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Extending Technology Roadmap through Fuzzy Cognitive Map-based Scenarios: The Case of the Wind Energy Sector of Pakistan

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Extending Technology Roadmap through Fuzzy Cognitive Map-based Scenarios: The Case of the Wind Energy Sector of Pakistan

by

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ABSTRACT

In this modern era, energy is a key element required for sustainable development and prosperity of a society. Pakistan is an energy deficient country facing problems due to the shortage of over 4000 MW of electricity. The national energy sector is heavily dependent on imported fossil-fuel resources. The energy crisis is negatively affecting all economic and business activities, and it is widely recognized as a severe obstacle to growth and poverty reduction in the country. Establishment of wind farms can help to overcome the energy crisis.

In this research, a national level wind energy roadmap is developed through scenario planning. Multiple future scenarios are developed using the fuzzy cognitive maps (FCM) approach. This research has extended technology roadmapping through FCM-based scenario analysis. Building scenarios with FCM is a very new approach, and for the first time FCM-based scenarios are developed for the wind energy sector of Pakistan. Based on these multiple scenarios, a technology roadmap has been developed. This research approach is applied to the wind energy sector of Pakistan as a case study.

This approach has been used to establish objectives and national targets of the roadmap. Then in a systematic way, critical roadmap barriers are identified against each scenario, and appropriate action items have been proposed to overcome barriers and promote deployment of wind energy projects in Pakistan.

The objectives and targets of the roadmap have been translated into action items. The technology roadmap has four layers: strategic objectives, targets, barriers, and action items. Expert panels have been utilized to develop scenarios and technology roadmaps. Validation of this research is also carried out using experts. This new approach has helped to develop a robust roadmap and enabled anticipation of a wide range of possible future outcomes.

This research fills an important gap by combining scenario planning and technology roadmapping techniques in future studies, and it has enhanced flexibility of the developed roadmap. Moreover, for the first time multiple and plausible FCM-based scenarios are developed, which combine the benefits of both qualitative and quantitative analysis. Moreover, the technology roadmap for the wind energy sector of Pakistan is developed with a comprehensive study of practical obstacles and barriers towards deployment of wind energy technology. The research findings suggest that policy, financial, economic, lack of competition with conventional power plants, and technical are the most critical barriers towards deployment of wind energy projects in the country. Appropriate action items required to overcome the roadmap barriers against each scenario are also proposed in the developed roadmap. The experts also assigned responsibilities for the key roadmap action items to the major stakeholders.

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1 Introduction

1.1 Research Objectives

The objective of this research is to develop a national level wind energy roadmap through scenario planning. Fuzzy cognitive maps (FCM) based scenarios are developed for the deployment of wind energy. This has extended the technology roadmapping through FCM-based scenario analysis. Developing scenarios with FCM is a very new approach combining the benefits of both qualitative and quantitative analysis. Scenario analysis has helped to develop a robust roadmap and enable anticipation of a wide range of possible future outcomes. This research uses the wind energy sector of Pakistan as a case study. The research objectives are grouped into the following two categories:

i. Method development:
   a. Develop multiple and plausible FCM-based scenarios for wind energy deployment; and
   b. Combine the FCM-based scenario planning and technology roadmapping process.

ii. Application of the new method:
   a. Development of the national wind energy roadmap to address the strategic objectives of the country;
   b. Identify practical insights on factors supporting and hindering deployment of wind energy projects in the country; and

c. Propose action items and plans for deploying wind energy on a large scale in the country.

1.2 Literature Background

As background for this research, a detailed literature review was conducted to address the following research questions:

Q1: How can FCM be used to develop plausible scenarios for wind energy?

Q2: How can the FCM-based scenario planning approach be integrated with technology roadmapping process?

Q3: What are the factors supporting and hindering the deployment of wind energy projects in the country?

Q4: How can the wind energy integration challenges be managed by a developing country?

Q5: What are the required action items and plans for implementing wind energy projects in the country?

A detailed literature review is presented in Chapter Two, covering topics related to technology roadmapping, scenario planning, expert judgment, sustainable energy roadmaps, and energy foresight. The following key takeaways and gaps were identified.

There is a need to combine scenario planning and technology roadmapping techniques in future studies [209, 286, 319], and this combination will enhance the usefulness of the technology roadmaps [286, 295, 319]. Therefore, it has been recommended to evaluate a concise mix of methods for future studies [209].

There is a weak link between qualitative and quantitative scenarios, which has been cited as a major obstacle towards development of integrated scenarios [170], whereas building FCM-based scenarios is a unique approach that can combine the benefits of both qualitative and quantitative analysis.

A literature review of 135 public-domain sustainable energy roadmaps [8] revealed that in these roadmaps, scenarios are generally created based on a few hypothetical assumptions without much deliberation, logical reasoning, and consideration of the causal relationships among various variables.

The literature review on the renewable energy sector in Pakistan reveals that it is limited to highlighting potential renewable energy resources and some generic barriers. There is no roadmap, scenario planning or implementation plan for wind energy projects in the literature. Moreover, the practical obstacles towards deployment of wind energy technology are also not thoroughly studied.

Wind energy is a variable and uncertain power source, and its deployment on a large scale requires significant changes in the power grid in order to make it more vibrant and interactive. This research will address the integration challenges associated with the deployment of wind energy on a large scale in a developing country.

1.3 Outline of Dissertation

This dissertation is organized into seven chapters and seven appendices. Chapter One presents the introduction and overview of this dissertation.

Chapter Two highlights a literature review of scenario planning, FCM-based scenario planning, technology roadmapping, expert judgment, sustainable energy roadmaps, and energy foresight. At the end of this chapter, gaps in the existing literature are identified.

Chapter Three introduces the research methodology and describes the research objectives, goals, and questions. It describes the research design and data collection methodology used for this research. Each research step and role of the expert panels for this research are also explained in this chapter.

Chapter Four describes the background of the research case. It provides an overview of the national energy sector, energy crisis, role of the government, and wind energy sector of Pakistan.

Chapter Five highlights the data collection and data analysis process and research validation approach. It includes details of the research steps taken for the development of scenarios and roadmaps.

Chapter Six presents analysis and discussion. Data obtained from the expert panels is thoroughly analyzed. The developed roadmaps are also presented in this chapter.

Finally, Chapter Seven provides the conclusion. It also discusses the research contributions, research limitations, and future research prospects.

Appendices included are: Appendix A, Agenda and Handout for the FCM Scenario Workshop; Appendix B, description of techniques for combining multiple FCMs; Appendix C, Agenda and Handout for Roadmap Objectives and Targets Workshop; Appendix D, Agenda and Handout for Roadmap Barriers Workshop; Appendix E, follow-up survey for ranking of roadmap barriers; Appendix F, Agenda and Handout for Roadmap Action Items Workshop; Appendix G, example of stability test (chi-square test) performed on the data of follow-up surveys for priortization of the roadmap barriers; Appendix H, details of the cluster analysis performed to group the roadmap barriers; and Appendix I, details of the FCM Simulation.

1.4 Publications Arising from this Dissertation

At the time of completion of this research, several papers related to this dissertation have been published in journals, accepted for publication, and presented at conferences. Some further papers are planned and under way. Following are the peer-reviewed papers related to this dissertation, which have been published and presented at international conferences on technology management:

- Application of Technology Roadmaps for Renewable Energy Sector, *Technological Forecasting and Social Change*, Vol. 77, No. 8, pp. 1355-1370, 2010.
- Development of Fuzzy Cognitive Map (FCM) based Scenarios for Wind Energy, *International Journal of Energy Sector Management*, Vol. 5, No. 4, 2011.
- Selection of Renewable Energy Technologies for a Developing Country: A Case Study of Pakistan, *Energy for Sustainable Development*, Vol. 15, No. 4, pp. 420-435, 2011.
- Technology Roadmapping for Wind Energy: The Case of the Pacific Northwest, *Journal of Cleaner Production*, Vol. 20, pp. 27-37, 2012.
- Technology and Science Policies in Transitional Economy, *Science, Technology & Society*, Vol. 17, No. 2, pp. 297-321, 2012.
- A Review of Scenario Planning, *Futures*, Vol. 46, No. 1, pp. 23-40, 2013.
- Development of fuzzy cognitive map (FCM) based scenarios, in *Portland International Conference for Management of Engineering and Technology (PICMET)*, Portland, OR, 2011, pp. 2695-2709.
- Scenario Planning for the National Wind Energy Sector through Fuzzy Cognitive Maps, in *Portland International Conference for Management of Engineering and Technology (PICMET)*, Portland, OR, 2013, Accepted Manuscript.

2 Literature Review

The detailed literature review was conducted along four perspectives: 1) scenario planning; 2) technology roadmapping; 3) expert judgment; 4) sustainable energy roadmaps and energy foresight.

2.1 Scenario Planning

During the last 60 years, scenario planning has been used in an increasing number of fields and domains [267]. Exploring uncertainty in the business environment is the key element of scenario planning studies [37]. Uncertainty is defined as “an individual's perceived inability to predict something accurately” [37]. In the present era, characterized by uncertainty, innovation and change, increasing emphasis is being placed on the use of scenario planning techniques because of its usefulness in times of uncertainty and complexity [291]. Scenario planning stimulates strategic thinking and helps to overcome thinking limitations by creating multiple futures. Scenarios outline some aspects of the future and, generally the word scenario refers to an outline of the plot of a dramatic work, or the script of a motion picture or television program [158]. Herman Kahn, considered one of the founders of futures studies and father of scenario planning, defines a scenario as “a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points” [160]. Godet defines scenario as a description of a future situation and the course of events which allows one to move forward from the actual to the future situation [107].

Scenarios are alternative, plausible and consistent images of the future and highlight the large scale forces that push the future in different directions [298]. Scenarios are useful whenever the problem is complex, uncertain and has a long-term effect [209]. Scenarios provide an intelligible description of a possible situation in the future, based on a complex network of influence factors [96]. Scenario planning techniques are frequently used by managers to articulate their mental models about the future in order to make better decisions [196]. Scenario planning has increasingly been applied as a useful tool for improving decision making processes and dealing with uncertainty by considering a number of possible future environments [338]. Therefore, scenarios significantly enhance the ability to deal with uncertainty and increase the usefulness of the overall decision making process [333, 339].

Systematic use of scenarios for clarifying thinking about the future started after World War II when the US Department of Defense used them as a method for military planning in the 1950s at the RAND Corporation [22, 50, 79, 158, 160, 333]. After that the scenario methodology was extensively used for social forecasting, public policy analysis, and decision making in the 1960s. Future scenarios exert a strong influence on human thinking and the decision making process, and they can help initiate public debate [121]. Schoemaker describes that scenario planning must outline the possible futures, capture a wide range of options, stimulate thinking about the future, and challenge the prevailing mindset and status quo [291, 292]. Futures studies help to see the present differently, and according to some futurists, these are a devise for “disturbing the present” [61]. Therefore, during the process of scenario building, it is important to encourage the participants to consider options beyond the traditional operational and conceptual comfort zone of the organization [49, 69, 319]. This encouragement will help in the exploration of new possibilities and unique insights.

Consideration of multiple possible future alternatives helps in conducting future planning in a holistic manner [153], significantly enhancing the ability to deal with uncertainty, and improving the usefulness of the overall decision making process [333, 339]. Scenarios are a useful way of looking at the future because due to cognitive limitations, people can only conceive a limited part of future possibilities [254]. Moreover, scenario planning presents all complex elements together in a coherent, systematic, comprehensive, and plausible manner [158]. Scenarios are also very useful for highlighting implications of possible future system discontinuations, identifying the nature and timing of these implications, and projecting consequences of a particular choice or policy decision [319]. Scenario provides a description of a future situation and portrays the path that leads us out of today and into the future [249]. Schwab, Cerutti, and von Reibnitz also state that the scenario approach develops the future situations and describes the path from any given present to these future situations [297]. Thus, the scenario planning process helps to make the desirable future real

[282]. Researchers also report a direct link between scenario planning activities and innovation [288].

Research indicates that there is a correlation between the adoption of scenario planning techniques and uncertainty, unpredictability, and instability of the overall business environment [194]. Increasing uncertainty has increased the importance of identifying the future trends and expected business landscape. Therefore, utilization of scenario has increased due to greater complexity and uncertainty in the business environment. In general scenarios can be developed for any time frame, but they provide greater usefulness if developed for the long-term [196]. Usage of scenario planning for long range planning and strategic foresight facilitates one to adapt quickly to the major changes [339]. Future uncertainty increases as we move away from the present and look further into the future. Figure **1** highlights the widening of scenario cone and broadening of the realm of future possibilities [249]. Various factors which may influence the direction of future development of an enterprise are also shown in Figure 1. There are several internal factors like decisions, strategies, vision, values, and knowledge as well as external factors like rules, regulations, and influences.

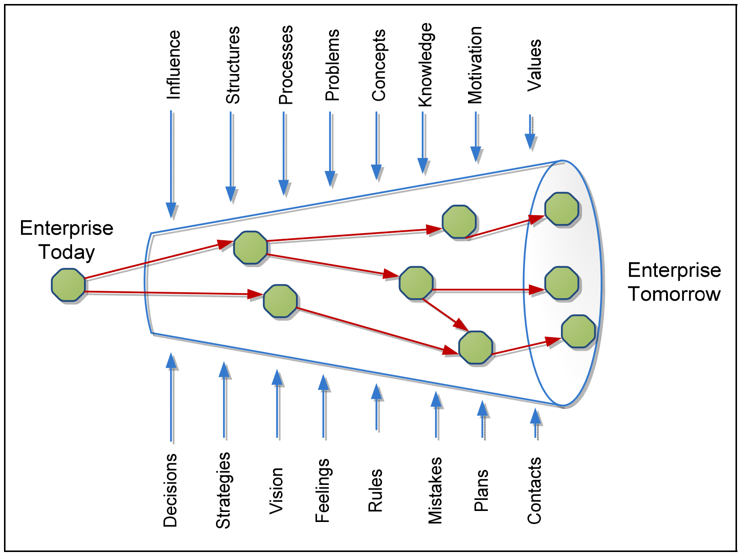

Figure 1: Scenario cone showing multiple possibilities [249]

There has been significant growth in the use of scenario planning, especially in the decade up to the year 2010 [263, 339]. Scenario planning has been extensively used at the corporate level, and in many cases it has been applied at the national level [50, 253, 287]. The scenario building process also contributes towards organizational learning [51]. Shell was one of the first companies to use scenarios at the corporate level, and usage of scenarios helped the company to cope with the oil shock and other uncertain events in the 1970s [50, 158, 294]. Scenarios are considered a valuable tool that helps organizations to prepare for possible eventualities, and makes them more flexible and more innovative [129]. Empirical research conducted by Linneman and Klein indicates that after the first oil crisis in the early 1970s, the number of U.S. companies using scenario planning techniques doubled [186, 187]. It was observed that at the corporate level the scenario planning approach was more popular among large companies, scenarios were generally used for long range planning (10 years or more), and the majority of scenario users belong to capital intensive industries like aerospace and petroleum. They further reveal that almost 50% of all US Fortune 1000 companies were actively using scenarios in the early 1980s [186, 187].

Pierre Wack presents scenario building criteria based on three main principles: identification of the predetermined elements in the environment, the ability to change mindset in order to re-perceive reality, and developing a macroscopic view of the business environment [37, 78, 345, 346]. A scenario does not predict the future, but it explores multiple plausible future situations with the purpose of extending the sphere of thinking of the participants in the scenario development process [106, 290]. Thus, scenario planning creates a set of plausible futures [353]. Table 1 highlights the important differences between scenario planning and future projections.

Table 1: Difference between projection and scenario [249]

	Projection	**Scenario**
Features	Attempt at an exact prediction of events, oriented to the past	Attempts to represent cross section of the future as alternatives, oriented to the future
Basis	Based on probabilities	Based on possible and imaginable
Temporal Scope	Short- to medium-term	Medium- to long-term
Decision Factor	Deterministic	Alternative scenarios as a basis for decision making
Variables	Facts, quantitative, objective, known	Objective and subjective, known and unknown, qualitative and quantitative

The literature on scenario planning indicates that scenarios mean different things for different users, and often scenarios are developed for various purposes [29]. On the basis of perspective, scenarios are classified into descriptive and normative scenarios [253]. The descriptive scenarios are extrapolative in nature and present a range of future likely alternative events. The normative scenarios are goal directed and respond to policy planning concerns in order to achieve the desired targets. Scenarios are also classified on the basis of scenario topic (problem specific verses global scenarios), breadth of the scenario scope (one sector verses multi-sector scenarios), focus of action (environmental verses policy scenarios), and level of aggregation (micro verses macro scenarios) [209].

2.1.1 Scenario Planning as a Tool for Strategic Foresight

Scenario planning is the most popular and commonly used tool for a strategic foresight project [79, 141, 209]. The word foresight generally describes long range forward-looking activities [210]. Strategic foresight is defined as “the ability to create and maintain a high-quality, coherent and functional forward view, and to use the insights arising in useful organizational ways” [312]. Martin states that technology foresight is a process to identify the strategic research areas likely to yield the greatest economic and social benefits by systematically looking into the longer-term future of science, technology, economy, and society [197]. In a foresight project, the scenario planning helps to better prepare for the future and improve perception of opportunities and options [42].

Scenario planning can significantly enhance the usefulness of a strategic foresight project and compliment the foresight process [22]. Bishop et al. state that the scenario development activities are the heart of a futures study [25]. An analysis of 860 future studies revealed that scenario planning is among the most commonly used technique employed in these foresight studies [54].

In strategic foresight projects, scenarios are employed to accomplish a broad range of objectives [22]. Important aspects of foresight are to look into a range of possible futures [311] and various strategic options [209, 343]. Scenario analysis helps to explore these alternative futures and systematically formulate and analyze various strategic options. Moreover, exploring the future uncertainty is a critical part of a strategic foresight project which can be accomplished through scenarios [22, 78]. The future uncertainty can be evaluated by considering multiple options across a number of scenarios each depicting a glimpse of the probable future [69, 79]. In future studies, scenarios highlight implications of possible future system discontinues and their implications [319]. Ringland describes two important roles of scenarios in supporting the foresight studies: providing a well understood methodology to explore the future and presenting a set of mental models [268]. Cairns et al. state that scenario methods offer an enabling mechanism to promote the foresight activities across multiple agencies [39]. Therefore, it can be concluded that scenario planning is a highly complementary technique and it is widely used in strategic foresight studies.

