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Structuring objectives to facilitate convergence of divergent opinion in hydrogen production decisions

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Abstract

Achieving a sustainable energy system obviously is an important goal of all societies. However, achieving that goal is complicated by multiple players with divergent interests promoting their views in the context of numerous complex technological considerations. The research described in this paper provides insights gained from the development of a multiple criteria decision-aiding process to aid such decisions and from an evaluation of convergence in decision maker opinion achievable using the process. The ability of an interactive multicriteria decision-aiding tool to facilitate convergence of decision maker opinions was tested in three phases: (1) development of an objectives hierarchy, (2) definitional clarifications, and (3) elicitation and refinement of criteria weights using shared judgment rationales. Each of these phases was conducted via repeated interactions among a disparate group of experts. Contrary to initial expectations of greatest convergence during the second and third phases of definitional clarification and weight elicitation and refinement, it was found that most convergence occurred during the initial objectives hierarchy development phase. This result demonstrates the value of structured thinking and interaction among decision makers. The structure of the exploratory model developed in this research and the insights gained may be useful for a wide range of real-world issues.

Keywords: Hydrogen; Multicriteria decision making; Objectives hierarchy

1. Introduction

1.1. Background

The quest for a sustainable energy system continues, with numerous pathways to consider and diverse players involved. A "Hydrogen Energy System," envisioned by many, is being extensively discussed as a solution to the current environmental, health and security concerns of societies. However, there are many complexities involved, emerging in multiple layers. The difficulties associated with novel technologies and the details involved with the processes themselves, along with the range of viewpoints leading the discussions, contribute to this multilevel complexity.

1.2. Problem statement

Hydrogen is abundant in nature, but not as a free element. It is bound to other atoms in water or organic material. Therefore, to produce hydrogen, another energy source is required to separate it from the atoms to which it is attached, which makes it an *energy carrier*, instead of an *energy source*. Production methods for hydrogen vary from advanced technologies to those that are still in the research and development phase. Any source of energy, fossil or renewable, may be used for the production process. Once generated, hydrogen may be utilized in every component of our energy system—as a fuel for transportation, a source for electricity, or heating.

US energy infrastructure has been in place long enough to establish market conditions that are favorable to fossil energy sources. In contrast, the envisioned hydrogen energy system is still largely in a conceptual phase, with many unknowns and concerns. Even though a hydrogen-based

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energy system offers many advantages as demonstrated by pilot applications, questions and criticisms remain. Some concerns are based on the unknowns inherent in the technologies, while others are due to misconceptions and lack of information. These factors give rise to an atmosphere that may hinder development or result in sub-optimal decisions and less favorable circumstances for both individual investors in hydrogen production facilities and society as a whole. A structured decision-aiding process that would help facilitate the objective consideration of all factors and interests of all involved parties may substantially assist the transition to a national hydrogen energy system in the US.

While the opportunity to choose from a variety of resources to generate hydrogen is appealing, it also presents a challenge, especially when many players are involved in the decision-making process. The research presented in this paper involved the development of a multiple criteria decision-making (MCDM) model aimed at assisting with complex decisions that need to be made by divergent decision makers.

The involvement of many disparate stakeholders in a decision-making process creates conditions under which optimum decisions may not be made unless some convergence of opinion is achieved. With hydrogen production decisions, the situation is especially complex due to the novelty of the technology, uncertainties involved and behavioral changes required. Fortunately, some success has been demonstrated in bringing together dissimilar stakeholders on hydrogen-related issues. For example, a study by the Milken Institute (Clark and Yago, 2005) brought together individuals from very diverse sectors, such as policy makers, financial professionals and non-profit organizations, with the objective of resolving the issue of hydrogen infrastructure development financing. Even though a wide range of interests were involved, important consensus conclusions were reached.

The paper describes insights gained from the assessment of the model that have important implications for decision problems at any level and scope. The focus of the investigation summarized herein concerned the extent to which the MCDM approach can facilitate convergence of divergent viewpoints. The following sections summarize extant literature on the nature of opinion convergence, describe the model, summarize the major aspects of the research and describe the results obtained.

2. Convergence of decision maker values

Due to the diversity of interests involved in selecting a preferred alternative from a large set of hydrogen production options, such decisions encounter a wide set of competing concerns and priorities in the face of the differing advantages, disadvantages, and impacts of the various alternatives. Such divergent interests may be based on factors such as local or regional pollution concerns, business goals, legislative restrictions, financial interests, environmental concerns, locational effects, availability of resources, and public relations considerations.

