LCA Methodology

Life Cycle Assessment of Fuel Cell Vehicles
A Methodology Example of Input Data Treatment for Future Technologies

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Abstract. Life cycle assessment (LCA) will always involve some subjectivity and uncertainty. This reality is especially true when the analysis concerns new technologies. Dealing with uncertainty can generate richer information and minimize some of the result mismatches currently encountered in the literature. As a way of analyzing future fuel cell vehicles and their potential new fuels, the Fuel Upstream Energy and Emission Model (FUEEM) developed at the University of California – Davis, pioneered two different ways to incorporate uncertainty into the analysis. First, the model works with probabilistic curves as inputs and with Monte Carlo simulation techniques to propagate the uncertainties. Second, the project involved the interested parties in the entire process, not only in the critical review phase. The objective of this paper is to present, as a case study, the tools and the methodologies developed to acquire most of the knowledge held by interested parties and to deal with their – eventually conflicted – interests. The analysis calculation methodology, the scenarios, and all assumed probabilistic curves were derived from a consensus of an international expert network discussion, using existing data in the literature along with new information collected from companies. The main part of the expert discussion process uses a variant of the Delphi technique, focusing on the group learning process through the information feedback feature. A qualitative analysis indicates that a higher level of credibility and a higher quality of information can be achieved through a more participatory process. The FUEEM method works well within technical information and also in establishing a reasonable set of simple scenarios. However, for a complex combination of scenarios, it will require some improvement. The time spent in the process was the major drawback of the method and some alternatives to share this time cost are suggested.

Keywords: Expert judgment; fuel cell vehicles; fuel cycle analysis; fuel upstream analysis; future technology analysis; interested parties' participation; inventory data treatment; technological forecasting; uncertainty analysis; well to wheels

Introduction

Urban air quality improvement, climate change concerns, and a reluctance to depend on non-renewable sources have been the main motivations for the development of fuel cell technologies and their applications in fuel cells vehicles (FCVs). The rapid development of these new vehicle technologies may also require the establishment of a new fuel infrastructure soon. Hydrogen can be used directly as the fuel cell fuel, as can other alternative fuels, such as methanol, or, alternatively, some special kinds of hydrocarbon fuels can be used as hydrogen carriers. A technology change of this magnitude may require a good understanding of the major risks of environmental impacts in the entire cycle of activities. This understanding can be necessary in order to prevent 'second order' problems and/or to help in the selection of the best social strategy to establish policy, allocate subsidies, and drive R&D programs.

The Life Cycle Assessment (LCA) methodology has the potential to be an important management tool in assisting decision makers to a holistic understanding of the entire system associated with a single product/service to be introduced. However, a common characteristic in this kind of situation is that the 'cleaner technology' always will occur in the future and, therefore, there will always be some subjectivity in the analysis, even in the inventory analysis phase of the LCA method, which is supposed to be very quantitative and objective.

Since 1998 the Fuel Cell Vehicle Modeling Program (FCVMP) at the University of California at Davis (UCD) has been studying and comparing existing 'cradle-to-grave' or 'well-to-wheels' studies related to fuels for transportation and vehicle technologies (Contadini et al. 2000a). In general, these kinds of studies (at UCD and elsewhere) focus on the inventory of air emissions (grams) and energy requirements (Joules or BTUs) over the entire range of fuel upstream activities (life cycle) associated with the vehicle operation (per km or mile). Some of the studies also do an assessment analysis for the climate change affected by the greenhouse gas emissions by using global warming potential factors (GWP). As a general statement, it can be said that the existing studies do not agree in their results and, depending on the case, they disagree to the extent of several orders of magnitude. Three levels of disagreement can be identified:

Geographical differences (US national average, South Coast California Air Basin, Canada, UK, etc.). Geographical differences are related to the initial study objective and, in general, are clearly delineated in the reports. Problems arise only if attempts are made to generalize the result. Such an attempt is very common in conference presentations, study comparisons, and study press releases.

Technology scenario composition (for example, natural gas pipelines propelled by turbines, reciprocating engines or electric motors, pressure of the gas pipe, electricity production mix per region). Within the same area and under the same technology umbrella (for example, natural gas feedstock), the assumptions can be very different and generate different results. The use of a single situation to represent all the feasible and viable technologies possible in the real world is very common. There are few studies that perform sensitivity analysis at this level.

Technology data (efficiencies and emission factors of different equipment). A lack of data for some equipment, as well as the use of deterministic values to represent a complex system (the average of the USA methanol production plant efficiencies, for example), generate part of the disagreement in results. A robust study should be very clear about the technology considered and kind of data used. Several studies do only a kind of bookkeeping process, with generic assumptions about generic technologies and do not go to the level of calculation involving equipment design, level of equipment activity and physical parameters. Even for the studies that do go to this level of detail in calculation a lack of reported information about the details and assumptions used is unfortunately frequent.

To deal with these uncertainties in the fuel cell vehicle life cycle assessment, the project (FCVMP) decided to develop a new model called FUEEM (Fuel Upstream Energy and Emissions Model). The model used two major approaches:

1. For the technology data problems in the inventory, FUEEM works with specified equipment and system design performing a quantitative uncertainty analysis. This approach is suggested in the ISO 14041 (1998). To our knowledge, this project was the first to put it into practice. To use the approach, FUEEM establishes probabilistic curves as inputs and propagates the uncertainties over the calculation by using Latin-Hypercube sampling, Monte Carlo simulation, and rank order correlations. This approach is similar to performing thousands of sensitivity analyses at once, with the advantage of establishing the importance of each scenario (expressed in the occurrence probabilities) at the end. For more details about this approach, results, and specific data, please contact the corresponding author.[1]
2. The other uncertainties are related to subjective and necessary decisions, such as the future technology compositions (scenarios), the modeling approach that affects the results (allocation of co-products credits, for example), the filling process for missing data, etc. All these major decisions were made with the participation of the interested parties.[2] This participation occurred during the entire process and not only in the critical review process. This procedure takes item 7.3.3 of the international standard for Life Cycle Assessment (ISO 14040 1997) a step further and is designed to enhance the credibility of the study results. This step is not a simple one since, in general, what differs among the parties are their different, and in most cases, conflicting interests. The objective of this paper is to present the methodology adopted by FUEEM to take maximum advantage of this participation and to explain the rationale behind the decisions made.