2.1.2 Benefits and Limitations of Scenario Planning

The literature on scenario planning reveals that there are numerous benefits of using this approach. Some of the major benefits of scenario planning are listed below:

- Clarifying thinking about the future [22, 50, 79, 158, 333];
- Exploring the uncertainties in a business environment [37, 338];
- Understanding nature and impact of the most critical and uncertain driving forces i.e. scenario drivers/trends [249];
- Providing a creative yet structured approach to explore what the future might look like [333];
- Improving the decision making process [196, 333, 339];
- Projecting the consequences of a particular choice or policy decision [319];
- Helping organizations to test their strategy [129];
- Identifying the emerging areas of strategic importance which leads to significant benefits and taking advantage of unexpected opportunities [293];
- Extending the traditional planning time horizons, conducting long-term strategic planning in a holistic manner, and making flexible long-term plans [153, 298];
- Enabling an organization to adapt quickly to major changes [339];

- Providing the ability to learn faster than competitors and gain a competitive advantage [36, 38];
- Highlighting the path from present to the future situations (scenarios) [249, 297];
- Challenging the prevailing mindset and status quo by encouraging to think the unthinkable [49, 69, 291, 292, 319]; and
- Extending the sphere of thinking of the participants in the scenario development process [106, 290].

In contrast to the above-mentioned benefits, scenario planning techniques have several weaknesses as well:

- Scenario planning is a very time consuming activity [206, 209];
- Due to limited expertise, scenario planning is unavailable to many companies [50];
- Scenarios are open ended and Describe a set of future circumstances, but do not give a pathway into the future [277];
- It is crtiical to ensure selection of suitable experts, and in somecases this could be a difficult task to fulfil [135, 209];
- Due to intensity of involvement, sometimes only the most financially secure companies use scenario planning [345, 346];
- Indepth knowledge of the field under investigation is necessary [209];

- In some scenario planning techniques, the possible impacts of scenario drivers on each other are not considered [135]; and
- Sometimes scenario work is undertaken on the basis of non-existing or very weak reasoning [38].

2.1.3 Application of Scenario Planning in Energy Sector

The scenario planning approach has been widely used in the energy and renewable energy sectors. As mentioned earlier, scenario planning helps to improve the decision making and learning process, long-term future planning, and identification of new challenges and problems which may arise in the future [121, 339]. Scenario planning helps to analyze the emerging issues in a complex energy system [27]. In the energy sector, some cases of scenario planning application are mentioned below:

- Assessment of energy resources [309];
- Reduction of global CO_2 emissions and increase the share of renewable energy to meet the worldwide energy needs [175];
- Assessment of the future energy consumption, composition of electricity generation, energy diversity, and greenhouse gases emissions [103];
- Improvement of the energy efficiency measures and reduction of energy consumption in the commercial buildings [362];

- Projection of the future energy consumption in the transport sector [323];
- Impact assessment of rural energy consumption in different sectors [277];
- Analysis of energy consumption mix and potential of energy exports [162];
- Analysis of the energy policy alternatives and assessment of the ecological footprint of energy consumption [34];
- Development of the hydrogen energy infrastructure [315, 352, 359];
- Deployment [55] and integration of renewable energy resources [12, 350];
- Analysis of promising opportunities for achieving alternative energy pathways like energy savings, renewable energy, and transportation activities [103];
- Evaluation of the future energy demand and share of renewable energy resources in the future [166];
- Assessment of future energy market to use industrial excess heat from the economic and CO_2 emissions perspectives [157];
- Analysis of the national level future primary energy demand [75, 166];
- Energy foresight and long-term energy planning at the national level [63]; and
- Renewable energy portfolio planning [48, 192, 219, 337].

2.2 Quantitative Scenario Development Methods

There are several methodologies for developing scenarios with many common characteristics [30, 50, 158, 339]. Bradfield et al., Keough et al., and Chermack et al. review various methodological approaches and guidelines presented in the literature for scenario building [30, 50, 167]. Due to the large number of scenario development techniques and models presented in the literature, some authors describe it as "methodological chaos" [30, 196]. The following methods are considered the most popular and widely used quantitative techniques for building scenarios [30, 115, 134-136, 209]. These methods are considered state of the art for developing the quantitative scenarios.

- Interactive Cross Impact Simulation (INTERAX);
- Interactive Future Simulations (IFS); and
- Trend Impact Analysis (TIA).

2.2.1 Interactive Cross Impact Simulation (INTERAX)

The INTERAX (Interactive Cross-Impact Simulation) methodology was developed by Enzer at the Center for Futures Research (CFR), Graduate School of Business Administration, University of Southern California [30, 83, 134, 136]. This technique uses both analytical models and expert judgment to develop a better understanding of alternative future environments. A comprehensive database containing important information of future trends and events is developed through a Delphi study of 500 experts to support the scenario building activities [83, 84, 135, 136]. This database contains information of 100 events and 50 trend forecasts and it is updated periodically. The database was developed due to the assumption that the macro societal conditions are common to most of the strategic issues; therefore, one environmental scan can be used to support several issues [84]. CFR highlights that scenarios developed using the INTERAX approach can help companies with major decisions for a large range of issues, including new product and market opportunities, capital investments, plant and equipment acquisitions, mergers and acquisitions, and R&D planning [134].

Huss and Honton state that the INTERAX approach consists of the following eight steps [135, 136]:

Step 1: Define the issue and time period of analysis: Clarify the issue, time frame of analysis, and scope of the scenario project;

Step 2: Identify the key indicators: Key indicators are the primary variables relevant to the forecasting. These are the characteristics of a system which can be measured, counted, or estimated at any point in time;

Step 3: Project the key indicators: Develop a model which independently forecast the indicators based on current and past data using econometric and time series techniques as well as forecasts available from the literature;

Step 4: Identify the impacting events: Identify the possible future events whose occurrence would significantly affect one or more of the key indicators using the INTERAX database, expert opinion, or any other source;

Step 5: Develop event probability distributions: Divide the forecast horizon into smaller time periods and estimate the cumulative probabilities that each event will occur prior to expiration of the time period;

Step 6: Estimate the impacts of events on trends: The models developed in step 3 are used to estimate the expected value of each indicator variable (trend) over the time period of interest;

Step 7: Complete the cross-impact analysis: The cross impacts of events on events and the trend impacts of events on trends are estimated; and

Step 8: Run the model: Last step is to perform the simulation and an envelope of uncertainty is created of the range of possible future paths for the key indicators.

2.2.2 Interactive Future Simulations (IFS)

Interactive Future Simulations (IFS) technique was previously known as BASICS (BATTELLE Scenario Inputs to Corporate Strategies) and it was developed by the Battelle Memorial Institute in the 1970s [25, 30, 135, 136]. The main differences between IFS and INTERAX techniques are that IFS does not use Monte Carlo simulation, and it does not require an independent forecast of the key indicators or variables [135, 136].

The IFS methodology consists of the following seven steps [135, 136]:

Step 1: Define and structure the topic, including unit of measure, time frame, and geographic scope;

Step 2: Identify and structure the areas of influence;

Step 3: Define the descriptors, write essays for each descriptor, and assign initial probabilities of occurrence to each descriptor state;

Step 4: Complete the cross-impact matrix and run the program;

Step 5: Select scenarios for further study and write the narratives;

Step 6: Introduce the low probability and high impact events and conduct the sensitivity analysis; and

Step 7: Make forecasts and study the implications of scenarios, and identify what strategies should be developed to take advantage of the opportunities presented while reducing potential threats.

The IFS methodology emphasizes the market and customer orientation, promotes a long range perspective and provides insights in the business dynamics using cause and effect relationships [30, 135, 136]. Additionally, this process identifies the novel and diverse ideas, encourages contingency planning, and provides an early warning system of any major changes in the business environment [135].

2.2.3 Trend Impact Analysis (TIA)

Trend Impact Analysis (TIA) is another quantitative approach for building scenarios developed in the 1970s. TIA is a combination of statistical extrapolations with probabilities. It provides a systematic approach to combine extrapolation based upon the historical trends with judgment about the probabilities and impacts of the selected future events [30, 50, 115, 135]. Thus, TIA considers the effects of the unprecedented events which may occur in the future. An unprecedented event with higher impact is likely to swing the trend relatively far in any direction from its un-impacted course based on the historical trends. Gordon describes that the following two principal steps are necessary to conduct the trend impact analysis [115]:

i. A curve is fitted to the historical data in order to calculate the future trend; and
ii. Expert judgments are used to identify a set of future events that could cause deviations from the extrapolation of the historical data. The experts judge the probability of occurrence as a function of time and its expected impact.

The Futures Group has proposed a detailed TIA methodology consisting of the following eight steps [135, 136]:

Step 1: Select the topic and identify the key scenario drivers;

Step 2: Create a scenario space by selecting a subset of multiple alternative scenarios;

Step 3: Identify the important impacting trends and collect time series data;

Step 4: Prepare a naive extrapolation based upon the historical data;

Step 5: Establish a list of the impacting events by a Delphi study, literature review, expert panel, or STEEP analysis;

Step 6: Establish probabilities of events occurring over time: years to maximum impact, level of maximum impact, years to steady state impact, and level of steady state impact;

Step 7: Modify the extrapolation and combine the impact and event probability judgments to produce an adjusted extrapolation with upper and lower quartile limits; and

Step 8: Write the narratives for each scenario within the scenario space based on the results of the trend impact analysis.

According to Gordon, the TIA method has been used frequently and it has been applied to determine future of the healthcare sector, pharmaceutical market future, and forecast petroleum consumption in the transport sector to assess effectiveness of several policies [115]. This approach has been used by many US federal agencies including the Federal Aviation Administration, Federal Bureau of Investigation, National Science Foundation, Department of Energy, Department of Transportation, and State of California [115].

2.2.4 Limitations of Quantitative Scenario Methods

The scenario building techniques have evolved due to the change in the futures research paradigm from a more quantitative approach (in the 1970s) towards a more qualitative and process-oriented one [209]. Strictly quantitative methods are often criticized because these methods rely solely on the historical data and assume that the same trends will prevail in the future [115]. Thus, relying only on the quantitative data may result in an inaccurate forecast.

Generally, the quantitative methods are considered useful for the narrowly focused projects having short time horizon, whereas the qualitative methods are considered appropriate for the projects having large scope and long time horizon. It is very likely that the current trends may change in the future [249]. It is highlighted in Figure 2, that usefulness of the quantitative methods declines steadily as we look further into the future, whereas usefulness of the qualitative approaches increases in this case [249]. Therefore, it can be concluded that both qualitative and quantitative approaches are complementary and strengthen each other when used together. However, some researchers has pointed out that there is a weak link between qualitative and quantitative scenario development approaches and it is considered a major obstacle towards development of integrated scenarios [170].

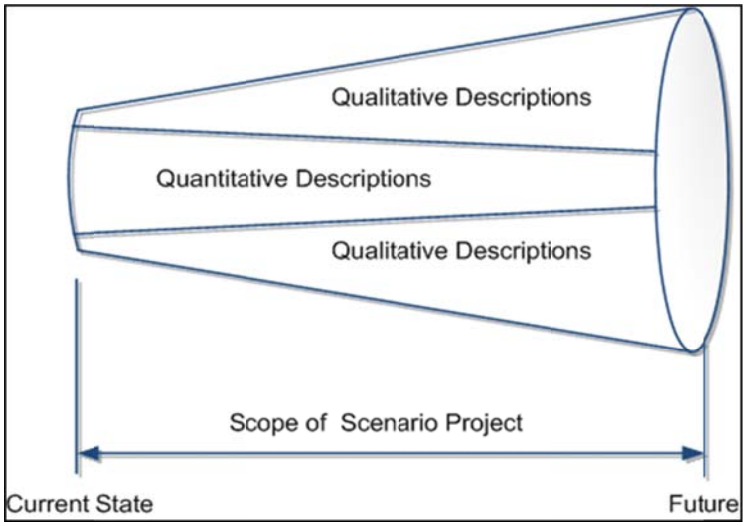

Figure 2: Qualitative verses quantitative scenario development techniques [249]

The scenario planning literature highlights some weaknesses of the prominent quantitative methods for scenario development [30, 50, 115, 134-136]. These weaknesses are summarized in Table 2. The FCM-based scenario development approach (described in the next section) has the potential to overcome the weaknesses these prominent quantitative scenario building techniques.

Table 2: Weaknesses of quantitative scenarios planning techniques

Method	Weaknesses of Quantitative Scenario Planning Techniques	FCM-based Scenarios
Trend Impact Analysis	This method does not evaluate the possible impacts which the events may have on each other.	Causal links highlights impact of concepts on each other
	Designed primarily for the evaluation of one key decision or forecast variable, which is quantitative and have the historical information.	All drivers and causal links in the FCM are considered for scenario development
	Process is sometimes constrained due to unavailability of reliable historic time series data.	Historic time series data of the important trends is not required.

Interactive Future Simulations	It is a probabilistic forecasting tool and computer algorithm generates scenarios, i.e. descriptions of a business environment likely to occur at the end of the forecast horizon.	Simulation examines how the scenario drivers will change based on the causal relationships among them.
	The user must use some creativity to incorporate the time dynamics.	Through activation of concepts time dynamics are incorporated
INTERAX	Needs an extensive database consisting of the most important events and trends.	Database of important events and trends is not required.
	The selection of events which occur in the first interval is based solely on a random selection using the initial user entered probabilities.	FCM simulation is conducted with input vectors consisting of the scenario drivers having the highest impact and uncertainty.

2.3 Fuzzy Cognitive Maps (FCM) based Scenarios

FCMs can be used for the development of scenarios and this approach has the ability to overcome the weaknesses of the quantitative scenarios building techniques. Building FCM-based scenario is a very new approach and recently Jetter et al. [152] and van Vliet et al. [334] propose the viability of FCM as a method for scenario development. Kok and van Delden identify that the weak link between qualitative and quantitative scenarios is a major obstacle towards development of integrated scenarios [170]. Literature also highlights the importance using imagination followed by a causal analysis for the scenario building process [353]. FCM uses the fuzzy logic and it can integrate qualitative knowledge with quantitative analysis. Thus, the FCM-based scenario development approach has the potential to combine qualitative approach with quantitative models [334]. Research also indicates that integration of multiple approaches in the scenario building process results in robust scenarios [36, 249].

2.3.1 Theoretical Background

Robert Axelrod introduced cognitive maps in the 1970s to represent social scientific knowledge as an interconnected and directed graph consisting of nodes and edges/arrows [163, 171]. Causal cognitive maps are widely used to capture causal knowledge and mental model models of the experts on the complex matters [154, 156]. Nodes represent various concepts and arrows highlight the causal relationship between various concepts. Every concept is influenced by the interconnected concepts based on the value of the corresponding causal weights. The visual nature of these maps facilitates understanding of the existing dependencies and contingencies between various concepts. Thus, the graphical nature and relative simplicity make the causal cognitive maps a useful tool for visualization and communication [156]. These maps are also used for developing scenarios [109]. In this approach diverse mental models are captured from multiple experts and this process helps the experts to identify the key issues of the scenario domain and explore the alternative futures [152]. The mapping process fosters system thinking and allows the experts to better assess their own mental models and indicate their subjective knowledge [152].

Kosko invented Fuzzy Cognitive Maps (FCM) as an extension and enhancement of a cognitive map with the additional capability to model the complex chains of the causal relationships through weighted causal links [172]. FCM is a modeling approach that makes the qualitative causal maps computable [156]. A link between the concepts is assigned weights to quantify the strength of their causal relationships. FCMs are mainly used to analyze and aid the decision making process by investigating the causal links among the relevant concepts [171].

FCMs can overcome the indeterminacy problems of the causal cognitive maps which occurs when one concept is influenced by an equal number of negative and positive ingoing arrows [296]. The causal maps encode the dynamic behavior ("something happens because and after something else has happened"), but sometimes due to complexity and cognitive limitations, causal behavior cannot be easily inferred from the maps [154, 156]. Moreover, applying the causal cognitive map can lead to a large and complex model and subsequently it becomes very difficult to analyze the indirect effects, feedback loops, and time lags [152]. Development of FCM involves the following three steps [201]:

- Identification of the key domain issues or concepts;
- Identification of the causal relationships among these concepts; and
- Estimation of the strength of the causal relationships.

FCM analyze interrelations between phenomena that are graphically represented in causal cognitive maps or influence diagrams [153]. Thus, it graphically models the cause and effect relationships in a decision environment. In general each concept (node) in a FCM model may reflect a state, variable, event, action, goal, objective, value, or other system component. These concepts are non-linear functions that transform the path weighted activation towards their causes. A finite number of FCMs can be combined together to produce a joint effect and capture opinion of multiple experts together in one collective map [163]. Therefore, the integrated FCM provides a more holistic overview of the pertinent issues surrounding the subject area [313]. Moreover, these maps allow systematic integration of multiple perspectives when considering the long-term planning [313]. Taber and Siegel propose estimation of expert credibility weights in order to combine multiple FCMs [325].

The FCM-based research approach has been used in a much wider range of applications in different domains [2]. It has been used to study and analyze foreign policy, stock-investment, software adoption, modeling IT project management, designing and improving information system evaluation (ISE), product planning, manufacturing problems, fault detection and troubleshooting for electronic circuits, supervisory system control analysis, web data mining, socio-economic modeling, ecosystem and water quality issues, immigration issues, drug control, child labor issues, and community mobilization against the AIDS epidemic [59, 130, 153, 163, 179, 236, 270, 279, 284, 303, 320, 324].