The attempt to facilitate the convergence of diverse values and interests of decision makers was based on the idea of *consensus building*. According to Saint and Lawson (1994), the development of consensus is based on "creating unity while valuing diversity." Moscovici and Doise (1994) point out that the extreme views of individuals tend to move towards a common denominator, converging towards compromise, when they are acquainted with each other's judgments and the underlying reasons. When each individual considers other's perspectives, all factors pertinent to the decision problem are considered, creating a common sense of understanding and a sharing of responsibility for the decision made (Snyder, 2001). Complete agreement should not be expected, as some differences in values are natural. However, the process of discussing relevant factors and reflecting on each other's values and perspectives allows for the discovery of the real lines of reasoning, the gaining of confidence in each other and the avoidance of misunderstandings and subjective judgments (Moscovici and Doise, 1994). Individuals who go through the process of discussing viewpoints recognize the importance of making use of differing views in inspiring more creative and detailed solutions, taking into consideration factors that previously were overlooked or otherwise not taken into account (Snyder, 2001). A fair platform is created by explanations provided about the judgments of others, and the respect for and consideration of these explanations, thereby reaching more effective, creative and just decisions (Avery et al., 1981).

3. Model description

The research summarized herein (development of a multiple criteria decision-aiding model for the selection among hydrogen production alternatives) consisted of two main phases: (1) model design and development, and (2) model application, assessment and testing. The first phase aimed at developing an objectives hierarchy that would be a collective representation of decision maker views on the important criteria to be considered when selecting among hydrogen production alternatives. The second phase included group clarification of evaluation criteria extracted from the objectives hierarchy and elicitation of importance weights for the criteria.

At the outset of the research, the first phase of model design (involving the development of an objectives hierarchy) was considered to be an essential step in providing a framework for the decision model as a whole and to provide input for the next phase. The second phase of model application and assessment was viewed as the core phase for evaluating the ability of the decision-aiding model to facilitate convergence in decision maker thinking. However, contrary to the original expectations, the principal driver of convergence occurred in the first phase of objectives hierarchy development, while some additional, but not as substantial, convergence occurred in the second phase. It is the first phase—including the process, results, and insights gained from that phase—that is the focus of this paper.

The research reported herein developed a MCDM model to assist with selection among different hydrogen production alternatives in order to pursue the following objectives:

- determination of the potential of the MCDM model to promote convergence of divergent viewpoints;
- determination of the extent to which selection among alternatives is robust with respect to conflicting interests;
- assessment of the functionality of the model with regard to aiding complex decision processes.

The design and development of the decision-aiding model (Phase 1) consisted of the following steps:

1. identification of decision makers,
2. identification of the method to obtain knowledge,
3. development of an objectives hierarchy,
4. selection of criteria.

In developing the MCDM model, the initial task involved identifying a group of decision makers that represented a wide range of interests. Twelve individuals agreed to participate in the research, including at least one from each of the following sectors:

- hydrogen production companies,
- government,
- state energy offices,
- automobile companies,
- oil and gas companies,
- utilities,
- environmental non-profit organizations,
- national laboratories,
- infrastructure developers,
- renewable energy financing companies.

The Delphi method (Delbecq et al. 1986) was used to obtain the information discussed below from these decision makers. Application of the Delphi technique was carried out in three phases. The first phase involved development of an objectives hierarchy for hydrogen production alternatives, the second phase involved clarification of criteria definitions, and the third phase involved the elicitation of importance weights for the evaluation criteria derived in the first phase. Under the Delphi method, respondents interact with each other to share their judgments in an anonymous format without a requirement to be in the same location. An initial survey is sent to the group of decision makers requesting their judgments. The information obtained is then organized (statistically if needed, depending on the data) and re-distributed to the decision makers in an anonymous format. The respondents are once again invited to provide their judgments, with the opportunity to consider the new information and possibly revise their previous judgments. This process continues for additional rounds until a pre-determined stopping rule is triggered.