The life cycle assessment (LCA) of future technologies, products, or materials will always, in some sense, face the same subjective problems in the necessary input assumptions. Even for the LCA of existing products/services, where the inventory phase could be a very quantitative measurement process, the assessment phase will require subjective decisions in the valorization of different environmental impacts, such as biodiversity decrease or non-renewable source depletion. In presenting this case study, we hope and expect that future assessments involving interested parties participation will be able to benefit from our experience.

In pointing out some specific areas of this case study, we hope to assist in future comparisons and extrapolations of this method. However, as a study case, there was no attempt to compare different methodologies at this point. Future attempts can be driven by Al-Alawi and Islam's (1996) statement that the best methodology is the one that accomplishes the project needs most effectively without compromising the quality of the project results. The interested parties previously established the quality of the FUEEM results to be a better representation of reality and to have the acceptance of all. Incorporating somehow the uncertainties into the calculation was one way to achieve a better representation of reality because of the common sense statement that "the only thing we know about the future is that it is uncertain".

The specific needs and the resources to achieve them are presented below but, as a general comment, it can be said that the Fuel Cell Vehicle Modeling Program (FCVMP) is a five-year program (1997–2002). This long-term definition gave the FUEEM the opportunity to develop incrementally, using pilot models to establish the 'final' calculation methodology and data treatment. Our search to express real systems evolves from deterministic values, to ranges bounding a most probable case, to probabilistic curves and finally to the dependency among curves. In all this process, three types of general information could be identified:

Future scenarios: Several topics should be evaluated at the same time in order to forecast (for 2010) what may happen

[1] The FUEEM operational unit is kilometer driven and the time frame is 2010, due to the development characteristics of the fuel cell vehicles and fuels development level. The boundaries are from the natural gas extraction to the vehicle operation, since the initial comparison is among three special fuels that use natural gas as feedstock (Hydrogen, Methanol and Fisher-Tropsch Naphtha). The model uses the global warming potential (GWP) to calculate greenhouse gas emissions (CO_2, CH_4 and N_2O) in terms of CO_2-equivalent and it also calculates the total energy required disaggregated in terms of petroleum and fossil fuel use. For five of the criteria pollutants (NO_x, CO, NMOG, PM_{10} and $PM_{2.5}$), which are considered in the study, the effort is to quantify how much is released in urban areas (Contadini 2000).

[2] The interested parties definition according to the ISO 14.040 (1997) is an 'individual or group concerned with or affected by the environmental performance of a product system, or by the results of the life cycle assessment'.

at different production sites and in the commercial activities that compose a life cycle study. Possible variations of the current trends, public concerns, environmental laws, fuel and vehicle cost and market competition, new technologies, safety, and public perceptions are only a few examples of the complexity that the study faced.

Technical background: Air emission calculations deal, in general, with equipment emission factors associated with the activity level or equipment load. The equipment activities (work generated, fuel produced, energy consumed, etc.) constitute important information and the 'design' or interaction and balance among all the pieces of equipment in an industrial/commercial process is fundamental.

Literature adaptation: Almost all the data, such as emission factors and plant efficiencies, that are currently available in the literature, are presented as deterministic values. The exception is Harrison et al. (1997), who present the values together with their associated errors. Since the FUEEM input data are probabilistic curves, an 'adaptation' process was necessary.

Other important situations were the participation of some of the major fuel companies (FCVMP sponsor donors), the involvement of some government agencies, and the UCDavis tradition in fuel analysis (Sperling 1988, Sperling and DeLucchi 1989, DeLucchi 1991 1993 and 1997, and others). These factors were fundamental in initiating and working with the concept of the expert network that became a very important part of the developed methodology. Other existing resources previously established in the FCVMP are the annual conferences and workshops. Both were incorporated into the FUEEM's assumption determination process.

2 The General Process

It was clear from the beginning that the best way to generate the input assumptions for the future was to split the task into two major problems:

1. To identify and understand the process values and their uncertainties in the present, and, based on that,
2. To estimate the values and their uncertainties for the future (year 2010).

A broad and comprehensive literature survey was identified as fundamental to analyzing the characteristics of the processes in the present. Eventually, complementing the data available in the published literature with industry surveys was expected to be plausible, depending upon the necessity, resources, and willingness of the companies to disclose their data. With the implementation of the methodology and the analysis of the existing data, the surveys became very important. The expert analysis was expected to complement these two data sources, since there is a lack of knowledge of data uncertainties in the current literature according to an EPA study of uncertainties in air emissions estimates (EIIP 1996). This EPA report recommended using expert judgment as the preferred method to quantify the uncertainties of the existing data.

On the other hand, to extrapolate existing knowledge to the future, the technology forecast literature employs several techniques and they are classified in different ways (Sullivan and Claycombe 1977, Armstrong 1985, Porter and Rossini 1987, Porter et al. 1991 and Al-Alawi and Islam 1996). Porter and Rossini (1987) present an interesting summary of five major techniques for forecasting:

A. **Monitoring:** To gather and organize information for use in forecasting (not a true forecast process but a support technique).
B. **Expert opinion:** To use when data are lacking and when modeling the situation is difficult or impossible. It is based on the idea that some individuals know more about a topic than others.
C. **Trend analysis:** To apply statistical techniques when there is a significant amount of good data over a time period. It assumes that the past trend will be repeated in the future.
D. **Judgment-based models:** To reduce a complex system to a manageable representation when an acceptable theoretical framework is available.
E. **Scenario construction:** To integrate forecasts from various sources and techniques into a coherent picture, may encompass a plausible range of possibilities for some aspect of the future; can be a fantasy if a firm basis in reality is not maintained.

Porter et al. (1991) comment that these approaches should be neither exclusive nor exhaustive in a real inquiry. According to them, better inquiries result from using a combination of these techniques and the FUEEM inquiry and forecast tried to follow that advice. However, the reality is that the data are limited for a trend analysis, and disqualifies any possible theoretical framework (assuming one were available) to build a judgment-based model, since fuel cell vehicle development requires new conceptions of fuel. Porter et al. (1991) also describe different techniques to collect expert opinions, such as individual input; committees, seminars and conferences; the nominal group process; surveys; and the Delphi process. As explained below, all these techniques are used in some way in FUEEM.