2.3.2 FCM-based Scenario Development Process

The following framework has been proposed for the development of FCM-based scenarios by integrating the scenario planning and FCM modeling processes [152]:

Step 1: Scenario Preparation: Clarification of the objective, time frame, and boundaries of the scenario project;

Step 2: Knowledge Capture: Identify the relevant concepts / potential scenario drivers through the experts and literature review, merge mental models of multiple experts, and subsequently translate these into a conceptual FCM scenario model;

Step 3: Scenario Modeling: Streamline the causal links and assign weights and signs to all links, choose the squashing functions for all the concepts;

Step 4: Scenario Development: Calculate the FCM model for different input vectors that represent plausible combinations of concept states;

Step 5: Scenario Selection and Refinement: The raw scenarios developed after step 4 are further assessed and refined; and

Step 6: Strategic Decisions: The developed scenarios are used for making the long-term strategic decisions.

The FCM-based scenario planning process is conducted with the help of an expert panel. Identification of the experts is considered the first step of the knowledge elicitation process [155]. Knowledge of the experts is captured in a weighted causal map/FCM model to identify the crucial concepts/factors. The expert panel member would be an experienced person having knowledge in the subject area along with some professional credentials and domain experience.

The map building process facilitates and encourages debate and discussion among the key stakeholders regarding the scenario theme [313]. Moreover, participation of the stakeholders in this process increases their input in the model and facilitates to develop consensus among them. The experts also help to identify the input vectors that represent plausible combinations of the conceivable concept states. Thus, FCM-based scenarios provide the benefits of intuitive scenario methods with quantitative analysis. The utility and usefulness of FCM-based scenarios significantly depend on the quality of the underlying causal map. Therefore, it is critical to select knowledgeable experts, and carefully examine the causal relationships, uncertainties, and assumptions of the FCM model. FCM-based scenarios are developed after collecting and combining the mental models of multiple experts. The literature also highlights the importance of capturing multiple mental models in foresight projects [69, 268].

The FCM-based scenario building approach is a very new method proposed in the year 2011; thus, it has not been applied to a variety of fields. The limited use of this method may be considered as a limitation. However, the researcher has conducted a pilot study of this approach and published the research findings in *International Journal of Energy Sector Management* [11]. The research framework was also presented at *Portland International Conference for Management of Engineering and Technology (PICMET)*, 2011 [7]. The participants in the conference discussed and appreciated this research framework.

2.3.3 Benefits of FCM-based Scenario

It can be inferred from Table 2 that there are several critical weaknesses of the prominent quantitative scenario building techniques. However, the FCM-based scenario development approach has the capability to overcome these weaknesses and it offers several benefits. Moreover, FCM-based scenarios are based on the combination of both creative (qualitative) and more structuring (semi-quantitative) approaches and it also allows the stakeholders to play a vital role. Unlike the use of an extrapolation model, in the FCM modeling the researcher excite the FCM matrix and examine how the scenario drivers will change based on the causal relationships between them. This approach develops alternative, plausible, and consistent future scenarios which consist of logically suited premises. Therefore, FCM is a comprehensive technique for developing scenarios and we can conclude that this approach has the ability to overcome the weaknesses of the other quantitative scenario building methods. Following are the major benefits of using FCMs for scenario development [2, 152, 170, 171, 334]:

- This approach can bridge the gap between the qualitative scenario development approaches and quantitative models;
- FCMs are based on causal cognitive maps which is an accepted intuitive method;
- FCMs can overcome the limitations of simple causal cognitive maps such as indeterminacy issues in cognitive maps;

- It incorporates system concept and the mapping process fosters system thinking;
- FCM-based scenarios can combine the benefits of intuitive scenario building methods with a quantitative analysis;
- FCMs represent knowledge in a symbolic manner and behavior of a system can be observed quickly, without the services of an operations research expert or an expensive and proprietary software tool;
- It is relatively easy to use FCMs for representing the structured knowledge and the subsequent inferences can be computed by numeric matrix operation;
- It can be performed in a short amount of time;
- It has a high-level of integration because the causal maps and the resulting FCMs can be easily modified or extended by adding new concepts, causal links, or changing the weights assigned to the causal links;
- The quantitative analysis of causal cognitive maps significantly helps to improve the quality of scenarios. After deciding the plausible combinations of input values for all independent FCM variables, the scenario planner calculates the alternative stable states of the FCM model when it settles down; and
- This approach can be used to analyze both the static and dynamic scenarios evolving with time.

Scenario planning is among the most frequently used method in the strategic foresight studies [18, 54, 190, 268, 286, 343]. Coates presents a generalized framework consisting of 11 steps to conduct a strategic foresight study [54]. A comparison is made of the FCM-based scenario development technique with the most prominent intuitive scenario building models presented by Schoemaker and Schwartz against the strategic foresight framework proposed by Coates in Table 3. Schoemaker presented a very comprehensive scenario building model consisting of 10 steps [292-294]. Peter Schwartz introduced the scenario methodology for the first time in “The Art of the Long View” and his model consists of eight steps which is also very popular and often used for building scenarios [36, 167, 298].

Table 3: Comparison of strategic foresight framework with prominent scenario models

S No	**Strategic Foresight framework [54]**	**Schoemaker's scenario building model [292, 294]**	**Schwartz's scenario building model [298]**	**FCM-based scenario building [152]**
1	Describe the system to be studied	**X**	**X**	**X**
2	Identify the key actors and all stakeholders	**X**	**X**	**X**
3	Define key elements of the system			**X**
4	Create a systems diagram			**X**
5	Identify the driving forces		**X**	**X**
6	Identify trends in the driving forces	**X**	**X**	**X**
7	Explore potential for change	**X**	**X**	**X**
8	Develop images of the alternative future	**X**	**X**	**X**
9	Define the desired future			
10	Identify policy, plans and actions			
11	Draw out implications	**X**	**X**	**X**

As shown in Table 3, the FCM-based scenario development technique covers most of the elements of the strategic foresight framework. Thus, it can be inferred that the FCM-based scenarios will significantly augment the strategic foresight process and improve future studies than the scenarios developed by any other scenario building model.

2.3.4 Scenario Selection and Appropriate Number of Scenarios

It is very important to develop an appropriate number of scenarios for a study, but there is no precise response to the question of how many future scenarios are optimal in the scenario planning literature. Various researchers and scenario planners have recommended different number of alternative scenarios ranging from three to six [10]. The scenario planners recognize that there can be innumerable plausible futures. However, it is critical to develop a manageable number of scenarios, in a logical manner, that best captures the dynamics of the situation and effectively communicates the core issues [209]. Durance and Godet recommend to develop scenarios around four to six fundamental hypotheses, otherwise the sheer magnitude of possible combinations will be overwhelming [79]. Some researchers recommend that the ideal set of scenarios consist three or four narratives, which should be structurally or qualitatively different [69]. Bezold suggests that scenarios should be developed by considering the most likely (expectable), challenging (what could go wrong), and visionary (surprisingly successful) possibilities [22]. Wilson states that the number of scenarios should not be fewer than two and more than four [354]. Schwab et al. recommend to develop three scenarios in the scenario building process: trend extrapolation, best-case, and worst-case scenario [297]. Schnaars reviews the scenario planning literature and states that the majority of researchers conclude that developing three scenarios is the best approach [290]. Table 4 provides a comparison of the recommended number of scenarios and scenario selection approach proposed by different researchers in the scenario planning literature.

Table 4: Recommended number of scenarios and scenario selection approaches

Source	Recommended number of scenarios	How do the scenario planners select scenarios?
Harold Becker [19]	3	Select plausible combinations of the key factors
Clement Bezold [22]	3	Develop scenarios for the most likely, challenging, and visionary possibilities
Durance and Godet [79]	4 to 6	Develop the fundamental hypotheses
Cornelis de Kluyver [70]	3	Judgmental translation into the optimistic, pessimistic, and most likely possibilities
Linneman and Klein [186]	3 to 4	Select plausible combinations of the key factors
Christine Ralph MacNulty [191]	3 to 4	Judgmental integration of trends and intuition
Vanston, Frisbie, Lopreato and Boston [336]	3 to 6	To conform the scenario themes
Van der Heijden [333]	2 or more	Identify the driving forces, mega trends, and critical uncertainties
Paul Schoemaker [292]	More than 2	Identify the key decision variables, trends, predetermined elements, and major uncertainties
Peter Schwartz [298, 299]	4	Rank the focal issues and key factors on the basis of their importance and uncertainty in a 2x2 matrix
Ian Wilson [355, 356]	3 to 4	Scenario writing and Cross Impact Analysis
Bradfield et al. (Intuitive Logics Methodology) [30]	2 to 4	Intuition, expert opinion, STEEP analysis, and brainstorming techniques
Bradfield et al. (PMT Methodology) [30]	3 to 6	Quantitative trend analysis and the use of expert judgment
Miles and Keenan [211]	3 to 5	Through scenario workshops and focusing on the key driving forces, likely developments, and desired outcomes

James Dator [68]	4	Develop alternative futures based on four scenario archetypes: Continued growth, Collapse, Steady state, and Transformation
Sohail Inayatullah [142, 143]	3 to 5	Develop scenarios through Causal Layered Analysis
Galtung [94]	4	Identify two major uncertainties and develops scenarios based on these uncertainties

Therefore, based on the literature review presented in Table 4, it can be concluded that development of 3 to 5 future scenarios is considered appropriate by the majority of researchers. Pillkahn discusses the number of scenarios and their implications, presented in Table 5 [249]. Generally, less than three scenarios are considered inappropriate and cannot highlight all the possible alternatives. Similarly, it is difficult to manage a large number of scenarios. Mietzner and Reger state that only a limited number of scenarios can be developed in detail, otherwise the process dissipates [209]. Moreover, in case of generating more than five scenarios, the cost of drafting and evaluating a large number of scenarios will be very high and not justifiable.

Table 5: Evaluation of number of scenarios in a project [249]

Number of Scenarios	**Implications**
1	It will be the most likely scenario, though it is convenient for the strategy formulation, but one scenario will not yield any alternate future or options
2	Two scenarios are usually based on two extreme situations (optimistic verses pessimistic) which are difficult to handle in the context of evaluation
3	Recommended by many researchers, but there is a risk of focusing on the middle (most likely) scenario
4	Possible and offering good cost-benefit ratio
5	Possible
More than 5	Possible, but cost of drafting and evaluating a large number of scenarios will be very high and not justifiable

Some useful tools presented in the scenario planning literature for the selection and development of scenarios are explained with examples. Since the FCM-based scenario development approach is a very new technique; therefore, it is proposed to use some well-established tools to facilitate and augment the FCM-based scenario building process.

Four Quadrants Matrix (Minimal Approach)

This approach is appropriate when the overview of all elements in an environment reveals that only two drivers or factors are enough and can be used to determine the future developments [248, 249, 298]. Scenarios are developed in each quadrant of a grid representing the most important and uncertain scenario drivers [298]. Thus, this approach helps to target the key drivers and organize the scenarios around them. Curry and Schultz state that reducing the focus on two drivers simplify the effort, but requires great care to choose the appropriate factors that are sufficiently different from one another in order to generate a strategic conversation [62].

Figure 3 illustrates an example of generating scenarios for the introduction of a new product. In this example, one driver is demand and the other driver is supply and it is assumed that the both factors can describe the future business landscape. It results in generation of four scenarios represented by each quadrant of the matrix shown in Figure 3.

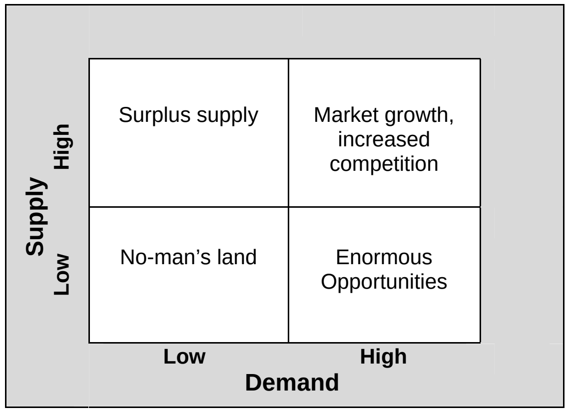

Figure 3: Minimal approach to develop scenarios [249]

Wilson Matrix

The scenario planning literature highlights the importance of identifying and prioritizing the most interesting, uncertain, and important scenario drivers [298]. Wilson matrix is used to evaluate and prioritize the influence/impact and uncertainty of each scenario driver. It ranks all drivers against two dimensions: potential impact and probability that the driver/trend will develop in to a significant issue. Therefore, it determines the degree of uncertainty and their potential impact on the future [249].

An example of the Wilson matrix used in a scenario case study is shown in Figure 4. The most important scenario drivers are assigned the highest priority and placed in the upper right side of the matrix highlighted in blue color. Similarly, the drivers of low priority are placed in the lower right left side of the matrix shown in green color.

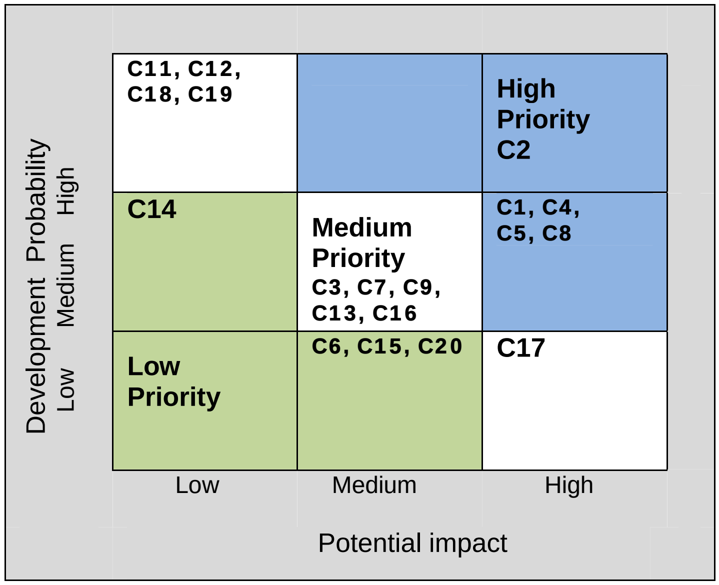

Figure 4: Use of Wilson Matrix to prioritize scenario drivers [7]

Van der Heijden also presents a similar concept in his impact-predictability matrix that resembles the Wilson matrix [333]. He recommends to select scenario elements that are expected to have the significant impact on the business/organization and also exhibit a higher degree of uncertainty [333].

Morphological Analysis

Fritz Zwicky proposed the morphological analysis in the 1960s to analyze the structure of a problem and explore the different possible solutions to a multi-dimensional and non-quantifiable problem [363]. It has been used by a large number of researchers in the field of futures studies, technological forecasting, and development of scenarios [29, 58, 79, 269]. This process is considered an improvement to the scenario selection and refinement activities [78]. Jenkins recommends using the morphological analysis to eliminate the incompatible combinations of the scenario drivers [151]. For FCM-based scenarios, the morphological analysis can be used to generate plausible input vectors which will be subsequently used to generate the scenarios. The following three steps are recommended in the literature to conduct the morphological analysis [249]:

Step 1: Enter the critical scenario drivers (concepts) at the top of each column;

Step 2: Identify the number of conceivable development variations (at least two) of each scenario driver; and

Step 3: Combine the development variations into plausible strands.

Figure 5 highlights an example of the morphological analysis for generating three input vectors. This process helps to ensure that there is no contradiction in these combinations shown in green, red, and purple color. It is a useful tool and helps to visually analyze the combinations of conceivable development variations and ensure plausibility.

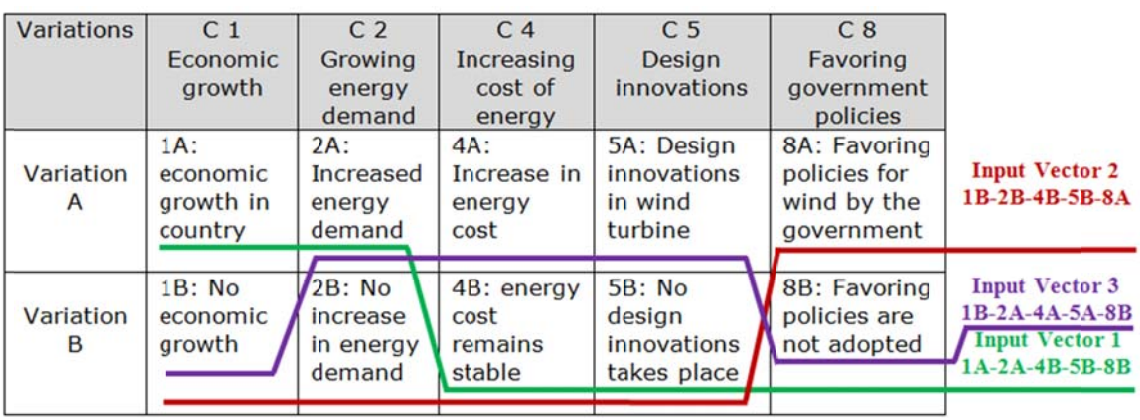

Figure 5: Morphological analysis to generate input vectors [7]

2.3.5 Scenario Validation

In the scenario planning literature several researchers and scenario planners have identified the scenario validation criteria. Chermack et al. highlight the importance of the scenario validation [50]. Wilson suggests the following scenario selection criteria [354]:

- Plausibility: The selected scenarios have to be capable of happening;
- Consistency: The combination of logics in a scenario has to ensure that there is no built-in internal inconsistency and contradiction;
- Utility/Relevance: Each scenario should contribute specific insights into the future that help to make the decisions;
- Challenge/Novelty: The scenarios should challenge the organization's conventional wisdom about the future; and
- Differentiation: They should be structurally different and not simple variations on the same theme.

Schoemaker highlights the importance of consistency of the scenario outcome [293]. He further explains that the scenario developer should ensure that the trends are compatible within the chosen time frame and the scenario outcome should be plausible (all events presented in the scenario outcome can indeed exist together without a contradiction) [293]. Schoemaker emphasizes the importance of consistency and plausibility in the scenario building activities [292].

Similarly, van der Heijden presents the following criteria for scenario validation in his seminal work [333]:

- At least two scenarios are needed to reflect uncertainity;
- Each scenario must be plausible;
- Scenarios must be internally consistent;
- Each scenario must be relevant to the client's concerns; and
- Scenarios must produce a new and original perspective on the issues.

