system could potentially be centrally controlled from anywhere, and operate a vast pipeline network.
		Interdependencies	**4** Natural gas system is highly dependent with several other infrastructures, and global nature of LNG exacerbates them	**5** Process relies on other infrastructures for fuel.	**3** Pipelines depend on information systems and telecommunications, transport, banking and finance, and other infrastructures for their reliable operation.

SECURITY		**Sector coordination**	4	N/A	N/A
			Limited levels of information sharing exist, but need to expand to effectively compact cyber and physical threats.	To early to tell.	To early to tell.
		History	3	N/A	N/A
			LNG industry claims no major fires or explosions over past 45 years. But pipelines have a somewhat significant history.	Don't know. There is a history here, but I was unable to find information regarding it.	Don't know. There is a history here, but I was unable to find information regarding it.
	Consequences of Infrastructure Disruption	**Economic impacts**	2	3	3
			LNG is a small, but increasing, portion of natural gas supply. As LNG plays an increasing role in supplying marginal demand, potential economic consequences of a disruption increase.	The economic damages could be relatively widespread, to the region supplied by the facility. But not devastating.	The economic damages could be relatively widespread, to the region supplied by the facility. But not devastating.
		Environmental impacts	3	3	2
			Potential air pollution from extended fire and effects on marine environments. But it's a relatively clean fuel.	Potential air and terrestrial environmental consequences would be local. Relatively clean fuel.	If the pipeline ruptured, hydrogen would vent to the atmosphere. Possibility for fire, but burns clean.
		Human health impacts	5	5	3
			Huge concentration of energy, and very flammable. Potential human health impacts very significant.	Potential high loss of life associated with a disruption at a facility containing high volumes of energy and a large number of employees.	Potential fire or explosion could be fatal. Might be unlikely that anyone would be nearby, however, depending on pipeline route.
		Interdependent systems	3	3	3
			Any disruption in the natural gas supply system could feasibly disrupt infrastructures dependent on it.	Significant effects on downstream infrastructures, less impact on upstream infrastructure.	Significant effects on downstream infrastructures, less impact on upstream infrastructure.
	Energy Security	**Import levels**	5	N/A	N/A
			Essentially 100% imports (some could come from Alaska, though)		
		Import concentration	4	N/A	N/A
			Trinidad and Tobago primary supplier, but other countries, too. Only a handful of possible suppliers, though, so import concentration will always be high.		
		Geopolitics	3	N/A	N/A
			Trinidad and Tobago has a parliamentary democracy and is ranked "partly free" by Freedom House. The economy relies on petroleum and natural gas exports. Other suppliers pose greater threats.		
		Chokepoints	3	N/A	N/A
			Imports to the West Coast from Trinidad and Tobago must go through Panama Canal, and imports from Middle East traverse dangerous chokepoints.		
		World excess production capacity	4	N/A	N/A
			Little excess LNG capacity in the world market.		
		Price volatility	3	N/A	N/A
			Imported LNG prices fluctuate, but not as wildly as domestic supply prices.		

Pathway #2

			Pathway #2		
			Stand-alone Electricity	**Distributed Electrolysis**	**No Transport**
ADEQUACY	**Capacity**	**Utilization and spare capacity**	4 System likely sized for specific application, with little spare capacity.	3 A distributed facility would likely be operating near its designed capacity, but little spare capacity required.	N/A No transport system.
		Intermittency	3 Likely that primary energy will be intermittent renewable resources (solar, wind), but this intermittency can be relatively well designed for.	N/A	N/A
	Flexibility	**vs. demand fluctuations**	3 Little spare capacity to meet demand fluctuations, but demand fluctuations small at single refueling station.	N/A Production facilities are important in safeguarding against demand fluctuations, but do so by increasing output, which is akin to utilization, above.	N/A No transport system.
		vs. equipment outages	4 Flexibility against outages relies on storage, which is somewhat difficult for large hydrogen in large quantities.	2 A distributed production plant can relatively easy provide storage to backup its low levels of production.	N/A No transport system.
		Ability to expand facilities	2 Small projects - can be difficult to site and expensive on a per-unit-energy basis, but pales in comparison to LNG.	2 Small capital investment needed, and can be done incrementally following demand increases. But if substantial expansion required, several new facilities would be needed.	N/A No transport system.
SECURITY	**Infrastructure Vulnerability**	**Physical security**	2 Small, co-located assets can be easily hardened and monitored.	2 Small, co-located assets can be easily hardened and monitored.	N/A No transport system.
		Information security	3 Rely on energy systems like anything else, but small and owner-controlled. All cyber systems vulnerable, however.	3 Rely on energy systems like anything else, but small and owner-controlled. All cyber systems vulnerable, however.	N/A No transport system.
		Interdependencies	1 Minimal interdependencies.	3 Relies on primary energy system.	N/A No transport system.
		Sector coordination	N/A To early to tell.	N/A To early to tell.	N/A No transport system.
		History	N/A To early to tell.	N/A To early to tell.	N/A No transport system.
	Consequences of Infrastructure	**Economic impacts**	1 Few consequences of relatively interdependent system except to owner.	1 Few consequences of relatively interdependent system except to owner.	N/A No transport system.
		Environmental impacts	1 Any consequences would be isolated.	1 Any consequences would be isolated.	N/A No transport system.
		Human health impacts	2 Feasible, but unlikely consequences. Renewable systems could be unmanned.	2 Feasible, but unlikely consequences. Renewable systems could be unmanned.	N/A No transport system.
		Interdependent systems	1 Minimal interdependencies.	1 Minimal interdependencies.	N/A No transport system.
	Energy Security	**Import levels**	0 A lack of imports adds to the reliability of this pathway.	N/A	N/A
		Import concentration	N/A No imports.	N/A	N/A
		Geopolitics	N/A No imports.	N/A	N/A
		Chokepoints	N/A No imports.	N/A	N/A
		World excess production capacity	N/A No imports.	N/A	N/A
		Price volatility	2 Generation costs should be relatively	N/A	N/A