2.1 The expert network

The FUEEM general process has a major component involving activities done by an expert network, and also contains activities done within the project only (but with a strong relation to the previous component). The expert network is an agreement among a panel of international experts to cooperate continuously with the project effort, based on their interest in the quality of the generated results. The expert network concept was introduced in the FCVMP agreements from the beginning of the program in the summer of 1997. **Fig. 1** shows a graphic representation of the adopted FUEEM participatory process.

The first step was to transform the early expert network idea, initially composed only of the project sponsor do-

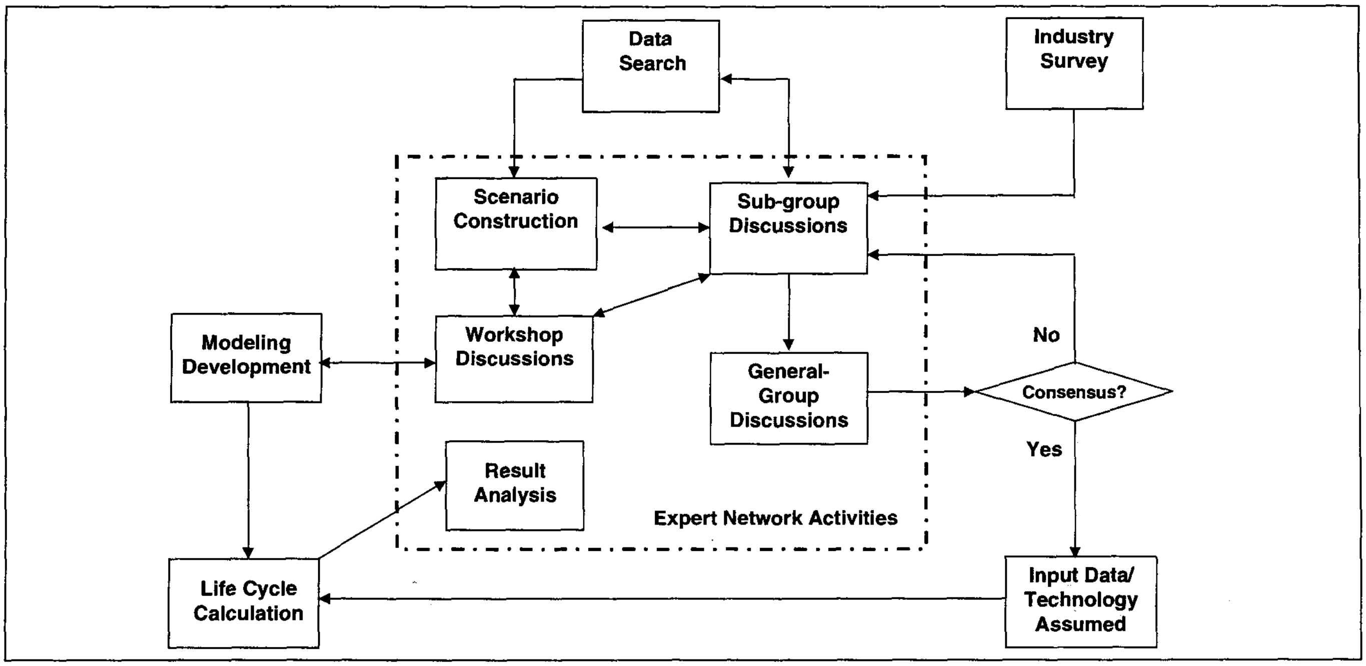

Fig. 1: FUEEM participatory scheme for future technology assessment

nor experts, into the concept of interested parties' participation. Experts from several other organizations were invited to participate. Around 25 to 30 experts have been involved in the process over the first two years. Organizations were invited to participate based on their industry membership (hydrogen, methanol, hydrocarbon fuels and equipment), involvement in previous modeling/analysis efforts and/or involvement in previous data generation, analysis of results or review process (universities, government agencies, national laboratories, NGOs and some private organizations). Two organizations required confidentiality and therefore are not listed among the participants presented here:

- Organizations participating full time since the beginning: Air Products, Methanex, Chevron, Exxon/Mobil, BP/Amoco, Acurex/ADLittle, California Air Resources Board, South Coast Air Quality Management District, Union of Concerned Scientists, Imperial College of London, Institute of Transportation Studies and University of California at Davis.
- Organizations participating part time (due to late entrance, specific interest or attrition): Aramco, Praxair, Hydrogen Burner Technology, Syntroleum, Directed Technologies Inc., National Renewable Energy Laboratory, Argonne National Laboratory, Environmental Protection Agency, Department of Energy and Princeton University.

The expert network activity details are discussed under Topic 3. Two other activities in the general process that are not conducted by the expert network are discussed next.

2.2 Data search

The objective of this activity is to gather and organize the existing published data about the performance of current processes alongwith any published forecast of future performance. In general, the existing data for fuel upstream activities and emissions are a collection of single numbers from different studies that hardly represent a unique technology or time series data for an eventual trend analysis. A discussion of the data characteristics necessary for trend analysis can be found in Welch et al. (1998), Armstrong and Collopy (1993), and Armstrong (1985).

The existing fuel life cycle models and studies (Acurex 1996, Wang 2000, DeLucchi 1997, ETSU 1998, Spath and Mann 2000, etc.) apparently established their input parameters based only on a literature review. It is very common for one single source to be the basis for all input parameters on a given topic within a study. On the other hand, in the FUEEM process, the result of the data search is very important but does not feed the model directly. Instead, it is used to feed an important discussion/consensus process that will generate the input assumptions to be used within the model.

In general, the results of this data search are presented to the expert network in table format. **Table 1** is an example of this output format used for a specific methanol (MeOH) plant analysis.