Durance and Godet argue that scenarios should meet five conditions: pertinence, coherency, likelihood, importance, and transparency in order to be credible and useful [79]. They further state that the transparency is an important condition and without it the intended audience will not consider the scenarios [79]. Alcamo and Henrichs also propose to evaluate the scenarios on the basis of plausibility, consistency, creativity, and relevance [5].

Bradfield et al. emphasize that regardless of the scenario development methodology; the coherence, plausibility, internal consistency, and logical underpinning are the common baseline criteria for scenarios validation [30]. Burt describes that a scenario should has a description of the plausible future and internally consistent account of how the future world unfolds [36]. de Brabandere and Alan Iny argue that good scenarios must be relevant to the decisions to be taken, coherent, plausible, convincing, transparent, easy to recount, and illustrate [69]. Foster states that ensuring consistency is the cardinal rule for scenario planning [92]. Porter et al. also highlight the importance of the internal consistency, plausibility, and quality of information used for scenario development to ensure scenario validation [253]. Table 6 provides a summary of the scenarios validation criteria from the literature.

Table 6: Summary of scenario validation criteria

Source	Scenario validation criteria						
	Plausibility	Consistency/ Coherence	Creativity/ Novelty	Relevance/ Pertinence	Importance	Transparency	Completeness/ Correctness
Alcamo and Henrichs [5]	X	X	X	X			
Van der Heijden [333]	X	X	X	X			
Durance and Godet [79]		X	X	X	X	X	
Bradfield et al. [30]	X	X		X			
Porter et al. [253]	X	X					X
Intuitive Logics Methodology [30]	X	X	X	X			X
La prospective Methodology [30]	X	X					X
George Burt [36]	X	X					
de Brabandere and Alan [69]	X	X	X	X		X	
Paul Schoemaker [292, 293]	X	X					
Peter Schwartz [50, 298]	X	X					X
Gausemeier et al. [96]	X	X					
Peterson et al. [237]	X	X					
Ian Wilson [354]	X	X	X	X			
Vanston, Frisbie, Lopreato and Boston [336]	X	X		X			
Kosow and Gaßner [168]	X	X				X	X

A summary of the scenario validation criteria presented in Table 6 highlights that the consistency, choerence, and plausibility are the most important criteria for scenario validation. Creativity, relevance, and correctness of the information presented in a scenario are also quite important. However, it can be conclude that the consistency and plausibility are the decisive conditions for assessing validity of scenarios. Moreover, the use of some well-established tools presented in the scenario planning literature also helps to ensure validation. In this research, the Wilson matrix is used to evaluate and prioritize the scenario drivers and morphological analysis is used to develop input vectors and access their plausibility.

In future research studies like scenario planning, the issue of scientific validation has always been problematic [260]. Despite the utilization of sophisticated tools and advanced simulation techniques, scenario development is still considered a highly subjective art [200]. The futures research is considered more an art than science, and good futurists rely more upon their skills and experience to ensure validation [209]. Vanston et al. states that experts should be asked to review the scenarios in order to ensure consistency, clarity, and completeness of scenarios [336]. Therefore, scenario validation is a very subjective process and it is based upon the gut feel and supposition of the experts and scenario planner. However, it is important to consider the scenario validation criteria given in Table 6 for building future scenarios.

For FCM-based scenarios, the scenario developer can ensure validity by following the standard modeling practices, cross checking with the experts, and proper translation of the experts' knowledge. The specific steps taken to ensure validity of FCM-based scenarios are explained in Section 5.3.1.

2.4 Technology Roadmaps

Technology roadmap is a practical tool used for strategic and technology planning and it is defined as "*A future based strategic planning device that outlines the goals, barriers, strategies necessary for achieving a given vision of technological advancement and market penetrations*" [357]. Technology roadmaps are extensively used in many diverse fields at the product, technology, organization, industry, and national levels. Roadmap is a high-level planning tool used to support the development and implementation of strategy and action plans, and it is also used for communication of the plan [239]. Roadmaps explore challenges and opportunities associated with the deployment of a technology or introduction of new products [174]. Roadmaps define strategic objectives, establish both long-term and short-term goals, prioritize various action items, and estimate resources requirement [31, 246]. Moreover, detailed action plans are elaborated for achieving the targets and implementing the desired future in a very systematic way. This tool is also very popular among the technologists to develop roadmap of a particular technology and roadmap acts as a focal point for the subsequent R&D efforts [173]. An increasing number of articles published on technology roadmaps indicates the growing popularity of this tool among the researchers from academia, industry, and government [8].

Roadmaps portray future market directions, technological developments, and help to make strategic decisions. Generally, roadmaps are used to answer three fundamental questions: (a) Where are we going? i.e. what are our vision, mission, objectives, goals, and targets; (b) Where are we now? i.e. present state of technology, products, markets; and (c) How can we get there? i.e. policy measures, R&D programs, action items, long-term and short-term strategies [238, 243, 246, 256].

TRM provides a framework to link the business and product plans directly to a technology by establishing linkages between the technological and commercial functions [31, 174, 224, 238]. Thus, TRM concepts integrate technology developments and business planning in order to achieve the overall business objectives. Roadmaps can facilitate the decisions of resource allocation and ensure better investment decisions in the right technologies over the lifecycle of products and businesses [238, 246, 256, 358]. Roadmaps also assist in filtering alternate technological options and as a result of this process, decision makers can focus on the promising technologies [174].

Technology roadmaps portray a concise and high-level integrated view of the future course of action. Usually roadmaps use a graphical approach that allows the managers and decision makers to visualize the complete technology and market status, key milestones, and action items on a sheet of paper [238, 242, 245, 246]. The graphical roadmaps consist of a chart having information of different functions and perspectives against an agreed timeline. A roadmap also visually highlights the linkages among markets, products, technologies, policies, resources and infrastructure; and identifies the gaps, opportunities, barriers, potential problems, and action items [238, 256]. Figure 6 highlights a generic multi-layered roadmap. There are several benefits due to graphical aspects of a roadmap including ease of understanding and ability to compress extensive and complex information into a small space [244, 246]. Therefore, roadmap is a very versatile tool and it can encompass a very broad scope of issues.

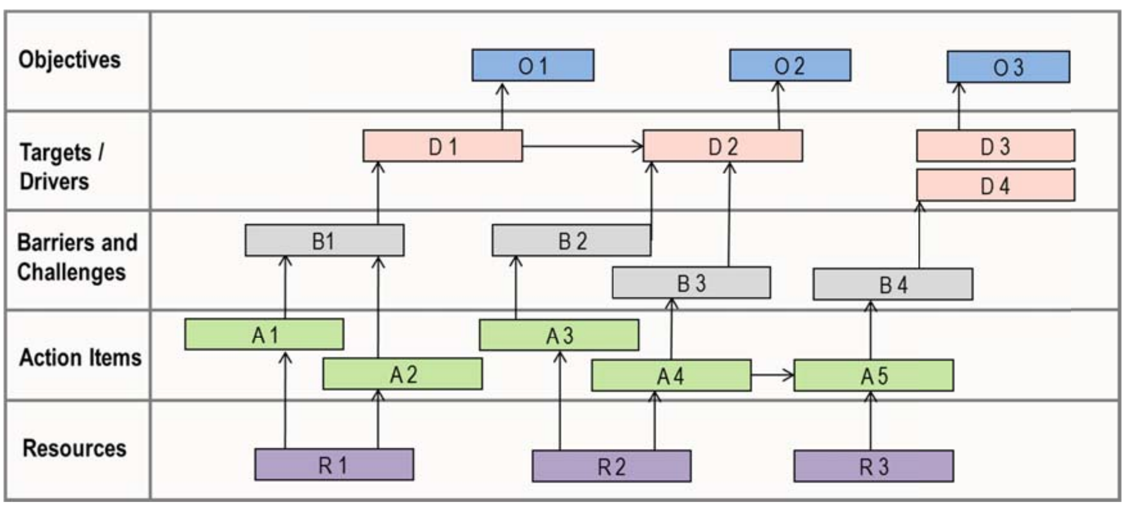

Figure 6: Generic multi-layered graphical roadmap

Roadmaps may be developed by aiming at the customer requirements (market pull approach) or trying to exploit the technological innovations which may result in new business opportunities (technology push approach). The development of a good and effective roadmap requires simultaneous consideration of market pull and technology push, and it is required to carefully balance the both aspects [120, 238, 246]. Most of the successful roadmapping efforts integrate both technology push and market pull perspectives [224]. Garcia et al. defined technology roadmapping as a needs-driven technology planning process which helps to identify, select, and develop technology alternatives for meeting the product needs [95].

2.4.1 TRM Process

There are multiple methods and approaches published in the literature for developing a technology roadmap and it has been recommended to use an appropriate methodology depending upon the overall goal and objective of the roadmap [31, 174, 180, 240]. Research based on an analysis of 80 different roadmapping exercises concluded that there are several good practices to implement TRM and it is not possible to declare one single best method or approach [71]. Moreover, different perspectives can be used to develop a technology roadmap [173]. However, most of the TRM literature emphasize that the roadmapping process should start by identifying the stakeholder (within a company/corporation in case of organizational roadmap or from the entire industry or sector in case of multi-organizational industry roadmap), bringing them together in the roadmapping workshops to share their ideas for the future, and defining the scope of the roadmap [238, 242, 243, 246, 357, 358]. Therefore, roadmaps provide a useful means for integrating multiple perspectives for strategic planning and innovation processes. Harmon et al. highlighted the importance multi-perspective approach for evaluation, assessment, and forecasting of promising technologies to address nergy issues [123].

The TRM process also results in building consensus across the company or entire industry/sector by bringing together all the key stakeholders and develops a vision of the future. The TRM process significantly enhances the communication within the company or industry which is a valuable benefit [99]. It is also recommended that the team members responsible for developing a roadmap should have an overview of the concepts and techniques of the roadmapping process. Generally, a facilitator having good knowledge of the TRM process manages the entire process and keeps the participants focused. Bray and Garcia presented the following three major phases in the technology roadmapping process shown in Table 7 [31]:

Table 7: Three phases in the TRM process [31]

Roadmap Phase	Activity in each Roadmap Phase
• Phases 1 Preliminary Activity	• Define the scope and boundaries for the technology roadmap • Satisfy essential conditions • Provide leadership/sponsorship
• Phase 2 Tech Roadmap development	• Identify the “product” that will be the focus of the roadmap • Identify the critical system requirements and their targets • Specify the major technology areas • Specify the technology drivers and their targets • Identify technology alternatives and their time lines • Recommend the technology alternatives that should be pursued • Create the technology roadmap report
• Phase 3 Follow-up activity	• Critique and validate the roadmap • Develop an implementation plan

Industry Canada also presented the guidelines for the development and evaluation of industry roadmaps after developing 26 industry roadmaps [144, 145]. Three phases of TRM are described in the guidelines with detailed recommendations for the role of government and industry. It has been recommended that government should facilitate the development of industry roadmaps and provide necessary support throughout the TRM process [145]. It is also important to monitor participation of the government and industry in the TRM Process and analyze the results of a roadmap [144].

2.4.2 Application of Technology Roadmaps

Technology roadmaps are used for the business strategy development, policy formulation, product and technology planning, strategy planning, understanding technology trends, keeping track of product and technology breakthroughs, and prioritization of R&D and product development projects. Technology roadmaps are also used for enhancing communication and information sharing within a company or entire industry, defining problems and needs, identifying barriers and hindrances, investigating technology and market gaps, establishing future vision and strategy, deciding short and long-term action items, assessing impacts of new technologies and market development, and helping the mangers for decision making, resource allocation, program / policy support, and evaluation [31, 65, 174, 238, 241, 246, 358]. Therefore, by identifying the gaps in the technology planning and market opportunities, companies can take better strategic decisions and accordingly plan resources allocation.

A technology roadmap also helps the R&D managers and policy makers to notice and track global trends in the research of promising, emerging, and disruptive technologies that have better potential in the future. After developing a technology roadmap, all stakeholders have a better understanding of the current market and technology status, vision, goals, objectives, and future plans. Kostoff et al. elaborated that roadmaps provide a comprehensive overview of the future technological landscape with an agreed view of vision to aid the decision making [174]. Therefore, technology roadmaps provide a vital information to the decision makers at different levels to make better strategic decisions [95].

Technology roadmaps also provide an opportunity for discussion among the researchers and business-oriented people from the academia, industry, and government to find out the reasonable ways for technology development [93]. Another reason of increase in the use of the roadmapping method is due to the fact that it can be integrated with other management techniques such as the Delphi method, scenario planning, balanced scorecards, SWOT (strengths, weaknesses, opportunities, and threats) analysis, quality function deployment (QFD), innovation matrix, technology Intelligence techniques, bibliometrics analysis, citation network analysis, patent analysis, and product development stage gates [120, 159, 161, 173, 176, 181, 242, 246]. These tools help to better assess the technology landscape and market situation.

2.4.3 TRM in Energy Sector

Technology roadmaps are extensively used in the renewable energy sector [8]. Increasing the share of renewable energy resources in the national energy mix is a multiple facets problem and a roadmap is considered an appropriate tool to address this complex issue. Research also indicates that roadmaps are critical when technology decisions are not straight forward [95]. In the energy sector, the roadmaps are generally developed based on the needs and during the roadmapping process, the needs are linked with the markets, industry, products, technologies, capabilities, resources, infrastructure, constraints, limitations, strategies, and policies [8].

In the energy sector, roadmaps can be grouped into the national, industry/sector, and organizational level roadmaps [8]. The national level roadmaps are developed to establish the national energy vision, goals, and targets, provide guidelines to the policymakers, decision makers, governmental organizations, research laboratories, and industry of the entire country or region. In the national level roadmaps, the important national issues related to the energy sector such as energy security, future energy dependence, policy and regularity requirements, and environment protection are discussed. These roadmaps usually present the high-level planning for developing or acquiring the required technologies and provide a framework for public-private collaboration.

The industry/sector level roadmaps represent the collective knowledge of the entire industry comprising of multiple companies, government departments, research laboratories, and universities [8]. These roadmaps are intended to communicate to a broad audience with varying levels of knowledge about the issue. The sector level roadmaps are also used for policy debate. These roadmaps establish the vision of an industry, provide detailed guidelines for the R&D future of that technology, and assess the political and economic issues that can impact the industry in the long run. The sector level roadmaps identify the common needs, help to focus on the critical technical issues, and facilitate collaboration for developing the required key technologies. These roadmaps also consider the technical, political, and market constraints and future uncertainty.

The sector level roadmaps also present the long-term competitive position of the industry and technology. The key technical and commercial issues and barriers are analyzed with a detailed root cause analysis. Subsequently, the issues are translated into the action items with an agreed timeline and responsibility. These roadmaps are also used for lobbying lawmakers in order to make favorable policies. In renewable energy sector, the industry roadmaps are generally emerging technology roadmaps which are different from traditional product-technology roadmaps. The emerging technology roadmaps focus more on forecasting the development, commercialization, and deployment of a new technology [347]. Generally, the development of an emerging technology is very expensive or risky for one company due to the associated technical and commercial risks. Thus, the sector level roadmaps facilitate and foster cooperation and collaboration for joint technology development. Partnerships and collaboration also accelerate the pace of technology innovations and reduce the associated risks.

The comparison of the national and sector level roadmaps reveals that there are some similarities and differences. These roadmaps are generally developed for a longer time horizon, create consensus among all major stakeholders, promote collaboration, and recommend policy measures. The major differences between the national level and sector level roadmaps are:

Table 8: Major differences between national and industry roadmaps

Differences	National Roadmaps	Industry Roadmaps
Roadmap Drivers	Energy security, high energy cost, global warming, environmental degradation, and enhancing national competitiveness are the main drivers for national roadmaps	Increasing energy cost, changing governmental policies, new business opportunities, desire to exploit new technologies and available resources are the main drivers for industry roadmaps
Strategies / Action Plans	Strategies are mentioned at a broad level	Detailed action plans are formulated and action items are identified
Barriers	Technical and commercial barriers are briefly mentioned	Detailed technical and market analysis is performed and key challenges and barriers are identified
Targets	Overall targets for energy generation from various sources / technologies are established	Detailed technology performance improvement targets and technology cost reduction milestones are established

The organizational level roadmaps are mainly used for the future technology planning and making appropriate organizational strategy to achieve the overall business goals. Companies use roadmaps to analyze alternatives, evaluate and prioritize the R&D projects, facilitate the technology investment decisions, comply with the policy regulations, and align the technology investments with the market and product needs. As a result, companies formulate their technology strategy in accordance with the organizational objectives.

2.4.4 Benefits of Combining Scenarios and Roadmaps

Literature highlights that both scenario planning and technology roadmapping have some strengths and weaknesses, which make it more desirable to integrate these two methods. Various ways have been devised to overcome the disadvantages and shortcomings of these individual methods; however, the multi method approach that uses both in a study is considered more appropriate [18, 286, 287]. Schoen et al. recommend to combine explorative and normative elements in a foresight project [295]. Mietzner and Reger emphasize that scenario building technique may improve if it is combined with another future research method such as the roadmapping or the Delphi method or both [209]. Strauss and Radnor emphasize that the combined use of scenario planning with technology roadmaps can enhance the flexibility and vision of the roadmap, capture and convey the full context of decisions, and enable anticipation of a broader range of possible changes [319]. A comparison of advantages and disadvantages of scenarios and roadmaps is presented in Table 9. It indicates that using both scenarios and roadmaps is very beneficial because both methods are complementary; disadvantages of roadmaps can be addressed by advantages of scenarios and vice-versa [286].

Table 9: Comparison of scenarios and roadmaps [286].