4. Development of an objectives hierarchy and selection of criteria

4.1. Structure

Many conflicting objectives typically are involved in real-world, complex decision processes. Commonly, optimal conditions for all objectives cannot be achieved simultaneously. An improvement achieved in one objective normally will result in less favorable performance on other objectives. Therefore, a compromise needs to be reached. MCDM models are designed to assist decision making in the face of such conflicting and non-commensurable objectives. According to Keeney and Raiffa (1976), a decision problem is composed of a goal, objectives, and attributes. A goal indicates something to be achieved. Objectives indicate the direction one needs to go for improvement. The extent to which the objectives are met is measured using attributes. In approaching a decision problem from a MCDM perspective, the issue is initially represented by a hierarchical structure called the objectives hierarchy, which is based on a main goal that is disaggregated into objectives and sub-objectives to accomplish that goal, and finally into attributes to measure the achievement of the objectives (Malczewski, 1999). The objectives and attributes can be thought of together as criteria. Once the objectives hierarchy is built, the decision makers need to establish importance weights for each of these criteria, in order to represent their value judgments. The MCDM model takes into account these importance weights, along with the performance of the alternatives considered on each of the criteria, to generate a preference order among alternatives. Therefore, a MCDM model essentially acts as a tool to enable decisions by ranking the alternatives by their levels of desirability, considering all relevant factors and decision maker judgments.

4.2. Interaction with decision makers

In a complex decision problem such as selecting from among a set of hydrogen production alternatives, the process of creating an objectives hierarchy is essential. In the instant research, an illustrative objectives hierarchy (consisting of economic and environmental criteria) was presented to the decision makers to initiate the process (see Fig. 1). The decision makers were asked to review this hierarchy and, as a representative of their sector, convey their judgments regarding objectives, sub-objectives and criteria they believed to be important.

Feedback from the initial interactions with the decision makers indicated that most of them suggested major

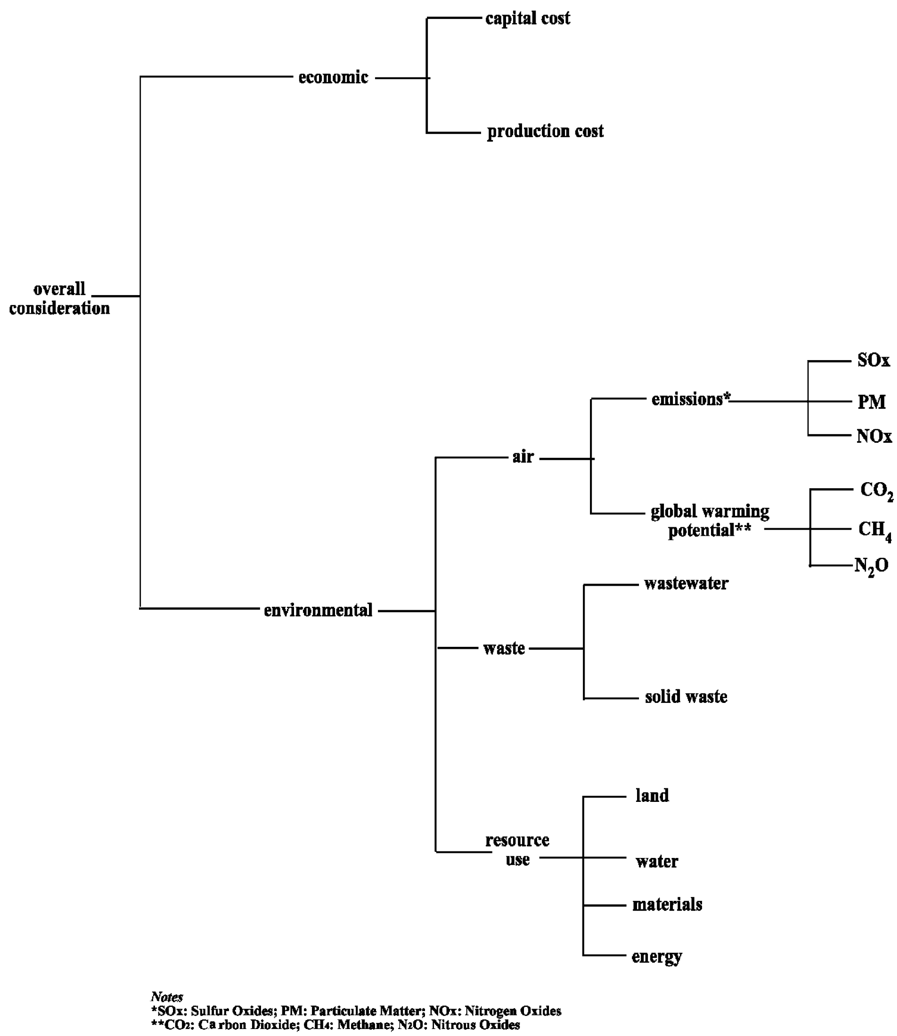

Fig. 1. Illustrative objectives hierarchy.

changes and all suggested at least some changes. The resulting hierarchy contained sub-objectives and criteria that went far beyond the scope provided in the illustrative objectives hierarchy, demonstrating that even an initial attempt at assessing key criteria can prove to be beneficial in terms of producing a comprehensive objectives set. While the initial feedback provided by the decision makers were not necessarily in an objectives hierarchy format (most responses were provided in the form of lists or narrative feedback), the concept of developing a hierarchical structure (of objectives) became more apparent in the latter stages of development.