Other important sources of information are the progress in Research & Development technology, the evolution of standards laws, evolution of policies and environmental public concerns. However, these sources of information are not considered here as part of the data search. They are mainly input into the discussions by each individual expert and become part of the scenario construction. According to the majority of the experts, their technical information is updated by news networks and conference participation. The FCVMP organizes an annual conference with this objective, where fuels and emission topics are always part of the agenda. Also, the project circulates some related fuel cell news for interested experts. For more information consult http://fcv.ucdavis.edu/.

Table 1: Example of the data search output format (Methanol 'MeOH' plant)

Typical Size: 2,500 metric tons of MeOH per day – Steam reformation syngas [a]						
Study /	**Efficiency (%)**		**Electricity used (%)**		**NG used as fuel (%)**	
Steam exportation	**Without**	**With**	**Without**	**With**	**Without**	**With**
Wang (2000)	69.6	71.6	0.2	<3.33>	17	24
Acurex (1996)	–	68.3	–	<0.02>	24.1	–
DeLucchi (1997, 1993)	65	–	0.2	–	–	–
Wang (1998)	65.6	–	0.2	–	(100)	–
Darrow/GRI (1994)	–	66.1	–	<0.007>	–	22.6
Ogden et al. (1994, 1998)	67.4	–	1.8	–	–	–
DTI (1998)	64	–	–	–	–	–
Chem. Ecn. HB (1996)	–	71.3	–	–	–	–
Dybkar (in Wang, 2000)	66	71.6	–	–	–	–
Islan (in Wang, 2000)	62–64	–	–	–	–	–
Borroni-Bird (1996)	59	70	–	–	–	–
DOE (1989)	61.1	70.4				
Sweeney (1998)	65	–	–	–	–	–
AMI (1998)	–	70				

[a] This table is presented only as an example here. Several parallel calculations and unit transformations were necessary to put these values together. The comments about them are included in the footnote of the original table. If you are interested in any specific data, please contact the correspondent author.

2.3 Industry survey

During the project development, some discussions led to a sense that there was a lack of knowledge or a strong subjectivity in the analysis. It was more intense in the detailed technical issues and on the questions with little or no data availability in the literature, such as the correlation among some variables, and the emission factors for some processes. To minimize these problems, some companies agreed to open their operational data in such a way that probabilistic curves have been generated and correlation studies have been performed. A drawback to this technique is that using the data of a single plant or process to generalize the results is far from being an ideal situation. However, it is the first step for the consolidation of the methodology adopted by the project and a tutorial basis for future studies. The generalization process occured at the expert group discussion level and at least the industry data analysis has been addressing new questions and bringing new expert information to the pool of knowledge. One example of the industry survey results can be found in Contadini et al. (2000b). The ideal situation may occur when organizations such as EPA or CARB that have access to considerable data, start to publish more detailed information, such as the standard deviations or the probabilistic curves, details of the technologies aggregated into the same cluster, details about the equipment activities considered (efficiency, production, etc.) and eventual correlations with other parameters. The current qualitative level of information about the uncertainties in the data is very poor.

To obiviate the necessity of obtaining detailed technical information, the companies have also been identifying specific operational experts and allowing them to interact with the project on a one-to-one basis. The first step is to establish the doubts, the questions, and the network-expert initial solution tendencies. Based on this information, a semi-structured interview is conducted and the results, in terms of new questions, technical examples, data and/or statements, become input into the expert group discussion. A follow-up phase is performed with the technical expert originally interviewed, until the group reaches consensus on that issue. The follow-up was done, in general, over the phone or through e-mail but a second interview could occur if enough questions were still in place.

According to the classification of Porter et al. (1991), in general, the one-to-one process starts with a focused interview. The idea is to obtain subjective information about the study topic. A typical example of questions of this phase could be 'What advances do you see in the development of H_2-SMR (Hydrogen Steam Methane Reforming) plants in the next ten-year period?' In the second phase of the process, structured questions are asked regarding project necessities, such as 'What is the typical operational hydrogen outlet pressure from the PSA (Pressure Swing Adsorption) installed in a H_2- SMR plant?' Finally, the final phase is a nonstructured interview where, based on the previous answers the expert is encouraged to express an opinion about some open issue in the expert network discussion. For example, the expert may be asked, 'Do you think it is possible for a H2-SMR plant to release the hydrogen at 31 bars? And what whould be the benefits and drawbacks of doing that?' A summary of the interview is discussed with the expert before submission to the expert network. The expert is also invited to participate in the network for the discussion of the topic correlated with the interview, creating a dynamic feedback most of the time.

This one-to-one method proved to be very efficient in solving some important technical questions that occurred in the discussion without solution. In the example above, the outlet pressure of the H_2-SMR dictates the compression requirement downstream. Some drawbacks here are the efforts and resources involved. It is necessary to interview at least two experts with different experiences (for example, operating/designing H_2-plants with pressures around 20 bars and 30 bars) and the method requires the physical presence of the interviewer. The success of the method is also dependent on the skill of the interviewer.

3 Expert network activity details

One idea of the expert network is to generate inputs for the model on which all interested parties can agree and to have them somehow help to build the inputs so that greater confidence in the final results can be justified. This decision was based upon the discussion of three alternatives:

1. A single modeler or single organization could decide on the inputs/methods of the analysis. Later on the interested parties could review it critically, as suggested by the ISO 14.040 (1997). The belief was that several details and pieces of information might be missed and that, in general, this approach would increase the risk that large modifications could be required at the end.
2. The interested parties participate in the entire process and the final decision could be based on a majority vote. In this case, however, a better representation of one industry sector over another in the expert network formation could bias the final result. This procedure could also block some information sharing.
3. The interested parties participate in the entire process and the final decision could be based on a consensus established with technical discussion and complementary information. This was the selected approach.

A second idea of the expert network is based on the hypothesis that some individuals know more about a topic than others. For the same reason, according to Porter and Rossini (1987), forecasts made by a group of experts are safer than those produced by a single expert. The hypothesis for the statement is that a group engaged in a fruitful learning process can elicit the best idea from the most knowledgeable expert and even improve upon it. **Fig. 2** shows a graphical representation of this idea. However, it is not clear that researchers have produced enough evidence that group opinion is always superior to individual opinion. According to Rowe and Wright (1999), this idea has been accepted as common sense. The authors also suggest that some studies have concentrated on the comparison among group opinion techniques and criticize them, based on their failure to use a specific technique. Future studies are still necessary to prove this 'many heads are better than one' hypothesis.