Scenarios	Roadmaps
Advantage: Scenarios can be exploratory and/or normative to explore alternative and desirable future	Disadvantage: Roadmaps are usually normative and target oriented, and focus merely on the desirable future
Advantage: Encourage open and creative thinking	Disadvantage: Suggest linear and isolated thinking
Advantage: Highly participative and interactive	Disadvantage: Sometimes difficult to communicate with non-participants
Disadvantage: Describe a set of future circumstances, but do not give a pathway into the future	Advantage: Connect the future with the present and propose short to long-term policies and actions
Disadvantage: It takes longer to understand scenarios	Advantage: Provide concise information in one single figure
Disadvantage: More open ended and may lead to many interpretations	Advantage: More precise and clear in terms of actions and strategies

A technology roadmap is generally focused on a single future with a complete action plan. The use of scenario planning in a project can introduce thinking and planning for multiple futures and strategic options. Thus, both approaches complement each other and scenarios enhance the roadmapping process by focusing on alternative futures. Pillkahn states that drafting of scenarios gives a sketch of the future and it is important to incorporate that into the roadmap [249]. Therefore, this process brings more new knowledge to the existing roadmap by identifying multiple alternatives of the future state of technologies, needs, policies and environment. Some benefits of integrating the scenario planning and the roadmapping process are summarized below [286, 287, 319]:

- Setting visions for roadmaps by considering alternative futures;
- Portraying alternative pathways for roadmaps;
- Adding an exploratory feature to roadmaps; and
- Increasing robustness of roadmaps against all scenarios.

The combined use of scenarios and roadmaps will identify multiple alternatives and strategic options, cater for the future needs and uncertainties, and facilitate development of responsive and robust action plans. Furthermore, the combined use of multiple techniques can offer a significantly clearer and richer insight due to the analysis from the multiple perspectives [66, 286]. In this process, the stakeholders are encouraged to focus on the solutions likely to meet multiple scenarios. Thus, the use of scenarios make people conscious of the future and subsequently based on the developed scenarios, the decision makers plan their future course of action and develop roadmaps.

2.5 Expert Judgment

Expert judgment is commonly used to develop scenarios and technology roadmaps. Expert judgment is the data given by an expert in response to a question or problem. Judgment is defined as an inferential cognitive process by which an individual draws conclusions about unknown quantities or qualities on the basis of the available information [271]. Meyer and Booker describe that expert judgment consists of information and data obtained from the qualified individuals that can be used to solve a problem or make decisions in various fields and domains [207]. Expert judgement is also defined as an expression of opinion, based on knowledge and experience, that the experts make in responding to problems [165]. In the literature, expert judgment is also called expert opinion, subjective judgment, expert forecast, best estimate, and educated guess. Expert judgment is often obtained and considered a very reliable option available when faced with an uncertain future and having a lack of historical data [79, 207]. Generally, decision making in these situations with a high degree of uncertainty about a future environment give rise to two specific needs [30]:

- The need for a methodology to reliably capture the opinions of a large and diverse group of experts; and
- The need to develop models of future environments, which would permit various policy alternatives and their consequences to be investigated.

The comparison of the various expert judgement methods reveals a set of generic phases/steps, which are used to a greater or lesser extent in each method depending on its objectives. Following are the generic phases of an expert judgement method [310]:

- Definition of the elicitation objectives;
- Identification and selection of the experts;
- Preparation of the questionnaires, instruments, and training materials;
- Process of obtaining the expert opinion;
- Analysis and aggregation of the expert judgments; and
- Synthesis.

There are various means to obtain expert judgment, and according to Börjeson et al. usually the Delphi method, workshops, and surveys are conducted to obtain expert opinion for the development of scenarios and roadmaps [29]. Scenarios and technology roadmaps are always developed based upon the expert judgment obtained through the workshops, expert panels, Delphi studies and surveys [8]. Therefore, the use of expert panels is a widely used approach for technology roadmapping and it has also been used in several PhD dissertations [98, 101].

Cooke provides a brief historical overview of expert judgement methods and argues that the systematic use of expert judgement for decision making was developed at the RAND Corporation in the United States after World War II [56]. The RAND Corporation developed the first two methods using expert judgement that were the Delphi method and Scenario Analysis.

2.5.1 The Delphi Method

The Delphi method was developed at the RAND Corporation in the 1950s as a spin-off of an Air Force sponsored research project, “Project Delphi” [56, 275]. The Delphi method is a popular technique for forecasting and an aid in the decision making process based on the experts’ opinions. The need to elicit and synthesize expert opinion inspired the development of the Delphi technique [261]. Linstone and Turoff define Delphi “*as a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem*” [188]. It is a systematic and interactive method relying heavily on the expert panels [199]. It is based upon the principle that the judgments and opinions obtained from a structured group of experts are better and more accurate than those obtained from an individual or an unstructured group [275, 276]. This method has gained popularity among the research managers, policy analysts, and corporate planners and has been used extensively in various fields. The Delphi technique is applied to technology forecasting and many types of policy analysis in various fields and domains [199].

The Delphi method is based on a structured process for collecting and distilling knowledge from an expert panel through questionnaires combined with controlled opinion feedback. A series of sequential questionnaires or rounds is conducted with controlled feedback in order to gain the consensus of opinion from an expert panel [188]. The feedback and opinion of the group members is summarized, combined, and given back to the experts after the first Delphi round and they are again asked the same questions [188, 199]. This process is repeated until a general consensus in the outcome is obtained or the results are stabilized. Research on the number of Delphi rounds indicates that most changes occur in the transition from the first to the second round when the expert panel members change their judgment, and generally four rounds are sufficient to reach a consensus [86]. This systematic control ensures objectivity to the outcome of the Delphi study and provides a sharing of responsibility, which releases the participants from group inhibition [185].

The Delphi Method also reduces the impact of the powerful members in a group by establishing anonymous group communication and avoids imposition of their point of views on the other group members [188]. Torrance states that the power or status of the group members influences the group decisions and less powerful members demonstrate an unwillingness to disagree with the most powerful member, even if they have the correct solution, so this may adversely affect the quality of the decisions [328]. Moreover, in highly structured cultures individuals may refrain from expressing their opinions freely, so Delphi can be used as a useful approach to overcome these cultural barriers [101]. The Delphi method is also used as a useful communication tool to generate a debate [255]. The following three characteristics of the Delphi method distinguish it from the conventional face-to-face interaction [199, 276, 360]:

- **Anonymity**

  The experts give their answers to the questions in an independent and anonymous way without any undue social pressures. The group members do not know who else is in the group. This gives an opportunity to the experts to freely express their opinion on the basis of merit alone.

- **Iteration with controlled feedback**

  The process is reiterated until a degree of consensus is reached or results are stabilized. Iterations allow the experts to change their opinions. The controlled feedback takes place after every Delphi round, during which each group member is informed of the opinions of the other group members. Thus, the participants are encouraged to review their answers in light of the combined judgment of the group.

- **Statistical group response**

  The set of responses (combined group judgment) is then sent back to the experts and they are asked if they wish to revise their initial feedback. This includes statistical information of the group response such as the mean or median and the extent of spread of the members' opinions.

In the first Delphi round, the expert panel members are asked questions related to the subject matter under consideration. The moderator collects their judgments and provides feedback of the first round to the experts. For the second round, the experts are asked to either adjust their estimates or provide a justification of their rationale if they differ from the majority judgment. Due to the controlled feedback from the previous rounds, sometimes the experts tend to achieve a consensus of opinion [149]. Therefore, this process is iterated until a consensus is generated or the results are stabilized between two rounds. Linstone and Turoff emphasize that the number of rounds should be based on when the stability in the responses is attained, not when the consensus is achieved [189]. Chi-squared test has been proposed in the literature to determine the stability of the results from an expert panel [43, 67].

Advantages of the Delphi Method

The Delphi method helps to achieve the consensus in a given area of uncertainty or lack of empirical evidence [72, 223]. The participants of a Delphi study bring their extensive knowledge and vast experience to the decision making process [223]. It is very useful in situations where individual judgments must be tapped and combined to overcome an incomplete state of knowledge [72]. The controlled feedback between the Delphi rounds stimulate new ideas and it is also motivating for the participants [247].

The Delphi process facilitates the experts to participate in a group communication process asynchronously at times and places convenient to them, which is another key benefit [189]. Absence of an obligation to meet in person improves the feasibility of the Delphi process, lowers its cost, and allows participation from diverse geographic locations [118].

Rowe et al. suggest that the structured approach and participant anonymity offered by the Delphi approach leads to a process gain [276]. Whereas, other methods of obtaining expert judgment or consensus like committees are considered to be prone to the biasing effects of personality traits, seniority, status, and domination by the powerful individuals [149, 223]. In the face-to-face interactive groups, there is a tendency among the low-status members to “go along” with the opinions of the high-status members despite of contrary feelings [328]. In contrast, the Delphi method can overcome these negative effects and in a Delphi study the consensus reflects a normative rather than an informational influence or tendency to follow the leader [223].

Brockhoff, Riggs, Larreche and Moinpour, and Bolger et al. state that a Delphi procedure produces superior predictions and accurate forecasts than a normal interacting group or a face-to-face committee meeting [28, 33, 178, 264]. Parente and Anderson-Parente evaluate the long-term accuracy of the Delphic approach and find that it correctly predicts the occurrence of the future events [232]. Rowe and Wright also reveal that the Delphi method outperforms other structured group procedures by providing more accurate assessments or judgments [275]. Woudenberg arranges the judgment methods in the order of increasing accuracy based on the literature review and expectations, as shown in Figure 7 and state that the Delphi is the most accurate method among various expert judgment methods [360].

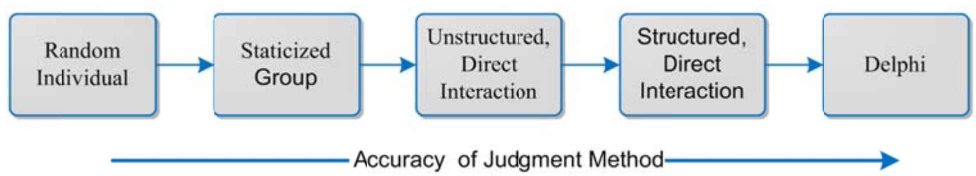

Figure 7: Judgment methods in order of increasing accuracy [360]

The Delphi technique is very useful in situations when no adequate models exists to develop a statistical prediction and Coates sates that Delphi is the last resort in these situations [53].

Disadvantages of the Delphi method

It takes long time to conduct a Delphi study due to nature of the process [149] and extensive time commitment is required.

Output of a Delphi process reflects the best opinion of the experts [247], so it is critical to choose suitable experts. Sometimes selection of an expert panel becomes very problematic.

It is possible that in pursuing the consensus among the experts, the process may lead to diminish some of the best opinion and the study may only generate a set of bland statements representing the lowest common denominator [278].

It is also argued that anonymity in a Delphi study may lead to a lack of accountability of views expressed and encourage hasty decisions [278]. However, the sequential rounds may positively discourage such action.

Sackman points out that it is difficult to determine reliability and scientific validation of the findings [278]. It is due to the fact that the Delphi studies are based upon intuitive judgments, collection of half formed ideas from the experts, therefore, one cannot judge it on the same basis as a concrete measurement [247].

Application

The initial application of the Delphi method was in the area of national defense and after that it has been extensively used in a wide variety of applications [188]. Martino states that it remains one of the most popular methods for technology forecasting [200]. The Delphi method has been successfully used in many applications and it is considered as a promising technique in future roadmapping [32, 98] and scenario planning activities [24, 63, 136]. The literature highlights that it has been extensively used for the policy analysis, healthcare, education, finance, management, marketing, human resources, manufacturing, information systems, transportation, engineering, national foresight planning, urban planning, energy foresight, environment, budget allocations, service planning, analysis of professional characteristics and competencies, and curriculum development [20, 32, 63, 122, 188, 255, 287]. The Delphi method has also been extensively used as a useful tool for solving the problems in the energy sector for creating energy roadmaps and conducting energy foresight projects [63, 146, 147, 234, 266, 274, 304, 321, 332].

At the national level, the Delphi method has been extensively used in several countries. There are examples of national level studies in Germany [26], Japan [32, 60], France [274], Thailand [102], India [44], Poland [63], Finland [266], Korea [308], and Austria [327]. In this research, the Delphi method was used to obtain judgment and opinion from the experts for the development of a national level wind energy roadmap. The experts were asked to rank and prioritize the roadmap barriers and challenges against different scenarios in the roadmap.

2.5.2 Other Expert Judgment Methods

There are several other methods based on eliciting the expert knowledge and judgment through a group of experts. Some methods used in the technology foresight studies and based on the use of the expert knowledge are mentioned below:

Nominal Group Technique (NGT)

Delbecq and Van deVen developed the Nominal Group Technique (NGT) in the year 1968 and it is a structured decision making method for working towards consensus [72]. In this method every participant of the expert panel gives their views and ideas for the solution and these ideas are prioritized using a ranking process [72, 212]. Its major strength is that opinions of all experts are taken into account, so every team member has an equal voice in sharing their ideas. During this ranking process, the duplicate solutions are eliminated and every participant ranks the ideas as 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, and so on. Thus, the output of NGT is a prioritized list of ideas generated by a group of experts. It is critical to carefully select the members of an expert panel, because the value of the NGT is based on their knowledge and expertise.

This technique has gained considerable recognition and it has been applied in the healthcare, social services, education, industry, and government organizations [272]. The NGT process consists of the following six steps after defining the problem [72, 272]:

- Brainstorm and generate ideas in writing;
- Round-robin feedback from group members to record each idea in a terse phrase;

- Discussion of each recorded idea for clarification and evaluation;
- Individual voting to prioritize ideas by anonymous rating;
- Brief discussion of the preliminary vote; and
- Final individual voting through rank ordering followed by the group discussion and group decision.

NGT is a useful approach, especially in the following situations [72, 212, 272]:

- When the discussion is dominated by some individuals of the expert panel and it may prohibit participation or creativity of the other members;
- When some members are reluctant to suggest ideas and freely participate due to apprehension of being criticized or any other reason;
- When the group members think better in silence;
- When some group members are new and less experienced than others or there is a difference in their social status such as manager and subordinate staff;
- When the issue is controversial or there is a heated conflict;
- When it is desired to generate a lot of ideas; and
- When it is required to prioritize a few alternatives for further evaluation.

Advantages and Disadvantages of NGT

The major advantage of NGT is that it provides a balanced participation of every member of the expert panel in the process and the final result. The NGT groups perform better than other interacting groups in accuracy, better use of group resources because all members participate, and it results in better decisions [126]. Moreover, NGT is a simple technique and usually it takes less than a day to complete the entire process. It is also less costly than other group methods.

The major disadvantage of NGT is that it is overly mechanical, simplified, and lacks flexibility [285]. It is focused on a single purpose and single topic. Only individual brainstorming is done and cross-fertilization of ideas is constrained [285]. NGT minimizes discussion and does not allow for the full development of ideas; therefore, it is less stimulating group process than the other methods. It is also quite possible that opinions may not converge and consensus is not achieved in the voting process. Due to these shortcomings, it has been recommended to combine NGT with other group techniques in order to overcome its limitations [148].

Focus Groups

The focus groups are generally used for idea generation [125]. In this technique, a group of experts focuses on a topic and they are asked about their views, perceptions, opinions, beliefs, and attitudes towards a product, service, concept, idea or advertisement [125, 220]. The focus questions are asked in an interactive group setting and the experts are free to talk with other group members in an open environment. Generally, the focus groups do not produce an actual technology forecast, but may be useful in generating an insight and list of items that may be used in conjunction with another technique. This method usually requires some group interaction prior to the creation of a list of ideas [212].

Brainstorming

Brainstorming is a popular and widely used tool for doing creative tasks in organizations such as developing products, redesigning business systems, and improving manufacturing processes [322]. Its main objective is to elicit ideas from a group of people [211, 322]. A brainstorming session brings new ideas on how to tackle a particular problem in a freethinking atmosphere and presents a wide range of ideas and solutions. The participants are encouraged to freely articulate their ideas followed by a rigorous discussion in order to stimulate creativity and thinking "out of the box", to let dissident viewpoints enter in the discussion at an early stage [211]. This technique also supports the future studies, but does not produce an actual technology forecast. An effective brainstorming session consists of 7 to 12 participants.

Weighted Sum Method (WSM)

The Weighted Sum Method (WSM) is a commonly used approach for ranking the alternatives, especially in a single dimensional problem [251]. It is a multi-criteria decision making method used for evaluating a number of alternatives against the decision criteria. The best alternative is the one with the maximum score. It is the most commonly used approach in sustainable energy systems [349]. The total value of each alternative is equal to the sum of products. If there are *m* alternatives and *n* criteria, then the importance of each alternative is calculated using the equation number 1 [195, 251, 314]:

$$A_{(WSM)i} = \sum_{j=1}^{n} a_{ij} w_j \quad \text{for} \quad i = 1, 2, 3, \ldots m \qquad (1)$$

Where,

$A_{(WSM)i}$ is the WSM score of the i^{th} alternative,

n is the number of decision criteria,

m is the number of alternatives,

a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and

w_j is the weight of importance of the j^{th} criterion.

2.5.3 Selection of an Appropriate Research Method

It is critical to choose an appropriate and accurate technique for a particular research application [45, 182]. Levary and Han highlight that the selection of a future research method depends on factors such as: stage of a technology development, degree of similarity between the proposed and existing technologies, number of forecasting variables, extent of the data availability, data validity, and technological uncertainty [182]. Chambers et al. highlight that selection of a method also depends on factors like the context of a research, relevance and availability of the historical data, the degree of desirable accuracy, and the time available for making an analysis [45].

Based on an in-depth analysis of nine case studies, Levary and Han conclude that the Delphi method and scenario writing approaches are suitable in circumstances having a very low level of similarity between the proposed technology and existing technologies, a medium number of variables affecting the technology development, less data availability, and low or medium degree of data validity [182]. They further elaborate that in these circumstances, it will be a reasonable choice to use a method based upon obtaining information from an expert panel and employ the Delphi method and/or scenario planning approach [182].

Rowe, Wright and Bolger argue that the Delphi process allows the experts to make a meaningful judgment, particularly in cases where a variety of factors (economic, technical, political, social, environmental etc.) affect the problem under consideration and it gives an opportunity to each expert to derive benefits from the other experts [276]. It is very useful approach, especially when no historical data exists for judgment [276]; and it is difficult to bring experts together due to time or cost constraints [188]. Linstone and Turoff state that sometimes it is necessary to benefit from the subjective judgments on a collective basis, because due to the peculiarity of a problem, it is difficult to address it with a precise analytical technique [188]. Moreover, it is a powerful tool to engage the stakeholders; and it is an appropriate approach in the situations having many stakeholders [97]. Many other researchers have also indicated that the Delphi approach generates accurate and reliable judgment than the other techniques [33, 178, 198, 264].