Feedback received from the respondents was organized to include all comments while eliminating redundancy. Revised hierarchies were fed back to the decision makers, along with their original responses, in an iterative fashion until all respondents indicated satisfaction with the form and content of the hierarchy. In that process, the decision makers were invited to add, delete, change parts of, or categorize the criteria differently, reflecting changes in their judgments. Three rounds of interaction were required to achieve consensus.

4.3. Criteria selection

The objectives hierarchy resulting from this process is displayed in Fig. 2. A principal characteristic of objectives hierarchies is that they branch with increasing specificity from top to bottom. This characteristic is illustrated by the fact that the lowest level (fifth level) contains the greatest detail. The level selected for use as evaluation criteria in a decision-aiding model needs to be sufficiently detailed for quantification and measurement, but not so detailed that it inhibits analysis by drowning decision makers in a plethora of information, distracting them from the main purpose of the process. The process of shaping the hierarchy into an operable form is an important aspect of developing a multi-criteria decision-aiding model, where an appropriate balance between being too general and too detailed needs to be struck. Therefore, some of the detailed criteria of the fifth level of the hierarchy shown in Fig. 2 were eliminated and categorized in a different way, so as to have more defining criteria in the fourth level, inclusive of the details that were removed.

The final objectives hierarchy created through this organization process is shown in Fig. 3. The hierarchy consists of four levels, starting with the main goal of providing societal welfare at the top (first) level. To reach this main goal, the four main objectives are to minimize *environmental impacts*, minimize *economic impacts*, maximize *energy security*, and minimize *social impacts*. The objective of minimizing environmental impacts is envisioned to be reached by minimizing *local/regional air impacts*, *global warming/global climate change*, *water impacts*, and *solid wastes*. Minimizing economic impacts is accomplished by minimizing *costs*, while maximizing