3.1 Scenario construction

Since the scenario construction within the expert network discussion has its own specificities, it is considered separately here. According to Porter et al. (1991) a scenario is a "descriptive sketch intended to produce a more or less holistic view of a future social state." Jones and Twiss (1978) contend that a comprehensive technology forecast must contain four elements:

A. Qualitative descriptions or scenarios,
B. Time,
C. Quantitative performance level and
D. Probability assessment.

Items (C) and (D) are the ultimate outcomes of the FUEEM technological forecast and they are discussed below. Time was pre-established early in the process, based on initial scenario discussions about fuel cell vehicle technology and fuel infrastructure. The qualitative description of what the model is considering and why it is considering it is then the major point here.

According to Porter et al. (1991), the innovation process is based on the interrelationships of the technological, economical, political, social and ecological environments. The uncertainties present in each of these issues are extremely high even when only a ten-year horizon is considered. Without a good discussion process, any scenario will be possible but the results will be meaningless. In agreeing with this idea, Sulivan and Claycombe (1977) state that a forecast is useful if it reduces the uncertainty surrounding an event. Based on this concept and because of the limitations of available resources a conservative scenario has been generated in the FUEEM forecast in order to select the 'most feasible' technical options initially for a relatively stable, economic, political, social and ecological environment.

For example, hydrogen can be produced by a variety of processes (steam methane reformation – SMR, partial oxidation, electrolysis of water, gasification, biologically, etc.) and by a variety of feedstocks (natural gas – NG, oil, coal, biomass, electricity, sun, etc.). It is possible that each of these process-feedstock pairs may have some probability of being used by the year 2010, depending on conditions in the analyzed region. However, since most of these probabilities will be very small for the majority of the locations, the modeling prior-

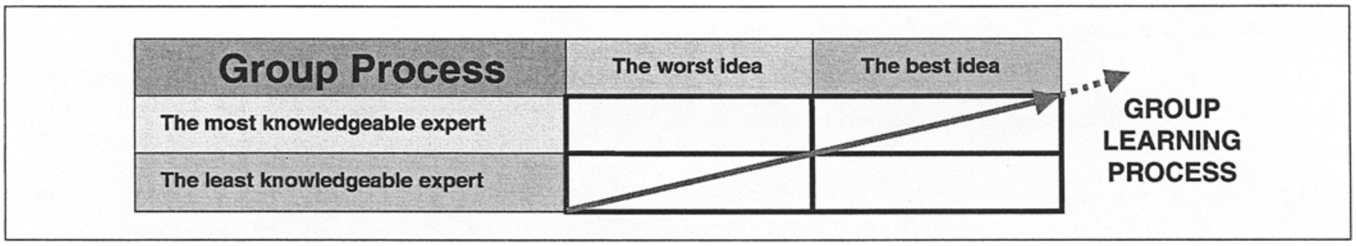

Fig. 2: Graphical representation of the concept that group opinion can produce better information than the individual opinion

ity chosen for FUEEM was the use of NG feedstock with SMR production process. This was considered to be the most likely to be used, based on costs, technology development, and other factors.

The scenario construction has an interactive relationship with the data discussion and model construction parameters. Using the same example above, a consensus was not reached on best plant size for NG/SMR. According to the experts, the most probable case should be the construction of centralized plants to supply the hydrogen. But because the demand for hydrogen is likely to be small in the introductory phase of FCV, a hydrogen pipeline is unlikely to be constructed on a large scale by 2010. It is possible that decentralized small plants, installed in fuel stations before 2010, could produce a considerable amount of hydrogen. Also, the discussions about the efficiency of the centralized plants show that enormous differences exist depending on the size of the plants and their co-production of extra steam. The model has now six options for hydrogen production: two decentralized and four centralized options (two sizes, with and without extra-steam generation). This approach reduces the uncertainty of each event considered, based on the fact that a specific technology can be analyzed more objectively and even be supported by available data. On the other hand, this approach transfers the subjective decision to the next step, where it requires the construction of a scenario establishing the possible distribution of regional hydrogen production across the six modeled options.

This step was called 'scenarios combination' and it generates most of the problems in reaching an agreement. The methanol scenario combination was a good, but most difficult, example. The new methanol plant designs are much more efficient than even the best existing ones but, on the other hand, there is now much more capacity for production methanol than there is demand for it in the world. It was barely possible to achieve a majority opinion on how many of the existing (and less efficient) methanol plants could be permanently decommissioned in the next ten years. Based on this decommissioning effort and on the new demand for fuel cell vehicles, a determination of how much of the new plant production could be considered also achieved barely majority opinion. The final solution was to use the majority (and not the consensus) to generate the combined scenario results but it was also necessary to present the results of the extreme cases as the 'bounding scenarios.'

3.2 Workshop discussion

The Fuel Cell Vehicle Modeling Program (FCVMP) conducts one conference and one workshop every year. The conferences are presented during the spring of each year, and are used to exchange information necessary for the scenario construction in FUEEM and to exchange news on R&D related topics. On the other hand, the workshops are organized every fall around the expert network and are used as a complementary part of the forecasting process. Four workshops have been conducted so far; and their main purposes were to discuss details about the methodology and the model effort and to identify options in the early stages of the problem definition for each fuel.

Basically, the techniques adopted in the workshops have been a mix of open discussions and the Nominal Group Process (NGP) developed by Delbecq and Van de Ven (1971). The technique combines a brainstorming process with some elements of the Delphi structure and it is known as the 'estimates-talk-estimates' procedure. The idea is to alternate situations in which the group interacts with situations without interaction. According to Delbecq et al. (1975), when interaction does not occur the participants generate the most creative ideas and when they do interact they perform the best evaluation. For more details about the technique see also Roper (1988).

Martino (1983) defined two important characteristics of a working group. One is that the knowledge of the group is at least equal to that of any one member. The other is that a similar statement can be made for the number of factors considered. So the intent of a work group is to increase the knowledge base for a decision by at least identifying bad decisions. The group also has at least as much incorrect information as any member, so to be effective the group must cancel out misinformation. One drawback of a face-to-face meeting is that influence of power, status, or authority can suppress input, thereby minimizing the benefit of pooling knowledge. The anonymous vote process in the methodology tries to minimize this effect.