In the recent years, the scenario planning approach has been used with the Delphi method as an effective hybrid approach to conduct the foresight studies of renewable energy technologies. The field of energy planning is associated with long timescales and high uncertainties [139]. Nowack, Endrikat, and Guenther assess the integration of the Delphi technique into scenario planning as a promising option and conclude that it enhances the quality of a scenario study [226]. There are several examples of Delphi based scenario studies in the literature [13, 23, 90, 108, 116, 330]. Moreover, there are also various examples of using these techniques for the long-term planning of sustainable energy resources [3, 63, 103, 307, 326, 350, 352]. For example, Czaplicka-Kolarz et al. used the scenario planning approach with the Delphi method to create the national vision of the energy sector of Poland and formulated the long-term strategies [63]. Similarly, Rikkonen and Tapio used scenarios with the Delphi approach to develop future prospects of alternative energy utilization in Finland [266] and renewable energy scenarios for Saudi Arabia [3].

Analysis of various tools and approaches used in the national level renewable energy roadmaps during the literature review highlights that the expert panels are very frequently used to develop the roadmaps [8]. The roadmap workshops are conducted to develop various tiers of the roadmap. In this research, the expert panels are used to develop the FCM-based scenarios and technology roadmap. Moreover, the Delphi method is used to prioritize the roadmap barriers. Based on the findings of the Levary and Han, both the scenario planning and the expert judgment methods are considered the appropriate due to the following reasons:

- Presently the energy sector of Pakistan is mostly dependent on the fossil-fuels and the contribution of wind energy in the national energy mix is almost negligible [9]. Wind energy has very low degree of similarity with the conventional energy technologies;
- Wind technology has limited data availability and a high degree of uncertainty because it is a new technology in the national energy sector; and
- There is a medium number of variables affecting wind technological deployment in the country [11].

Also due to the following reasons, it is appropriate to use the expert judgment and Delphi method to support the development of technology roadmaps for this research:

- There are several external factors impacting the deployment of wind energy technology in the country;
- Due to lack of the historical data, problem has to be solved by utilizing expert judgment;

- Being a member of a highly structured culture, individuals (experts) may refrain from freely expressing their opinions;
- Time and cost constrains make the group meeting difficult;
- Diverse expertise is required to solve the problem and members of the expert panels belong to various organizations and sectors; and
- Bandwagon effect and domination by a single person or small group may affect the validity of research.

2.5.4 Formation of Expert Panel and Selection of Experts

It is very important to carefully select members of the expert panel because the quality of the expert judgment is directly based upon their knowledge, capability, and experience. The expert judgment is used to forecast the future, utilizing information derived from the individuals who have extraordinary familiarity with the subject under consideration [212]. An expert is a person who has the background and knowledge in the subject area and considered qualified to answer those questions [207]. Usually questions are posed to the experts when they cannot be answered by any other means. The members of an expert panel should reflect current knowledge and perception as well as be impartial to the research findings [149].

The literature also highlights that well known experts should be selected who are respected among their peers, and the careful selection of the experts increases credibility to a research project [208]. Camerer and Johnson describe that an expert is considered an experienced person having some professional or social credentials and knowing a great deal about their domain [40]. McGraw and Haribson-Briggs state that the domain experience, commitment, patience, persistence, ability to communicate ideas and concepts, introspection of own knowledge, honesty, and willingness to prepare for sessions are the important personal characteristics of the experts [202]. Landeta highlights that selection of suitable experts helps achieving reliability of the study [177] and Rowe, Wright, and Bolger enforce this by stating that the degree of panelist expertise is a key influencing factor on the accuracy of the group judgment [276]. The quality and validity of the elicitation process is further improved when the experts feel that they are knowledgeable and well-informed [155].

In the context of scenario planning, van der Heijden states that the experts are remarkable people who have some knowledge of the related field or industry, and are acute observers of the environment [333]. The members of a scenario expert panel are expected to be fairly knowledgeable of the socio-economic contexts of the region [211]. Schaller highlights the importance of competent experts to ensure quality of a technology roadmap [289]. More qualitative approaches require a strong emphasis on the careful selection of suitable experts [209]. Therefore, the experts should be selected based on their experience and knowledge in the relevant area as well as their ability to provide a fair and objective viewpoint.

Usually the experts with different backgrounds are brought in the expert panels. It is critical to ensure diversity in the expert panel so that the problem under consideration is thoroughly analyzed from many viewpoints [208]. Murphy et al. argue that diversity in an expert panel leads to better performance because it helps consideration of different perspectives and a wider range of alternatives [223]. In support of this argument, Rowe and Wright suggest that diverse background of the members of an expert panel ensure a wide base of knowledge [275] and group situations may inhibit creativity and bring possibility of resolving ambiguous and conflicting issues [276]. The members of a diverse expert panel bring a wide range of direct knowledge and experience to the decision making processes [223]. Linstone and Turoff suggest that diversity of viewpoints helps to generate interest and involvement among the participants of an expert panel [188]. Diversity of experience of the experts is considered as an important asset to the success of a scenario exercise [211]. Delbecq et al. cite that the heterogeneous groups produce the acceptable solutions of higher quality than the homogeneous groups [72]. In addition to the professional qualifications and expertise, the expert panel members should be the creative thinkers, who can bring diverse viewpoints, work well in groups, and freely express their views and opinions [211].

Diverse backgrounds of the expert panel members also help to assure that any bias from any member would have little impact on the overall outcome of the study [101]. Gathering diverse experts in a panel minimizes the influence of a single powerful individual. Ascher state that there is a human tendency to stick with the status-quo and not to look outside of the comfort zone when considering the future and utilization of multiple experts with different viewpoint helps to overcome this human tendency [14]. An empirical study indicates that diversity among the expert panel members can improve the perceived quality of the decision [137]. Thus, diversity among the members of an expert panel plays a vital role and it will lead to better quality of the judgment [14, 208].

It is critical to have the appropriate number of experts in an expert panel. Mitchell state that the expert panel must have at least 8 to 10 members [218]. Whereas, Meyer and Booker recommend to have around 5 to 9 experts in a group [208]. Some researchers suggest that more participants are better because their combined opinion will increase the reliability of the composite judgment [223]. However, if there are many participants in an expert panel, then it will be more difficult to coordinate with them and analyze their feedback. Therefore, it is important to balance the size of the expert panel. Research indicates that a group of 11 to 15 experts is preferred for achieving a high correlation [72, 199, 230]. It has been empirically proved that panel reliability increases with increase in panel size and 11 to 15 is considered an optimum size of an expert panel [199]. Powell emphasizes that success of a Delphi study clearly rests on the combined expertise of the members of the expert panel and highlights the importance of appropriate panel size [255]. The number of experts also depends on the scope of the problem, objective of the study, and available resources and sometimes a larger group may be useful if the study seeks to increase the group support or understanding rather than decision making [72, 208].

Issues related to logistics are also important for the selection of experts such as willingness of an expert to join the panel, willingness to devote their time for the study, and permission from their employer to participate in the research [208]. It is very important that the expert panel members are willing and able to make a useful contribution [188, 255]. Thus, there is a tradeoff between finding the appropriate experts who have the expertise and organizational position; and finding panelists who have sufficient time to participate in the complete study.

The following criteria have been proposed in the literature for the identification and selection of the experts and formation of the expert panels [57, 64, 127, 276]

- Experience in the subject/field under consideration;
- Reputation in the subject/field under consideration;
- Interest and willingness to participate in the study;
- Availability for the project;
- Publications in the field of interest;
- Experts should represent a great diversity within the relevant discipline;
- Familiarity with uncertainty concepts;
- Balanced viewpoint in a group to compensate for individual biases on the outcome;

- Absence of evident conflicts among the expert panel members; and
- Absence of forceful dominators by position and personality.

Meyer and Booker state that the expert panels are frequently criticized because sometimes answers of the experts are skewed and it generally happens if the majority of the experts are selected from one place or one organization [208]. Therefore, it is important to select a balance group of experts from the government, universities, research institutes, regulatory agencies, and various segments of the industry. It will ensure that the members in the expert panel have diverse backgrounds and they cover all segments of an industry.

2.6 Research Gaps

It has been revealed in the literature review that many researchers have highlighted the need of combining scenario planning and technology roadmapping techniques in the future studies [209, 286, 319]. It has been recommended that this combination will enhance the flexibility and vision of a roadmap, capture and convey the full context of decisions, and enable anticipation of a broader range of possible future outcomes [286, 295, 319]. Thus, this combination will significantly improve the usefulness of a technology roadmap. Despite these benefits, the combination of these two techniques is not common and it is not used at the national level for long range energy planning.

The literature review also highlights that there is a need to evaluate a concise mix of methods for the future studies [209]. In this research, the technology roadmap has been developed for the national wind energy sector based on multiple scenarios. Based on the literature review, it has been revealed that both scenario planning and technology roadmapping techniques complement each other and it is an appropriate approach to combine these techniques.

It has been very recently proposed to use FCMs for the development of scenarios. In this approach, the scenarios are developed based on causal cognitive maps. Thus, it is an intuitive scenario methods coupled with quantitative analysis. The literature has identified that there is a weak link between qualitative and quantitative scenarios, which has been cited as a major obstacle towards the development of integrated scenarios [170]. Generally, the scenario based on intuitive logics approach are qualitative in nature [25, 30]. Therefore, the development of FCM-based scenarios is a unique approach that can combine the benefits of both qualitative and quantitative analysis. In this research, FCM-based scenarios have been developed for the first time for the wind energy sector.

The literature review of 135 public-domain sustainable energy roadmaps [8] revealed that generally in these roadmaps, scenarios are created based on a few hypothetical assumptions without much deliberation and logical reasoning. In contrast to this, the FCM-based scenarios are based on detailed FCMs which are based on logical reasoning, causal relationship between various variables (scenario drivers), and developed after combining individual causal maps of several experts.

The research contributions related to the wind energy sector of Pakistan are:

For the first time scenarios and technology roadmaps are developed for the wind energy sector of Pakistan. In spite of the fact that the national power policies emphasize the importance of developing the indigenous renewable energy resources, there has been no roadmap or framework developed for the implementation of such projects. The existing literature related to the renewable energy sector of Pakistan is also limited to identifying potential of the indigenous renewable energy resources and highlighting some generic barriers and challenges. There has been no scenario analysis, technology roadmap, action plan, or strategy proposed in the literature. This research also identifies and highlights the challenges and obstacles towards the deployment of wind energy technology in the country. It contributes towards addressing the country's energy security concerns, achieving the targets of national sustainable development, provisioning of the economic and social benefits to the people, and improving the environmental conditions in the country.

The research has also addressed the deployment and integration challenges associated with the deployment of wind energy projects in a developing country. Wind energy is a variable and uncertain power resource and its deployment on a large scale requires significant changes in the power grid operations.

The research gaps are identified in the literature review of topics related to scenario planning, foresight, technology roadmapping, sustainable energy roadmaps, and literature on the renewable energy sector of Pakistan are summarized in Table 10:

Table 10: Research Gaps

Topic	Research Gaps
Technology Roadmap	Roadmaps primarily focus on the desired future without taking alternative developments into account
Scenario Planning	In the existing scenario planning approaches, there is a weak link between qualitative approaches and quantitative models
Energy Roadmaps	Generally, in the energy roadmaps, scenarios are created based on a few hypothetical assumptions without much deliberation and logical reasoning
Wind Integration	Integration challenges associated with the deployment of wind energy on a large scale are not adequately researched for the developing countries having lower grid reliability
Literature on the renewable energy sector of Pakistan	No roadmap, concrete action plan, framework, or strategy exists in the literature for the implementation of renewable energy projects in the country

3 Research Approach

3.1 Research Objectives and Goals

The aim of this research is to develop a national level wind energy roadmap through scenario planning. Multiple scenarios are developed using a fuzzy cognitive maps (FCM) based approach. This research has extended the technology roadmapping through FCM-based scenarios. Building scenarios with FCM is a very new approach, and it combines the benefits of both qualitative and quantitative analysis. FCM-based scenarios have never been developed for the wind energy sector, however. Scenario planning facilitates development of a responsive and robust roadmap and increases flexibility and vision of a roadmap. In this research, a technology roadmap based on multiple scenarios is developed. This roadmap has been used to establish the long-term and short-term targets, investigate the barriers and challenges associated with the deployment of wind energy technologies, and suggest appropriate action items in order to promote deployment of wind energy projects in the country. The research also explores the challenges associated with integration of wind energy, which is a variable and uncertain power source, to the national grid and proposes action items to achieve this task. The research objectives are grouped into the following two categories:

i. Method development:

   a. Developing multiple plausible scenarios for wind energy deployment using fuzzy cognitive maps (FCM).
   b. Combining the FCM-based scenario planning and technology roadmapping process.

ii. Application of this new method:

   a. Develop a national wind energy roadmap to address the following strategic objectives of Pakistan [110]:
      - Energy security;
      - Economic and social benefits; and
      - Environmental sustainability.
   b. Identify practical insights on the factors supporting and hindering deployment of wind energy projects in the country.
   c. Propose the action items and plans for the deployment of wind energy technology on a large scale and give recommendations to the stakeholders in order to better develop and implement wind energy projects in the country.

Research goals and research questions are summarized in Table 11:

Table 11: Research goals and research questions

Research Goals	Research Questions
Develop a technology roadmap by combining the FCM-based scenario planning and technology roadmapping process	**RQ1**: How can FCM be used to develop plausible scenarios for wind energy?
	RQ2: How to combine the FCM-based scenario planning and the technology roadmapping process?
Develop a national wind energy roadmap to address the following strategic objectives of Pakistan: • energy security • economic and social benefits • environmental sustainability	**RQ3**: What are the factors supporting and hindering deployment of wind energy projects in the country?
	RQ4: How can the wind energy integration challenges be managed by a developing country?
	RQ5: What are the suitable / appropriate action items for implementing wind energy projects in a developing country?

Two major research goals have been established to address the literature gaps. Figure 8 links the literature gaps to the research goals and research questions.

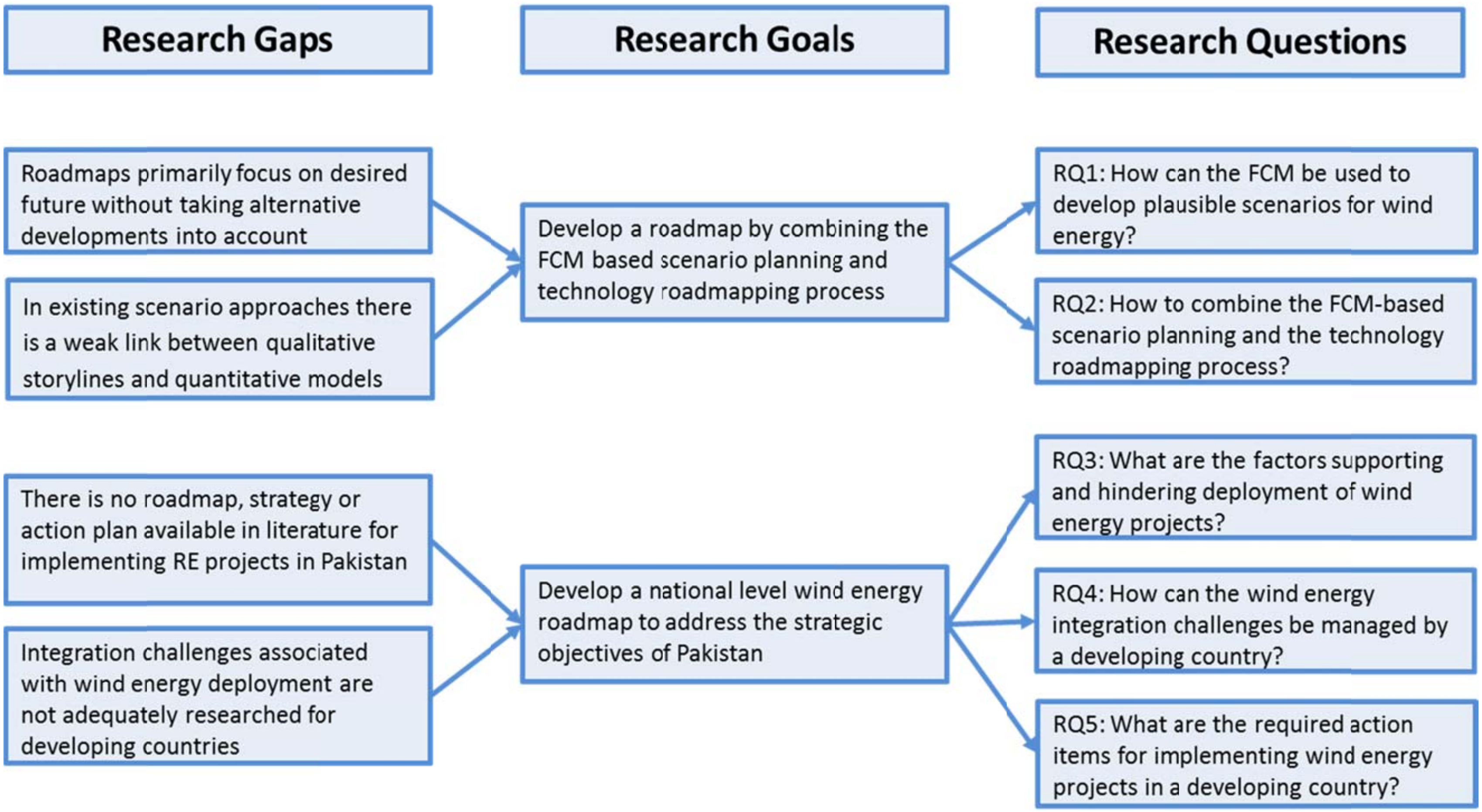

Figure 8: Literature gaps, research goals and research questions

3.2 Research Framework

For the development of wind energy scenarios and technology roadmaps, expert panels were formulated consisting of experts with diverse backgrounds from the public and private sectors. Their multiple and diverse input is integrated into plausible future scenarios and roadmaps. FCMs are developed to capture knowledge from the experts as they express their mental models. Subsequently, the integrated FCM is used to formulate plausible scenarios. Based upon the developed scenarios, a roadmap is developed for each scenario. The high-level overview of the research framework is presented in Figure 9:

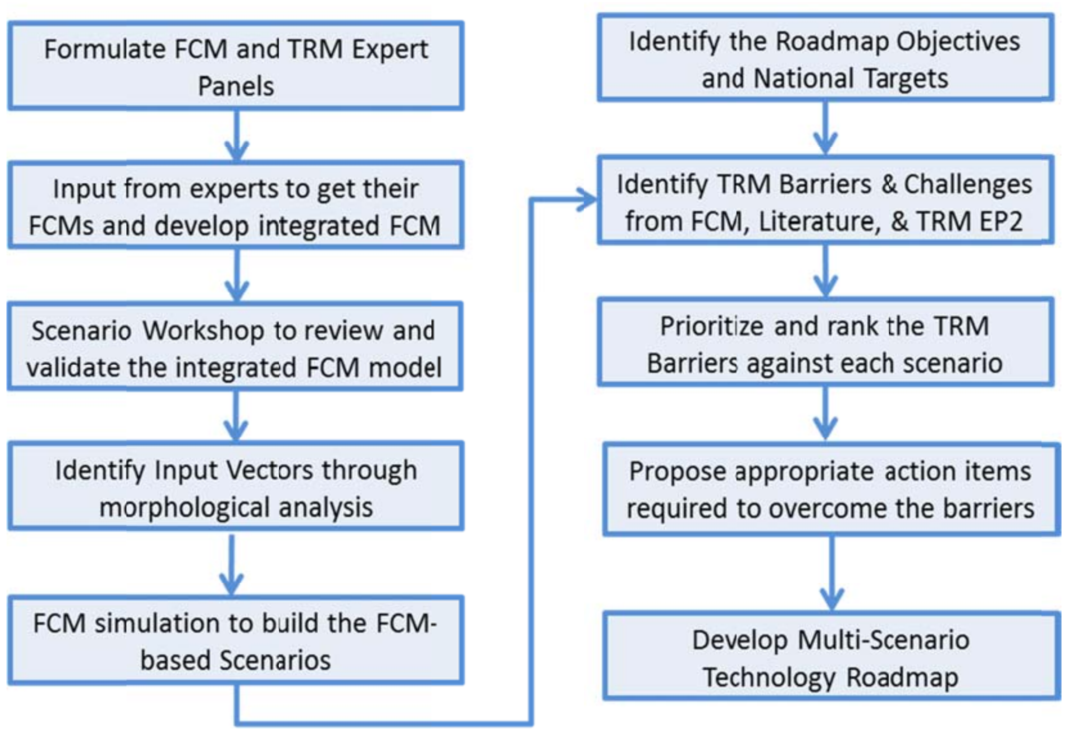

Figure 9: Overview of the research framework

In this research, one FCM and two TRM expert panels were formulated to develop the scenarios and the technology roadmaps. As stated earlier, the quality of information obtained from the expert panel significantly depends upon the knowledge and experience of the participants. Therefore, members of the expert panels were carefully selected for their in-depth knowledge and experience of the relevant fields. Based on their backgrounds and experiences, some experts also served on two or three panels. Members of the expert panels were selected from the government, private sector, utility companies, industry, and academia. The role of each expert panel in the proposed research is described in the next section. Background information of the experts and composition of the expert panels are also explained in the next section.

3.2.1 Expert Panels

Various guidelines and criteria presented in the literature for the selection of the experts were considered in the planning to formulate the expert panels. Identification of the main organizations in relation to the proposed research case is the first step towards selection of the members of the expert panels [101]. That was followed by identification of the important personnel working in these organizations. Review of the literature on the renewable and wind energy sector of Pakistan was also carried out to identify the individuals who have authored papers in peer-reviewed journals on the subject area. For this research, the following government departments, organizations, regulatory bodies, universities, research institutions, independent power producers, utilities, and private companies were identified, and the experts were selected from these organizations / companies:

- Planning Commission (PC), Government of Pakistan;
- Alternate Energy Development Board (AEDB);
- Pakistan Council of Renewable Energy Technologies (PCRET);
- Ministry of Science and Technology (MOST);
- National University of Science and Technology (NUST), Islamabad;
- National Transmission and Dispatch Company (NTDC);
- University of Engineering and Technology (UET), Taxila;
- University of Engineering and Technology (UET), Lahore;
- Center for Advance Studies in Engineering (CASE), Islamabad;
- Fauji Power Company Limited (FPCL);
- Water and Power Development Authority (WAPDA);
- Islamabad Electric Supply Corporation (IESCO);
- National Electric Power Regulatory Authority (NEPRA);
- Oil and Gas Development Company Limited (OGDCL);
- Private companies working in the wind energy sector of Pakistan:
    - Clean Power Limited (CPL);
    - Renewable Resources Limited (RRL);
    - RWR Limited; and
    - Integrated Sustainable Technologies (IST).

TRM Expert Panel 1 (TRM EP1)

The TRM expert panel 1 was used to identify the strategic objectives and establish the national targets of the wind energy roadmap for the next 20 years. The TRM EP1 was composed of a group of renewable energy policy makers responsible for planning and establishing the national renewable energy targets and initiating wind energy projects in the country. In this expert panel, government officials (from Planning Division, AEDB, PCRET etc.), CEOs / senior managers from the private companies working on wind energy, and prominent research scholars from the local universities were included. The TRM EP1 consisted of 10 experts. Table 12 highlights the background affiliations of the members of TRM EP1.

Table 12: Background of the TRM EP1

Organization	Academic	Government	Private	Utilities	
AEDB		X			
CASE	X				
FPCL				X	
IESCO				X	
MOST		X			
PC		X			
PCRET		X			
RRL			X		
RWR			X		
UET-L	X				
Total	**2**	**4**	**2**	**2**	**10**

TRM Expert Panel 2 (TRM EP2)

The TRM expert panel 2 was used to identify and prioritize the roadmap barriers and challenges hindering the deployment of wind energy projects on a large scale in the country and to propose various action items required to overcome the roadmap barriers and challenges. Thus, the TRM EP2 was used to develop the bottom layers of the technology roadmap. In the TRM EP2, engineers, scientists, and project managers who are working on wind energy projects and power distribution companies in Pakistan were included. The experts in this panel had practical knowledge of the wind technology, supporting technologies required to implement the wind energy projects, grid operations and limitations of the national grid, and the peculiar situation of Pakistan related to wind energy technology.

The TRM EP2 had 15 members; most of them were professionals from the government sector, private companies, universities, and power distribution companies. The following Table highlights the background affiliations of the TRM EP2.

Table 13: Background of the TRM EP2

Organization	**Academic**	**Government**	**Private**	**Utilities**	
AEDB		**X**			
AERO		**X**			
CASE	**X**				
CPL			**X**		
FPCL				**X**	
IESCO				**X**	
IST			**X**		
NUST	**X**				
OGDCL		**X**			
PC		**X**			
PCRET		**X**			
RRL			**X**		
RWR			**X**		
UET-T	**X**				
WAPDA				**X**	
Total	**3**	**5**	**4**	**3**	**15**

FCM Expert Panel (FCM EP)

The FCM expert panel was used to identify the scenario drivers (concepts) that affect the deployment of wind energy on a large scale in Pakistan, in the form of a causal map. These maps consist of concepts which are interconnected through the causal links representing the cause and effect relationships between various concepts. The experts highlighted the strength (weight) of the causal links between these factors. The FCM EP members also reviewed and critiqued the integrated FCM, prioritized the concepts, and highlighted the input vectors (plausible combinations of the most important concepts/trends from the Integrated FCM) in order to create the scenarios.

The FCM EP included professionals working at the policy and strategic level as well as technical experts working at the operational level so that they were aware of the overall picture of all factors affecting the deployment of wind energy in the country. Therefore, some members from both the TRM EP1 and TRM EP2 were included in the FCM EP. Table 14 highlights the background affiliations of the FCM EP members.

Table 14: Background of the FCM Expert Panel

Organization	Academic	Government	Private	Utilities
AEDB		X		
AERO		X		
CASE	X			
CPL			X	
FPCL				X
IESCO				X
IST			X	
OGDCL		X		

PC		X			
RRL			X		
RWR			X		
UET-T	X				
Total	**2**	**4**	**4**	**2**	**12**

3.2.2 FCM-based Scenario Development

The expert panels were used to develop the FCM-based scenarios for wind energy. Members of the FCM EP were asked to provide their causal maps and highlight the factors that may affect deployment of wind energy on a large scale in Pakistan. Miles and Keenan recommend that the researcher should provide background material to the participants of a scenario workshop so that they have similar background information [211]. Therefore, introductory information was provided to the experts so that they could understand the context of the research along with instructions to develop causal maps. The agenda and the handout documents of the FCM scenario workshop are attached as Appendix A to this dissertation. The handout highlights the purpose of the workshop, focus questions, detailed instructions for the construction of causal maps, and examples of FCMs for the experts. The agenda and the handout documents were provided to the participants four weeks prior to the workshop.

Individual FCMs were obtained from the FCM EP members prior to the scenario workshop. The experts were asked to look into the social, technological, economic, environmental, and political aspects while identifying the concepts which are likely to influence the wind energy sector of Pakistan. Subsequently, all individual maps were combined into an integrated FCM by the researcher. In the workshop, the purpose of the research, the basic principles of scenario planning, and FCM-based scenarios were also explained to the members of the expert panel. During the workshop, the participants reviewed and critiqued the integrated FCM and highlighted the input vectors for creating FCM-based scenarios.

For the development of the FCM, the following steps recommended in the literature were followed [152, 201, 334]:

1. Identify and define the important factors:
    a. Write down issues on Post-its; and
    b. Cluster these issues as a map and discuss their importance.
2. Define the causal link between these factors:
    a. Identify factors which are linked together;
    b. Determine that the relationships is positive or negative; and
    c. Define relative strength of the relationships by assigning causal weights using a 5-point Likert-type scale, with values that range from 1, representing a very weak causal link, to 5, representing a very strong causal link.
3. Review and discuss the combined / integrated FCM:
    a. The moderator individually obtains the FCMs from every expert prior to the workshop and combines those into an integrated FCM.
4. Identification of the most uncertain factors in the integrated FCM:

   a. Paste red dots on the most uncertain factors (5 red dots are provided to every expert).
5. Identify plausible input vectors consisting of the most important factors from the integrated FCM:
   a. The moderator will provide a tabular worksheet highlighting the critical scenario drivers at the top of the each column and indicating the number of conceivable development variations of each scenario driver; and
   b. Combine the development variations into plausible strands (input vectors) using markers of different colors.

Combining of Multiple FCMs

Multiple FCMs can be combined together to produce a joint effect and capture the opinions of multiple experts together in one map for further analysis [163]. The combined FCM is considered more useful than an individual FCM because the information is obtained from a multiplicity of sources [324]. After combining the FCMs, the experts are asked again to review the integrated FCM and highlight the most uncertain factors/concepts.

An example of combing multiple FCMs is shown in Figure 10, developed for a pilot study project [11]. The central objective of this integrated FCM is to investigate the factors that will cause the large scale deployment of wind energy in a developing country. This integrated FCM is created after obtaining individual

FCMs from seven experts and taking the average of the causal weights. The concepts highlighted by a continuous boundary line are identified by all of the experts (from concept 1 to concept 14 and concept 16), whereas the remaining concepts highlighted by a dotted line are identified by two experts.

Taber and Siegel proposed a method for combining multiple FCMs. This method computes the expert credibility weights based on the Hamming distance between the inferences vectors obtained from the FCMs of various experts [324, 325]. The integrated FCM shown in Figure 10 is composed of 20 concepts, where 15 concepts are identified by all of the experts and two experts identified five additional concepts highlighted by a dotted line. It was found that the credibility weight of the two experts who identified additional concepts is reduced because they differed from the majority. The credibility weight of the five experts, who proposed the same concepts, is 0.90. Whereas, the credibility weight of the two experts who identified additional important concepts in their FCMs is 0.75. Thus, this method estimates a lesser expert credibility weight for those experts who differ and disagree from the majority. For scenario planning, it is critical to collect diverse input from multiple experts and identify the weak signals that have the potential to play a vital role in the future. Therefore, this approach is not a suitable approach for combining FCMs for scenario planning.

In the other method, multiple FCMs are combined by taking the average of the causal weights. This is another commonly employed technique and it has been used to combine multiple FCMs developed for building scenarios [7, 11, 152]. Both approaches presented in the literature for combining multiple FCMs are explained in Appendix B.

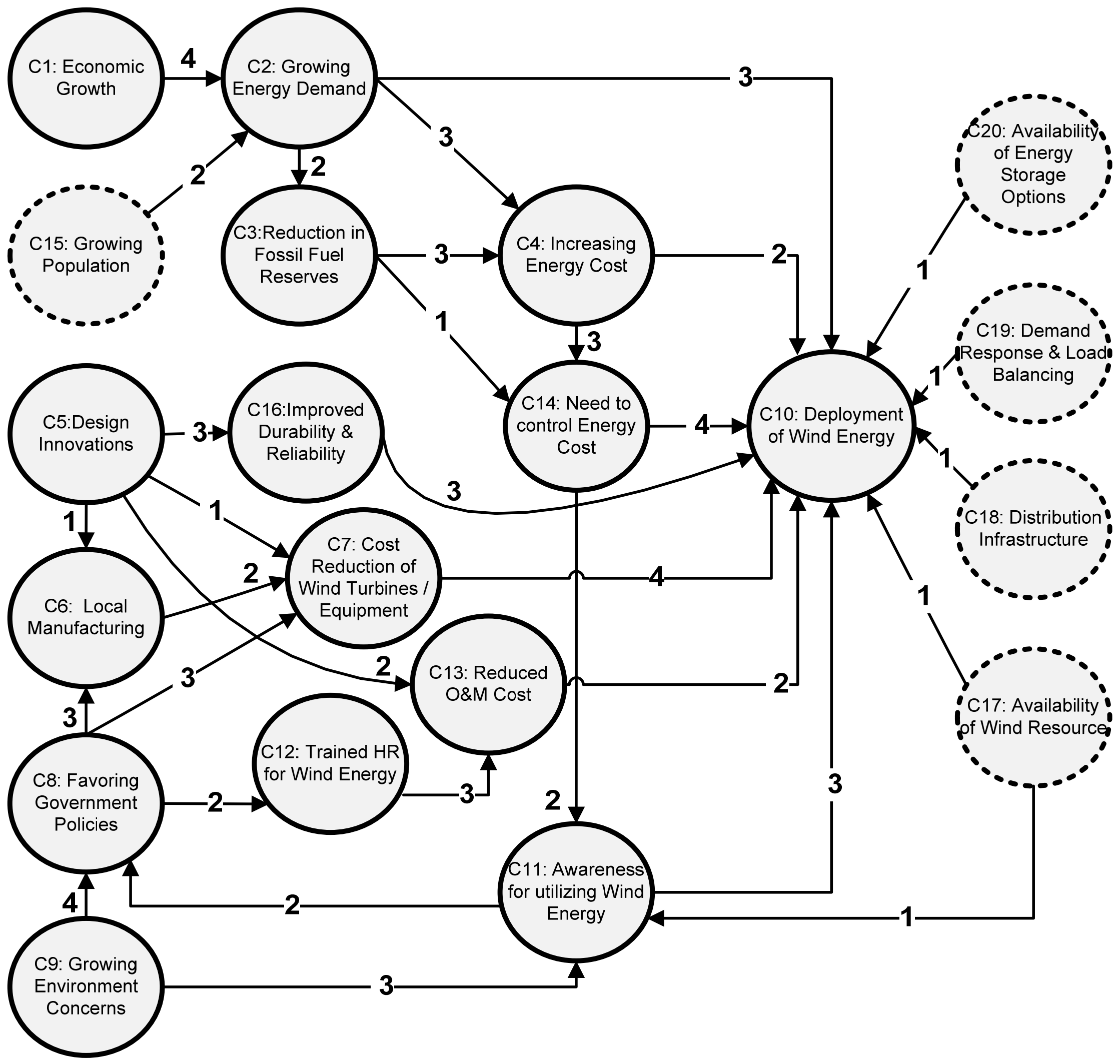

Figure 10: Integrated causal map/FCM for deployment of wind energy

After forming the integrated FCM, the experts were asked to identify the most uncertain and important scenario drivers (concepts), because it is important to identify and prioritize the most critical and uncertain scenario drivers [298]. After ranking the scenario drivers, the morphological analysis was used to develop the input vectors.

FCM Simulation

The input vectors are used for conducting the simulation and generating the FCM-based scenarios. Although, a few important scenario drivers are used to form the input vectors; but in the FCM simulation all of the scenario drivers (concepts) in the FCM model are considered for generating scenarios. It happens because when a concept changes its state, it affects all concepts that are causally dependent on it, and this process depends on the direction and strength of the causal link [152]. The newly activated concepts may further influence other concepts which they causally affect and this activation spreads in a non-linear fashion in the FCM model until the system attains a stable state [152]. Due to the meta-rules, it is also possible that in some cases several input vectors may lead to the same final system state [156]. The FCM simulations can be used to experiment with different input vectors and compare their outcome [156]. Therefore, it helps to deal with a complex situation and holistically evaluate all concepts of interest. Moreover, despite using the input vectors consisting of the critical scenario drivers, all drivers/concepts and their causal links in the FCM model are considered during the development of FCM-based scenarios.

The FCM simulation is performed until the output vector is stabilized. It is performed by multiplying the input vector with the FCM adjacency matrix. A squashing function is applied after every multiplication as a threshold function to the output vector. A simple binary squashing function is used which squeezes the result of multiplication in the interval of (0, 1). For n number of concepts, the input vector is *1 by n*, the FCM adjacency matrix is *n by n*, and the output vector is *1 by n* [324]. The new output vector is again multiplied with the FCM adjacency matrix and this process is repeated until the multiplication results in equilibrium [152, 296, 324]. As a result, the system is settled down and stabilized, and then new matrix multiplications will result in the same output state vector. Implications of the FCM model are analyzed by clamping different concepts and the vector and adjacency matrix multiplication procedure, to assess the effects of these perturbations on the state of a model [2]. Thus, the FCM simulation process provides a holistic overview and investigates the internal dynamics of the model.