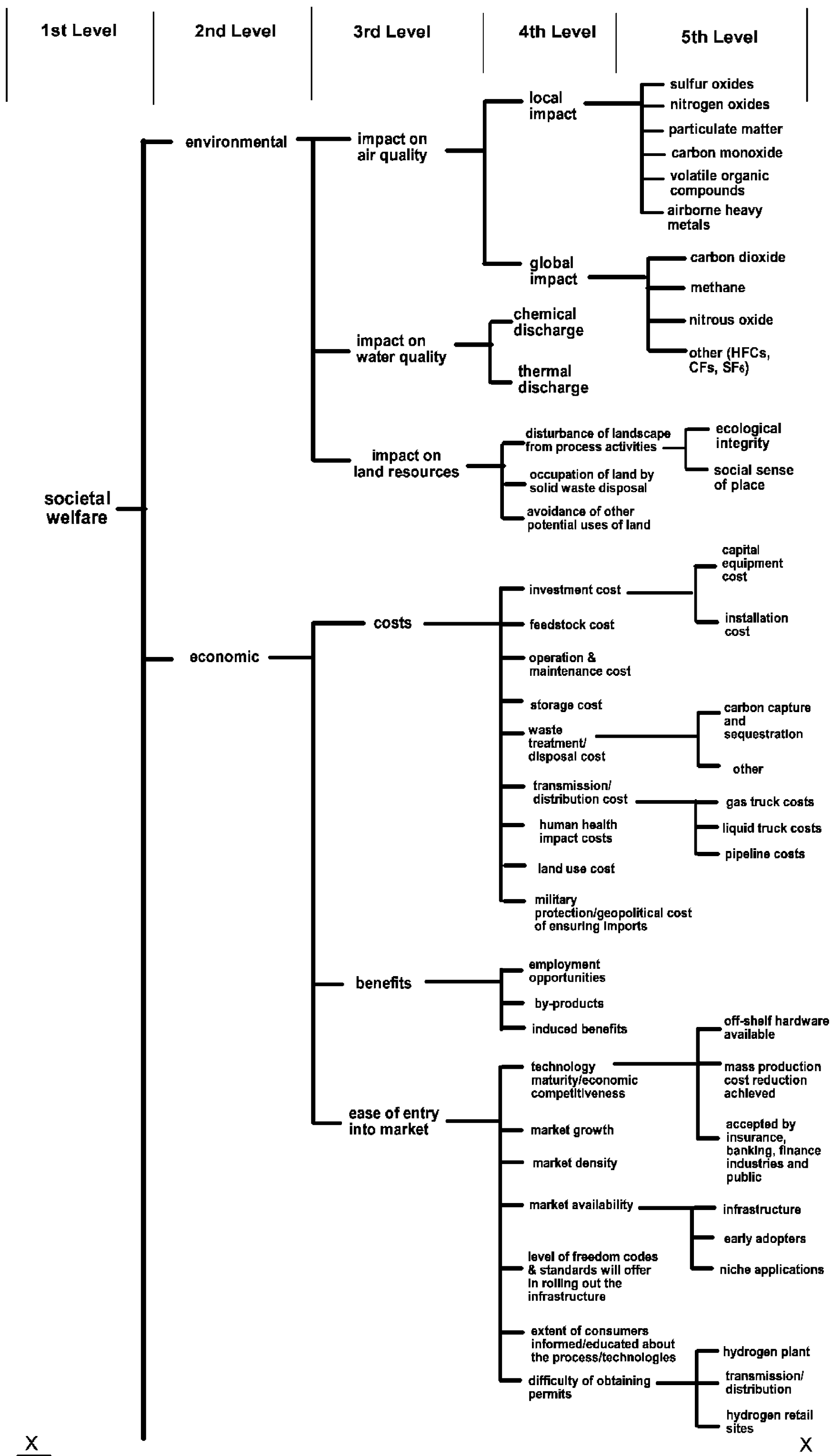

Fig. 2. Objectives hierarchy following three rounds of interactions with decision makers.

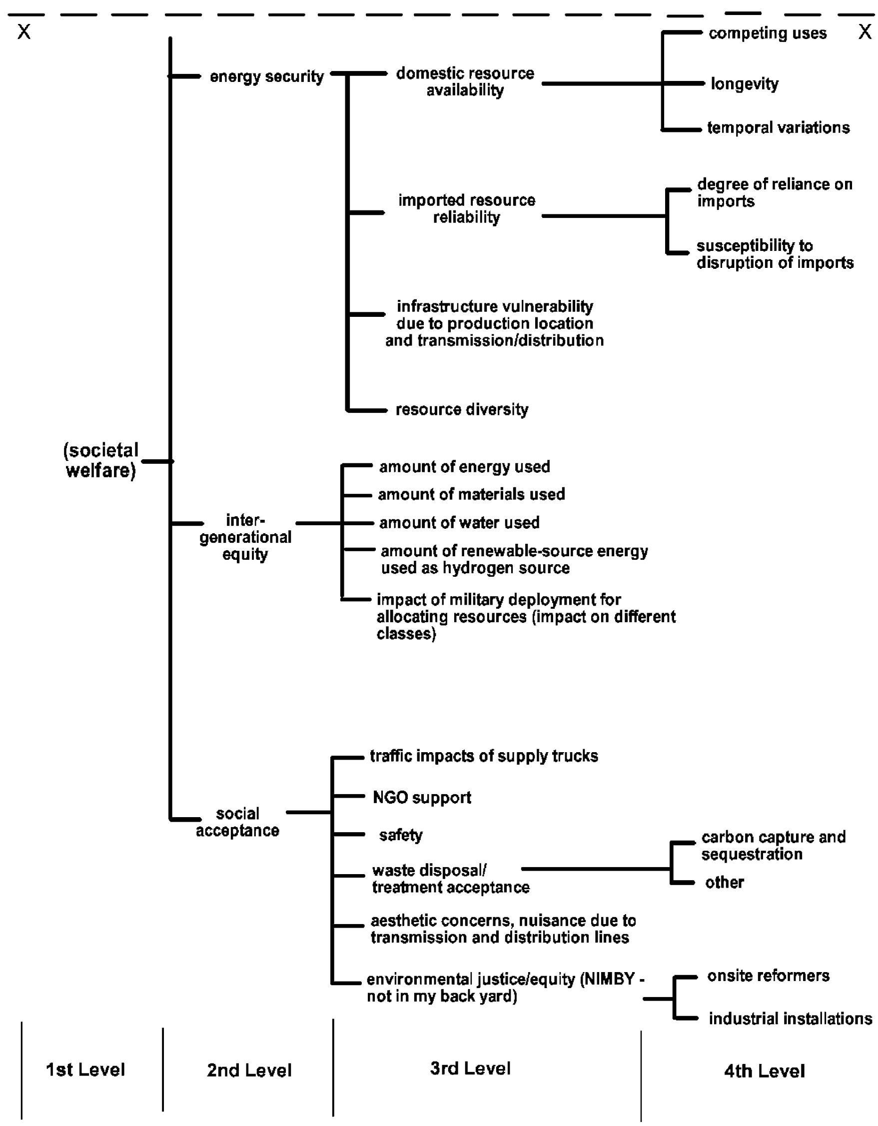

Fig. 2. (*Continued*)