According to Porter et al. (1991), NGP is a "good technique for problem definition, to identify options and questions and also to build strong group identity." All of these topics were discussed in the first workshop (September 1998), when the expert team had just agreed to contribute to the fuel life cycle analysis effort and when the building of a new model was considered for the first time. After one year of working together in the expert network, the second workshop (September 1999) was conducted with the consolidation of the methanol and hydrogen fuel scenarios in mind, giving more emphasis to the group interaction and to the evaluation process. The third workshop (September 2000) concentrated on a detailed FUEEM software analysis in order to obtain agreement on the characteristics of the final version of the model. To do that, a more open discussion process was emphasized. A similar procedure was assumed in the last workshop (July 2001), when the final results were discussed.

Since the interested parties participation occurred over the span of the entire project, the final results brought no surprises and the reactions were very positive. This may be a good indication that the FUEEM method is on the right track to bring more confidence to life cycle studies. Similar reactions occurred even with the external public when the first results were published (Contadini et al. 2000b and 2000c).

3.3 Group discussions

The group discussions were the main activity for the expert network, which was divided into sub-groups. Allocation of the experts to sub-groups was conducted according to the expert's preference and his or her area of expertise. Initial discussions start in the sub-groups, and, after some results are reached, the summarized discussions and results are submitted for discussion to the general group. The sub-groups established are hydrogen, methanol, hydrocarbon, natural gas and methodology. Several experts decided to participate in more than one sub-group and they promised to get the opinion of another expert within their organization when the survey topic necessitated an expertise different from their own. When this extra opinion was not obtained, the experts do not send any answers and express their inability to do so.

Several techniques exist to collect opinions from a group of experts. Examples include traditional surveys, the Delphi process, staticized groups, interacting groups, the nominal group technique, dialectic procedure, etc. An extensive literature can be found for each of these techniques and it is not the purpose of this paper to explain them.

Due to the limitation of available time for the project and to the international nature of the FUEEM expert network, all techniques that require the physical presence of the experts were rejected for this phase. The final technique adopted has most of the principles of the Delphi technique. This technique 'is named after the ancient Greek oracle at Delphi, who offered visions of the future to those who sought advice' (Cassino 1984 in Gupta and Clarke 1996). Delphi is a special form of survey, designed to evaluate qualitative scenarios, to generate subjective probabilities, to obtain consensus, and to obtain more information (Sullivan and Claycombe 1977). The Delphi process was developed by the Rand Corporation in connection with several defense-related studies that it made from 1948 to 1963. After Dalkey and Helmer (1963) published the technique it has become a widely used tool for measuring and aiding forecasting and decision-making in a variety of disciplines (Rowe and Wright 1999). Gupta and Clarke (1996) conducted a comprehensive bibliographic survey of the Delphi Technique as it was used between 1975 and 1994. They identified 463 papers, indicating that Delphi has been applied to a large number of domains such as automotive engineering, environmental studies, transportation, and utilities, and has been used to address areas such as energy generation, project evaluation, productivity, technology planning, police analysis, the impact of legislation and tax reforms, and risk management.

The main idea of Delphi is to use questionnaires to collect the opinions of the panelists and build the most reliable consensus of the group, while avoiding the negative aspects of face-to-face interaction. A good definition is provided by Rowe and Wright (1999): "...the technique is intended to allow access to the positive attributes of interacting groups (knowledge from a variety of sources, creative synthesis, etc.), while pre-empting their negative aspects (attributable to social, personal and political conflicts, etc.)."

The four key features of the technique are the participants' anonymity, controlled feedback, interaction, and statistical aggregation of the group response. According to Porter et al. (1991) many variants exist for each of these features. Anonymity allows the experts to change their positions without any social pressure and reduces the tendency of the expert to defend an untenable position to preserve credibility or to maintain an institutional view. This feature helps in the creation of a final consensus. Two degrees of anonymity exist. The first is the identity of the participants and the second is the identity of the input. According to Sullivan and Claycombe (1977), the latter is far more important. In the FUEEM process, the feedback summary is always anonymous and the questionnaires are done by e-mail using the bcc (blind carbon copy) mode, thereby concealing the identity of the participants. However, since the project has also used the workshop technique, most of the participants know each other. According to Parent et al. (1984) a 'groupthink' effect may occur when the experts share their opinion *a priori*. This possibility might constitute a limitation for discussions such as scenario construction, but this is a minor consideration, as discussed in Sullivan and Claycombe (1977). It can be compared with the experts participating in a conference where they need not necessarily agree or disagree with the presentations.

The group interaction occurs by a sequence of questionnaires called rounds, in which feedback from the previous round is provided. The occurrence of several rounds enables the group to build its own body of knowledge and find the best solution at the end. The interaction in FUEEM occurs at least three times, giving each participant (from the sub-groups and the general group) the opportunity to be involved at least twice. In the FUEEM process there is no interaction limitation, which means that the rounds continue until an open discussion is resolved. One solution adopted to resolve reasonable but conflicting positions was to include the alternatives in the model and analyze both situations. This transferred the decision to the regional analyses, where more information (from inventories) was available. Another approach is to delay the next round until new data (from an industry survey, for example) is available.

In spite of the fact that a final consensus is part of the process, the major focus in the FUEEM case is to obtain as many high-quality responses and opinions as possible. Jones and Twiss (1978) suggested avoiding too much emphasis on the achievement of consensus and Van Dijk (1990) showed with empirical experiments that Delphi could be used as a learning and research instrument tool. Based on these perspectives, the FUEEM emphases are on the expert comments and on the group learning process. Comment space is provided for every single topic, in contrast to the classical Delphi process, in which comments are requested only for inputs falling outside of pre-specified limits or in the first round of the process. The feedback feature is the tool allowing this information flow among the experts through consecutive rounds. A summary of the comments was included in the feedback with every new set of data provided.

In the classical Delphi process, quantitative data is statistically summarized (mean and quartiles, in general) and reported, allowing the participants to check their initial positions in comparison to the group's current position. Each expert provides a judgmental response to each topic and the result is an equal weight of the members, similar to a staticized group. Since most of the rounds in the FUEEM process are performed at the sub-group level, the number of experts participating is not high enough to generate a statistical curve from a single value input by each participant. Instead of a single value, each expert is required to provide what is essentially a probability density histogram, follow-

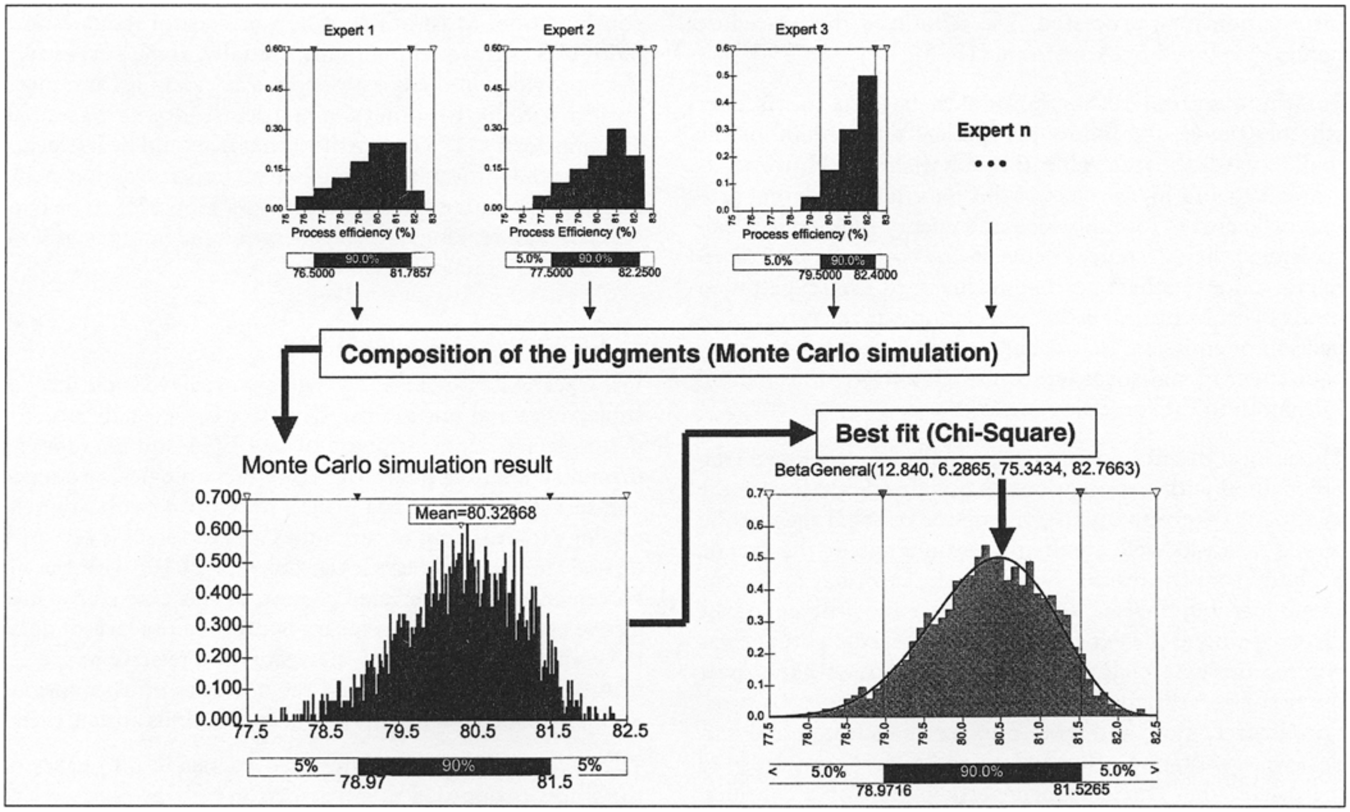

Fig. 3: Expert opinion combination procedure for the FUEEM Delphi method

ing Vose's (1996) suggestion. A minimum of three curves was established as an acceptable level in each round, and the composition of the judgments was done by Monte Carlo simulation. The resulting overall distribution is included in the feedback, not only the mean and quartiles. **Fig.** 3 shows an example of expert opinion combination for the Delphi discussion round. A resulting curve with double (or more) modes indicates that more discussion rounds are necessary, even if the open comments are in agreement.

According to Vose (1996), for technical information a weighting procedure is preferred over a simple average of expert judgments. The FUEEM weighting factor is decided based on the expert's open-ended comments to support their judgments, on the expert's experiences and also on the expert's personal judgment of their level of confidence in their answers. According to Winkler and Makridakis (1983), a combined forecast obtained through weighted averages can be quite accurate and superior to an unweighted method. Dransfeld et al. (2000) have recently applied this method to a study of interactive television.

Clemen's (1985) idea of discarding the opinion of an 'extraneous' expert (an expert who brings no additional information to the aggregated information) was also adopted in the FUEEM model. In a few cases, an expert provided technical information very different from the others' and no comments about it were provided even after a new request to the expert do so. **Table 2** summarizes the variant of the Delphi procedure adopted in the FUEEM process, according to the

Table 2: Summary of the procedures adopted in the FUEEM group discussion according to the type of information involved

FUEEM Delphi Procedures		**Information Type**		
ForecastProcedure	**Detail**	**ScenarioConstruction**	**TechnicalDesign**	**LiteratureAdaptation**
Amalgamated	Each result's round is the composition of the majority's vote	℗ New scenarios may be generated to support conflicting opinions	℗ Modified by the weighting process and possible elimination of extraneous information	**X**
Polling	Several rounds. Each participant is polled at least twice	**X**	**X**	**X**
Feedback	The group consensus predictions are made known to the panel members prior to repolling	**X** With extra focus on comments to support extreme opinions	**X** With extra focus on the technical details of the comments	**X** With extra focus on new data and examples provided

X = Always used; ℗ = Partially used

information type processed. The table uses the procedure names developed by Armstrong (1978).