beneficial by-products, *job creation*, and *entry into market*. The objective of maximizing energy security is reached by maximizing *availability* but minimizing *vulnerability*. The social impacts are minimized by minimizing *resource use*, while maximizing *safety*, *environmental justice*, and *inter-generational equity*. Some of the objectives in the third level are broken down further in the fourth level, and the achievements of these sub-objectives are displayed in Table 1. The criteria in the final objectives hierarchy are defined in Appendix A, arranged according to their respective levels in the hierarchy.

5. Results

In the initial stages of the three rounds of interaction with the decision makers to create an objectives hierarchy, the suggestions received spanned a wide array of relatively detailed considerations. As the process continued, decision maker understanding of the process improved considerably and constructive suggestions for the removal, addition or categorization of criteria were obtained. Perhaps one of the most important results of the exercise was the emergence of criteria from some respondents that had been overlooked by others. The "piggyback" effect of respondents tiering off objectives suggested by others was an important phenomenon that not only led to an improved objectives hierarchy, but also was determined in subsequent phases of the research project to be the most powerful driver of decision maker opinion convergence among the three drivers tested in the research (objectives hierarchy development, definitional clarifications among decision makers, and interactive specification of criteria weights). The structured method of reasoning and interaction among decision makers facilitated by the Delphi process resulted in the creation of a level of understanding and appreciation of criteria that initially were perceived by some respondents as insignificant. This was illustrated at one point in the process by a decision maker who pointed out that his initial