For the quantitative assumptions it is hard to discover whether the results follow the 'pull of the median' or the 'pull towards the true value' (Brockhoff 1984). However, as a first step and first project of this nature (considering probabilistic curves for emissions and energy requirement calculations) the differences between the two pulls may be irrelevant, due to other uncertainties involved. One expectation of the FUEEM project is that it will motivate the future publication of emission factors and levels of activity of current equipment in statistical terms, bringing more objective information to the forecast panel.

The project did not attempt to compare the developed Delphi method with any other one. A qualitative analysis in the methodology group discussion pointed out that the method served the tasks well, eliminating or minimizing the agenda pushing from the results, bringing new information for the group learning process, and eliminating the problem of the distance among the experts. The cost, in terms of time, was pointed out as a major problem. On the other hand, over the first two years the project had very few losses by attrition. In fact, more and more organizations (interested parties) were willing to provide data and expert knowledge to the discussion. The sustained participation of a considerable number of experts in the FUEEM effort with no material gain can be a signal that the methodology was technically respected, participative, and motivational.

It should be pointed out that there is an ongoing debate about the value of the Delphi technique. Linstone and Turoff (1975) were concerned about the limited amount of controlled experimentation using the technique, compared with the number of applications. Several years later Rowe and Wright (1999) concluded that the applications have increased considerably and the limited experimentation done so far has suffered from several methodological problems. According to them, no conclusions about the right way to proceed can be made yet. To review this debate, see Armstrong (1999) and Ayton et al. (1999). According to them, there is a presumption that social pressures result in poor judgment. They also state that Delphi and other group techniques are still only 'loosely connected to ideas and discoveries from social psychology and cognitive psychology.'

In spite of these criticisms, several reports point out the benefits of using expert information and the fact that the choice of the experts is fundamental for a good forecast. The project did a careful selection of the organizations invited to participate in the effort and good representativeness can be claimed. However, some of the experts were not selected by the organization but were self-selected, because of previous contact with the project. Vose (1996) provides other sources of bias and errors in expert opinion, with references to other studies.

Finally, as in any survey, special care must be taken in the questionnaire design. The advice presented in Belson (1981) and in Sudman and Bradburn (1982) was always taken into consideration. Most of the time, a pre-test of the questionnaire was performed internally. Initially, some suggestions were provided in the questionnaires as examples and motivation for the beginners. This decision was based on Trommsdorff's (1982) statement that it should be irrelevant whether the information changing an expert opinion stems from an internal or an external source. However, to be conservative, and taking into consideration the findings of Vose (1996), this practice was stopped.

4 Conclusions and Suggestions

Life Cycle Assessment (LCA) will always have some level of subjectivity and uncertainty. This fact is especially true for the impact assessment phase of any LCA and also for the inventory analysis phase of future technologies, products, and services. The FUEEM project developed a robust methodology to deal with uncertainties and to forecast activities of fuel for fuel cell vehicles in the year 2010, with the involvement of the interested parties. In this case study, subjective estimates were necessary because of the lack of data, the context of a completely new situation relative to special future fuels and vehicles, and the necessity of assumptions to obtain probabilistic curves and correlations among them.

The involvement of the interested parties in all phases of the study as opposed to participation only as reviewers at the end of the study suggests that it is possible to obtain a higher level of technical credibility in LCA through a more participatory process. In the case of technical information on common and specific activities (such as, for example, hydrogen production in a 27 metric tons per day steam reformation plant), the participatory process associated with probabilistic curves to represent them can generate consensus among the different economic sectors and players. Future studies and new correlation data (such as the plant efficiency related with the natural gas composition) can create a very respectable database, removing even the regional differences. Petroleum extraction, natural gas pipelines and electricity production are examples of common activities that should have this kind of consensus because they may appear in several kinds of life cycle studies. A necessary step in this direction is to stimulate the 'data collectors' such as EPA (Environmental Protection Agency) and CARB (California Air Resources Board) to move towards better information on data uncertainties.

Another benefit of generating a consensus at this technical level is to reduce the space for manipulation when an organization attempts to use LCA to push its agenda. The FUEEM method, using a modified Delphi technique coupled with data search and industry surveys, appears to be very effective in this sense. The focus on the technical comments of the experts in the Delphi rounds was fundamental to generating the consensus. Further studies should confirm if this method generates the consensus towards the real value, as it is supposed to do.

For the scenario construction, the method also appears to be very efficient, especially eliminating ideas that are far from the possible reality. A well-conducted process, leading a good group learning process, can screen the best solution and perhaps even improve it. A future study to check the consistency and generalization of this statement would be interesting. The common sense in the expert network is that the decision of the group in most of the cases would be superior to the decision of a single modeler or single organization.

On the other hand, the FUEEM method was not able to perform well for the extreme cases of the scenario combination, in which no consensus was reached and the majority's result was used. The scenario combination is the part of the study in which the most subjectivity was present. It was also the final opportunity for some organizations to try to influence the final result. The scenario combination, using the majority value, can be very sensitive to the expert network formation. The FUEEM expert network formation tried to be as representative as possible but it is hard to claim an absence of bias since some industries were more represented than others. An alternative solution adopted for the scenario combination was to present the results of the extreme cases as 'bounding scenarios.' This solution brought much more information to the final answer. As the use of probabilistic curves is similar to performing several sensitivity analyses in the study, it provides more and richer information. The quantity of information presented when both solutions are put together can be excessive and its usefulness should be better investigated.

The major drawback of the FUEEM method is the relative higher cost in terms of time and resources necessary to perform a good investigation when it is compared with studies using the decisions of a single modeler and only a few data points collected from the published literature. From the reaction of the internal and external public to the initial FUEEM results, as well as from the perseverance of the expert participation during the long process, it can be said that the benefits may compensate for the costs. Future studies could try to quantify these benefits. On the other hand, if this method generates some information that has a general consensus in such a way that several studies can benefit from them, than the relative cost can be much less, while the benefit in each study will be greater.

Finally, according to Sullivan and Claycombe (1977), 'no forecast should be accepted as final', especially in the area of advanced technology, in which development occurs very quickly and there is considerable interest. The FUEEM method should be viewed as an additional and interesting tool to help the improvement of LCA, and as a platform for constant improvement.

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