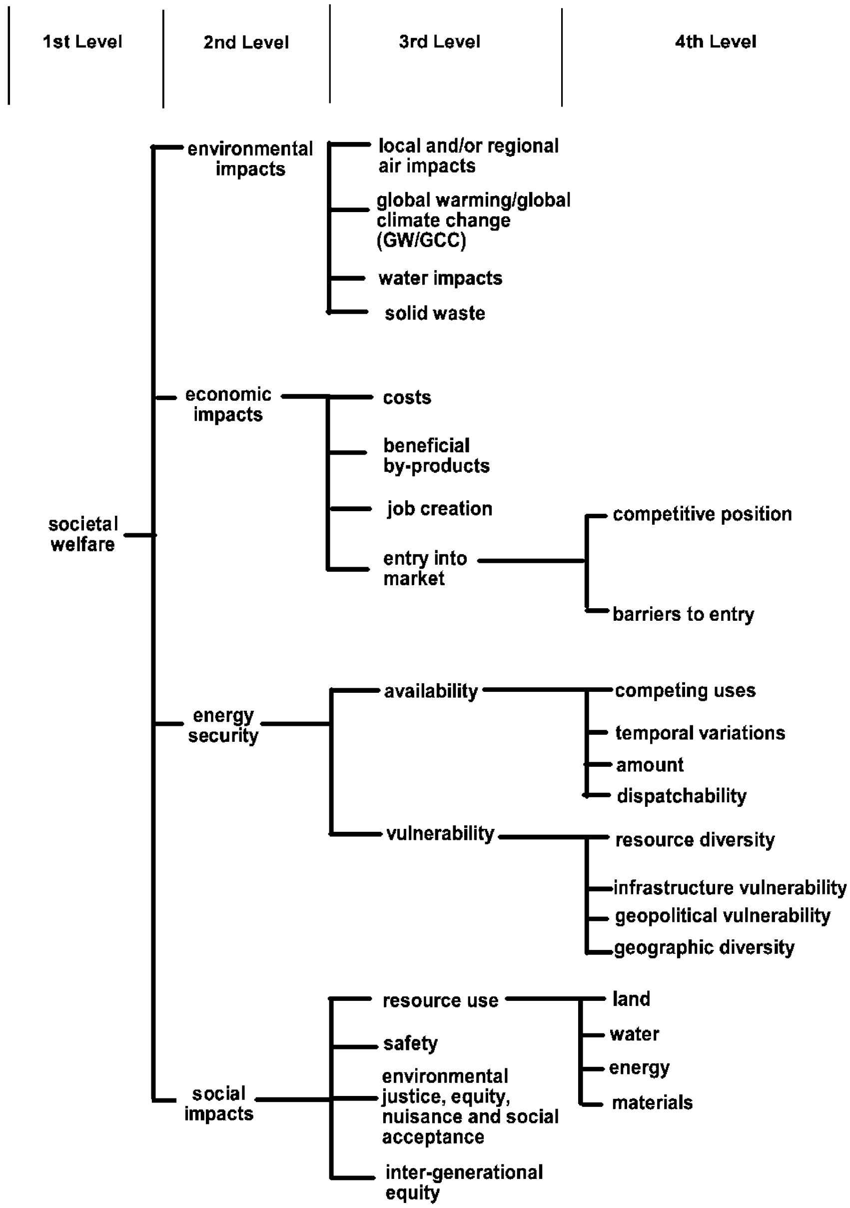

Fig. 3. Final objectives hierarchy.

perspective that cost-related factors were overwhelmingly important in hydrogen production decisions was changed into a wider perspective and better appreciation of other criteria that should be considered.

During the investigation of decision maker opinion convergence described herein, it was observed that the individuals were able to better express their opinions by shaping their responses to inquiries related to hydrogen production alternatives within the structure of a *hierarchy of objectives*. Such structures facilitate enhanced communications among stakeholders, enabling both similarities and differences in judgment to be displayed more clearly than in unstructured environments.

This observation has significant implications for hydrogen production decisions and policies at all levels. Whether a locality needs to decide on the best way to utilize its resources for hydrogen production, or a nation needs to develop a comprehensive hydrogen plan for a sustainable energy future, unstructured discussions (where decision makers miss opportunities to move toward consensus, or where they miss important criteria) may be turned into productive dialogues. Through the approach described herein, similarities in judgment may be found and differences in judgment better appreciated by others through enhanced understandings of alternative views.

While the limitations of this paper preclude discussion of the two subsequent phases of research (definitional clarifications and specification of weights) that were undertaken, it is instructive to also summarize the results of that work. While, as mentioned above, the objectives development

Table 1
Achievement of sub-objectives in the fourth level of the objectives hierarchy

Sub-objective	Maximization	Minimization
Competitive position	√	
Barriers to entry		√
Competing uses		√
Temporal variations		√
Amount	√	
Dispatchability	√	
Resource diversity	√	
Infrastructure vulnerability		√
Geopolitical vulnerability		√
Geographic diversity	√	
Land		√
Water		√
Energy		√
Materials		√

process described in this paper unexpectedly provided the greatest degree of convergence, the subsequent phases of investigation yielded further convergence due to the following four processes:

- achievement of common criteria definitions,
- enhanced understanding of the views of other respondents,
- comprehension of underlying reasons behind respondent judgments,
- consideration of the distribution of group weights (means and other measures of central tendency).

In conclusion, the research described above further underscores the value of consensus building processes and methods in making decisions relevant to hydrogen production alternatives. A MCDM process was used to investigate possibilities of opinion convergence in the context of various hydrogen production options. While the principal focus of this investigation was on examining the consensus building process and the capability of the MCDM-based approach in facilitating opinion convergence (rather than the actual application of the model for selection among hydrogen production options), the investigation was undertaken in the context of a hydrogen production problem and the results were found to be well suited to helping facilitate hydrogen production decisions involving widely divergent stakeholders.

Appendix A. Criteria definitions

A.1. 1st level of the objectives hierarchy

Societal welfare: The general well being of the society, as defined by impacts on the environment, on the economy, and on the society, as well as considerations of energy security.

A.2. 2nd level of the objectives hierarchy

Environmental impacts: Negative impacts of hydrogen production and related process[1] activities on air quality and water quality; exacerbation of GW/GCC; production of solid wastes requiring disposal/treatment.

Economic impacts: Impacts on the overall economy of the nation, defined by negative impacts of costs of the process; positive impacts created by beneficial by-products and job creation; conditions of entry of the technology into the market.

Energy security: Security of the resource utilized to produce the hydrogen, which depends on the availability (for use) of that resource and its vulnerability (due to factors that affect its susceptibility to disruption).

Social impacts: Impacts that encompass a range of issues such as use of resources, safety, equity, nuisance, etc., which affect people and their community.

A.3. 3rd level of the objectives hierarchy

Local and/or regional air impacts: Local and/or regional negative impacts to air quality caused by emission of air pollutants (such as NO_x, SO_x, PM, CO, VOC and airborne heavy metals) during the process.

Global warming/global climate change: Emission of CO_2 or CO_2-equivalent emission of other greenhouse gases during the process that leads to GW/GCC.

Water impacts: Emission of chemical or thermal water pollutants during the process, which have negative impacts to water quality.

Solid waste: Creation of solid wastes during the process that would need to be disposed of in a landfill or treated otherwise.

Costs: Total cost of the hydrogen production technology and related process components. Includes investment, O&M, storage, delivery, feedstock and waste disposal/treatment costs.

Beneficial by-products: By-products created as a result of the process, such as heat or oxygen. These by-products are beneficial in the sense that they add value and reduce cost by creating an opportunity to be used in other processes (e.g. by-product oxygen from electrolysis being used by nearby biomass gasification plants).

Job creation: The potential of a hydrogen production technology and related process activities to create new job opportunities, thereby benefiting the overall economy.

Entry into market: Indicates the ease of entry into and acceptance by the market of the hydrogen production technology and related process components, as determined by the technology's competitive position and barriers it faces.

Availability: The availability of a resource for use in hydrogen production, as defined by how much is available,

[1]The term "process" used in the definitions refers to hydrogen production and all related steps (e.g. storage, delivery, etc.).

when and where it is available and if there are any competing uses for the resource (limiting its availability).

Vulnerability: Factors that affect how vulnerable the resources being considered for use in hydrogen production are to disruption, which may be due to items like the nature of the resource, the characteristics of the infrastructure, and geopolitical factors.

Resource use: The amount of resources (land, water, energy, materials) used up for the hydrogen production process activities.

Safety: The extent to which the hydrogen production technology and related process activities/components are safe (e.g. Is there more or less of a risk of accidents, natural or intentional? Do the characteristics of the technology/process pose a threat to people in the vicinity?).

Environmental justice, equity, nuisance and social acceptance: Includes the following issues:

- *Environmental justice:* Process components (e.g. large gasification plants, transmission lines, waste disposal sites) being located in disadvantaged communities, who do not have the power to stop this development.
- *Equity:* Access to affordable energy; group of people affected by the need for military processes for securing resources to be used in hydrogen production.
- *Nuisance/social acceptance:* Dislike, discomfort and/or opposition by the general public to components like waste disposal sites, reformers close to population centers, transmission lines, wind farms, and traffic load caused by hydrogen delivery trucks, etc.

Inter-generational equity: The extent to which sustainable resources are utilized for hydrogen production, so as to meet the needs of the process without negatively impacting the availability of resources for the needs of future generations.

A.4. 4th level of the objectives hierarchy

Competitive position: Indicates the technical maturity and market-readiness of the production technology (e.g. has mass-production cost reduction been achieved, has the technology been developed past the basic research and development stage, etc.?).

Barriers to entry: Indicates the barriers that might make it more difficult for the production technology (and related infrastructure) to enter the market (e.g. the level of freedom codes and standards and required permits may pose; the extent of educated consumers, etc.).

Competing uses: Determines if there are any competing uses for the resource being considered for use in hydrogen production (e.g. renewable resources like wind or solar energy might be more feasible to use for electricity production. Biomass feedstocks may be intended for other agricultural purposes.). These competing uses may reduce the amount of the resource available for hydrogen production.

Temporal variations: Includes the seasonal and/or daily variations in the availability of the resource (e.g. daily/seasonal variations in the amount of wind/sunlight available).

Amount: Indicates the physical amount of useable resource available for hydrogen production (e.g. coal and natural gas reserves, agricultural wastes available).

Dispatchability: Ability to stockpile (and have available when needed) the resource used for hydrogen production.

Resource diversity: The extent to which the production technology is vulnerable due to the resource it uses to produce hydrogen. If a technology can use only one resource (e.g. wind), as opposed to more than one resource (e.g. coal or biomass for gasification), then it would be more susceptible to disruption and non-availability.

Infrastructure vulnerability: Susceptibility to failure in the infrastructure, due to being more interconnected (e.g. more electrolysis units connected to the electric grid).

Geopolitical vulnerability: Susceptibility to disruption due to where the imports (of resources used for hydrogen production) come from and the degree of reliance on these imports.

Geographic diversity: The geographic distribution of the resources being considered for hydrogen production (e.g. are they available throughout the country, or located in one specific region?).

Land: Extent of land taken up by the process components.

Water: Amount of water used in the process activities.

Energy: Extent of energy use by the process activities, as defined by efficiency (i.e. input energy requirements vs. output energy).

Materials: Resources (except the main feedstock) such as fossil fuels, minerals and metals that are used in process activities.

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