FCM Validation

The literature recommends that every step should be validated through the experts as an ongoing activity [156, 317]. Participation of the experts help to address the validity and acceptability aspects of the model [133]. It is important to accurately translate experts' feedback in the FCM model [156] and weak facilitation may lead to poor quality of the model [109]. Therefore, it is critical to strictly follow the FCM modeling guidelines through a high quality process [155, 156]. The steps taken to ensure validity of the FCM model developed for this dissertation are explained in Section 5.1.6.

3.2.3 Technology Roadmap Development

A technology roadmap is a high-level planning tool used to support the development and the implementation of strategy and plans [239]. In this research, the roadmap is developed using multiple scenarios as an input to the technology roadmapping process. Workshops and follow-up surveys are conducted to obtain the expert judgment for the roadmap development. The strategic objectives of the country are defined and the national targets for the wind energy sector are established. The challenges and barriers associated with the deployment of wind energy in the country are identified, explored, and prioritized keeping in mind the constraints and limitations of the country. The roadmap action items are proposed and gaps / needs are identified in order to achieve the roadmap targets. As a result, the TRM approach identifies future directions of the national wind energy sector, help to plan the energy future in a very systematic way, and provide guidelines for the exploitation of wind energy in the country.

The roadmap is developed using a top down approach. In the proposed research, input from the experts is obtained through workshops and follow-up Delphi surveys. The workshops help to bring the experts together in order to share and brainstorm their ideas for the future and subsequently develop the roadmap [238, 242, 243, 246, 357, 358]. The workshops are the most commonly used technique for the development of a technology roadmap [8]. Separate workshops are conducted to develop various tiers of the roadmap.

The Delphi method has also been used in many roadmapping applications and it is considered a promising technique for the development of a technology roadmap [32, 98]. This approach reduces the impact of the powerful members in a group and avoids the imposition of their points of view on other group members [188]. Online (computer-based) Delphi method increases the efficiency of the process, shortens the time to perform a survey, accommodates the expert availability, and reduces drop-out-rates; and this approach has been used in multiple applications [42, 98, 105, 114]. Chi-squared test is used to determine the stability of results of an expert panel [43]. The Delphi method is used to prioritize the barriers and challenges of this roadmap against each scenario.

The national level wind energy roadmap is developed for multiple scenarios. The experts identified the most critical barriers and challenges against each scenario. This approach has significantly improved the usefulness, flexibility, and vision of the roadmap, and enabled anticipation of a wide range of possible future outcomes. The roadmap objectives and targets are shown in the upper layers. Whereas, the roadmap barriers and detailed action items proposed to overcome these barriers against each scenario are portrayed in the lower layers.

In this research, two expert panels were formulated to develop the technology roadmap. A top-down approach was used and the following steps were taken for the development of this roadmap:

Step 1: Strategic Objectives of the Roadmap: TRM Expert Panel 1

Identify the strategic objectives of the roadmap in accordance with the national renewable energy policy. The experts are asked to discuss, deliberate, and brainstorm the strategic objectives.

Step 2: Targets of the Roadmap: TRM Expert Panel 1

Establish the national targets of the wind energy roadmap for the next 20 years. Again, the national renewable energy policy of Pakistan is used as a baseline document for establishing the roadmap targets. The agenda and handout documents for the roadmap objectives and targets workshop are attached as Appendix C. These documents highlight the purpose of the workshop and the focus questions.

Step 3: Roadmap Barriers: FCM Model / TRM Expert Panel 2

Identify and explore the important barriers and challenges towards the deployment of the wind energy projects against each scenario. Then prioritize the most important barriers on the basis of their impact on the roadmap targets. The important barriers and challenges have been identified through the literature review and integrated FCM model. In the roadmap barrier workshop, the experts are asked to add additional barriers and challenges if they think that some important barriers are not included in the handout. In the second phase, the experts rank these barriers and challenges on the basis of their importance and impact on the roadmap targets. Weighted sum method (WSM), which is a commonly used technique for ranking, is used to prioritize the roadmap barriers. The agenda and handout documents for the roadmap barrier workshop are attached as Appendix D. These documents describe the purpose of the workshop, focus questions, barrier prioritization criteria, list of potential roadmap barriers, and detailed instructions for this step. After the roadmap barriers workshop, a follow-up Delphi survey is conducted and the experts are asked again to prioritize the roadmap barriers for each scenario. The follow-up survey is attached as Appendix E.

Step 4: Roadmap Action Items: TRM Expert Panel 2

Identify, discuss, and propose various action items in the wind energy roadmap to overcome the roadmap barriers and achieve the roadmap targets. Thus, the experts translate the roadmap objectives and the targets into the action items. The experts propose the appropriate action items to overcome the roadmap barriers against each scenario. The experts also highlight the action items which have already been taken by the major stakeholders (government, power regulator, wind industry, and utilities) and state if there is a need to modify these action items already undertaken by the major stakeholders to address the barriers. Moreover, the new action items (i.e. gaps/needs) that are required to overcome the roadmap barriers are also proposed. At present, these new action items are not undertaken by any major stakeholder. At the end, the experts assign the responsibility for each action item and specify the estimated time frame when these action items are required to be undertaken. The agenda and handout documents of the roadmap action item workshop are attached as Appendix F. These documents describe the purpose of the workshop, important tasks, instructions, and examples for identifying the action items in this research step.

This four step process for developing the national level wind energy roadmap is highlighted in Figure 11.

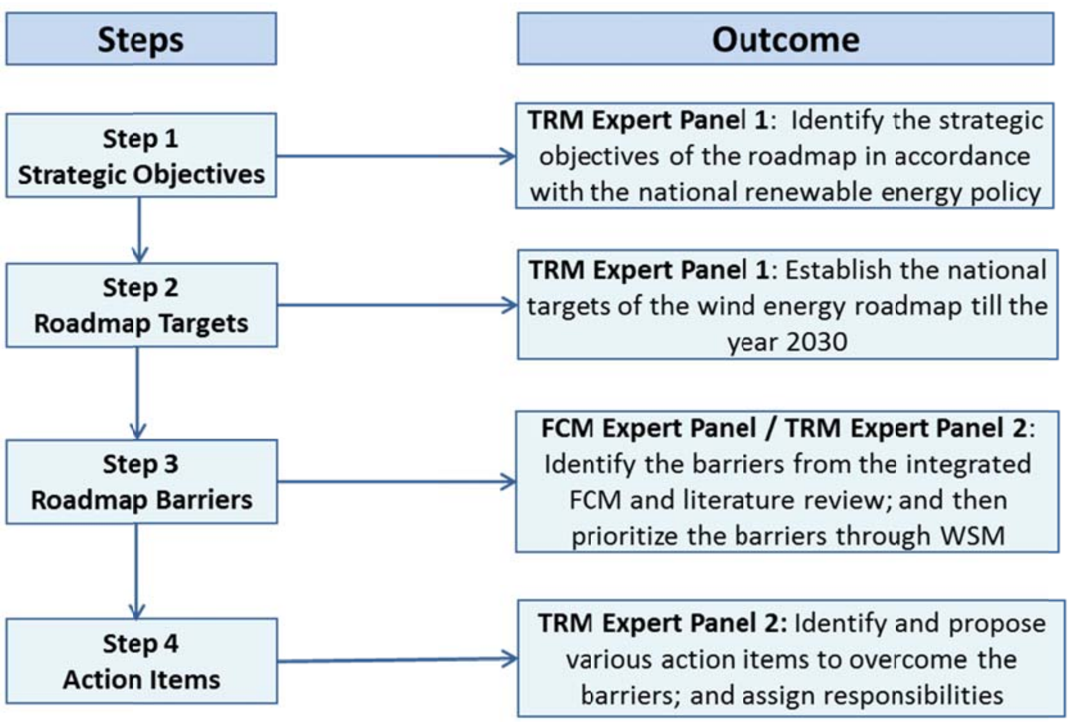

Figure 11: TRM process for the roadmap

3.2.4 Consistency of Expert Judgments

Consistency is the degree to which an individual is consistent in his/her own judgment. Inconsistency describes a situation where the expert judgment changes over time. The consistency of responses between the successive rounds of a Delphi study is also referred as stability [43, 67]. Kastein et al. state that the consistency of responses of the expert panel members over the successive Delphi rounds reflects high reliability [164]. Dajani, Sincoff, and Talley recommend to conduct chi-square (x^2) test to measure whether the stability of group response has been achieved or not. The responses of two successive rounds obtained from a group of experts are required to conduct this test.

Chaffin and Talley argue that it is more important to establish individual consistency than determining the consistency of a group [43]. They extended the work done by Dajani et al. and empirically demonstrated that the individual stability does imply the group stability, whereas the group stability does not necessarily imply the individual stability [43]. Thus, the individual stability test provides more information and it is used for measuring the consistency of responses between the successive Delphi rounds.

An example is used to illustrate the stability test in two consecutive Delphi rounds. Table 15 highlights the responses by 122 panelists for three response intervals (A, B, and C) in rounds two and three of a given Delphi study. The expected frequencies are computed based upon the assumption that the null hypothesis of independence is true [42]. The responses of the panelists for round *i* and round *i+1* are shown in Table 15. The equation number 2 is used [43]:

$$x^2 = \sum_{k=1}^{n} \sum_{j=1}^{m} \frac{(O_{jk} - E_{jk})^2}{E_{jk}} \qquad (2)$$

Where O_{jk} and E_{jk} are the observed and expected frequency indicating the number of respondents who voted for the *j* th response interval in the *i* th round, but voted for the *k* th response interval in round *i+1*.

m and *n* are number of non-zero response intervals in the round *i* and round *i+1*

In order to test individual stability in a Delphi study, we need to determine whether there is a significant difference between the individual responses in two consecutive rounds using the chi-square test. The following hypotheses are tested:

H_0: Individual responses of rounds *i* and *i+ 1* are independent.

H_1: Individual responses of rounds *i* and *i+ 1* are not independent.

If the individual responses in the consecutive rounds are dependent, it means that the same respondents who voted for a given response interval in the round *i*, have also voted for the same response interval in the round *i+1*. Thus, by rejecting the null hypothesis (H_0) and accepting the alternative hypothesis (H_1), it can be concluded that there is individual stability between the consecutive rounds. Rejection of the null hypothesis means that the individual stability has been achieved. For the example shown in Table 15, there are 4 degrees of freedom and it is calculated from the equation number 3:

$$\text{Degrees of freedom} = (m-1)(n-1) \quad (3)$$
$$= (3-1)(3-1) = 4$$

Table 15: Observed and expected individual frequencies

Observed Frequencies

Response Interval		**Second round**			**Total**
		A	**B**	**C**	
Third round	A	26	7	0	33
	B	0	62	0	62
	C	0	2	25	27
Total		26	71	25	122

Expected Frequencies

Response Interval		**Second round**		
		A	**B**	**C**
Third round	A	7.0	19.2	6.8
	B	13.2	36.1	12.7
	C	5.8	15.7	5.5

The chi-square value is calculated through the equation number 2 and using the observed and expected frequencies shown in Table 15. The calculated value of x^2 is 197.5. At a 0.05 level of significance and four (4) degrees of freedom, the critical chi-square value is 9.488. Since the calculated chi-square statistic is greater than this critical value, we reject the null hypothesis and conclude that the individual stability has been demonstrated.

The chi-square test is used to measure the stability of group responses in a follow-up Delphi survey conducted to prioritize the roadmap barriers for each scenario.

3.2.5 Disagreement among Experts

Disagreement is the extent to which the participants of an expert panel are in difference to each other in their judgments. There is a misperception and some people assume that the experts will always reach the same conclusion and if the experts conclude differently, they consider that the judgment is questionable [207]. However, this concept is misleading due to two reasons [207]. Due to different educational background and professional experience, each expert differs in expertise and knowledge. Even if all the experts have same expertise and knowledge, they may think in different ways to approach the same problem and come up with different judgment. Second reason is that usually the expert judgment is obtained in an uncertain situation, where no clear standards or well developed theories exist. Therefore, the expert judgment may lead to some disagreement among the experts.

The experts may disagree because they think differently about a complex and uncertain problem [221]. Difference among the expert brings different perspectives and research indicates that it brings better chance of covering the right solution [207]. Torrance argues that the more effective groups are characterized by greater participation and wider divergence of the expressed judgments [328]. Shanteau state that sometime due to the disagreements, the experts increase their understanding of a subject [302].

In the Delphi studies, the disagreement occurs due to the expert selection procedure, clarity of questions, complexity of issue under consideration, and criteria for iteration [43, 67]. Rohrbaugh states that feedback after every Delphi round is the compelling force towards reducing the disagreement [271]. Kastein et al. recommend that through the standardized expert selection process, group size, adequate background information, proper design of the questionnaires, and provision of the feedback; the disagreement can be reduced among the experts [164].

The following five levels of agreement are presented in the literature shown in Table 16 [67]:

Table 16: Levels of agreement in Delphi studies [67]

Levels of Agreement	**Description**	**Example of a study with 12 participants/experts**
Consensus	Occurs when unanimity is achieved concerning any given issue	Unanimity among all 12 participants
Majority	Occurs when more than 50% of the respondents exhibit consistency	With 7-11 participants responding the same
Bipolarity	Bipolarity occurs when respondents are equally divided over an issue	With a 6-6 split on an issue
Plurality	Occurs when a larger portion of the respondents (but less than 50%) reach agreement.	With the largest subgroup of respondents between 2 and 5
Disagreement	Occurs when each respondent maintain views independent of each other	Every respondent in a different subgroup

It has been recommended to terminate the study when the consensus or majority is achieved with stability [67]. For the bipolarity, it is recommended to determine the nature of the stability among the two bipolar groups and terminate or rewrite the particular question. When the plurality occurs with the stability, it is recommended to terminate the study or administer a new round of questions if stability is not established. When the disagreement occurs and stability is achieved for a given question, the decision must be made whether to terminate or rephrase the question statement [67].

It has been observed that greater concern is given towards the disagreement among an expert panel in studies related to the healthcare, medical diagnostics, and risk and safety assessments. In some studies related to the healthcare sector, Cronbach's alpha (α) [118], Variation Factor (v) [326], and intraclass correlation coefficient (ICC) [164] are used to determine degree of agreement among the members of an expert panel.

On the other hand, in the fields of scenario development and technology roadmapping, it is encouraged to have diverse input from the experts. The literature highlights the importance of identifying the weak signals and future surprises. In this case, the objective of the work is to explore a variety of potential futures in order to allow the stakeholders to prepare for the surprises and contribute to shape the desired outcome. However, the following steps are taken to increase reliability of this research:

- Ensure that instructions are clear in all the workshop handouts and questionnaires;
- Delete or replace any unclear and ambiguous instructions or questions; and
- Careful selection of the members of expert panel.

3.3 Research Assumptions

The following assumptions are made for this research:

- It is assumed that the expert panel members are to be knowledgeable in the assigned areas. They have the ability to articulate and prioritize their judgment consistently. In order to cope with this assumption, the researcher has carefully selected the members in all three expert panels based on their professional qualifications, designations, and responsibilities in their organizations. All the experts are capable and possess the relevant experience to understand the wind energy sector of Pakistan.
- It is assumed that the information and judgment obtained from each expert have little or no bias.
- Biases of the experts are balanced in each expert panel. Efforts are made to minimize the biases by balancing the participants in every expert panel through their different backgrounds, experiences, positions, and

affiliations. For example in order to minimize impact of these individual biases; the TRM EP 2 consists of the government officials, researchers from research centers and academia, and representatives from the private companies.

- It is pertinent to mention that the dominant scenario drivers, barriers, and other environmental forces as well as each expert's preference and perception may change over time. This research is highly dependent on the subjective judgment of the human experts. Therefore, the result from this research represents the experts' preferences and perceptions at a certain point in time. However, the research approach can be applied again in different conditions to modify and update the research outcome.
- It is assumed that the concepts identified by the experts in the integrated FCM model, represent all the important factors that may affect the deployment of wind energy on a large scale in Pakistan. Moreover, it is also assumed that only the concepts interconnected through the causal links in the FCM model may affect the other concepts.

4 Background for Specific Case

Some background information for the specific research case is presented in this section. Seven major areas in relation to the case study are reviewed including: overview of Pakistan, overview of the national energy sector, energy crisis in the country, importance of wind energy, institutional support from the government, wind energy sector of Pakistan, and wind energy deployment and integration challenges.

4.1 Overview of Pakistan

Pakistan emerged as a new country on 14 August 1947, after the division of former British India. It is located in South Asia, bordering the Arabian Sea on the south, India on the east, Iran and Afghanistan on the west and China in the north. It is a densely populated country and covers 796,095 sq.km with a population of 132.35 million according to the last population census [113]. The country has a literacy rate of 53% [113]. Urdu is the national language with several regional languages. The country has coastline of approx. 1100 km long.

The national economy is based on agricultural; wheat, cotton, rice, and sugar cane are the major crops. The country also has an expanding industry. Cotton, textiles, sugar, cement, and chemicals play important roles in the national economy. The textiles sector accounts for most of Pakistan's export earnings [52]. Over the 2004-07 period, GDP growth in the 5-8% range was spurred by gains in the industrial and service sectors, and between the 2001-07 period, poverty levels decreased by 10% as the government steadily increased the development budget [52]. However, the economic growth slowed down during the 2008-09 period due to several reasons including the global financial crisis and severe electricity shortfalls [52]. The record floods in July-August 2010 lowered the agricultural output, contributed to a jump in inflation, and inflicted a massive damage of $10 billion on the country's economic structure [113]. The national economy is still recovering from the flood damage.

4.2 Overview of National Energy Sector

In this modern era, energy is a key element required for sustainable development and prosperity of a society. Pakistan is a developing country requiring sustainable sources of energy to foster a sustained economic growth and social development in the society [351]. The total primary energy supply (TPES) of Pakistan was 62.6 million tons of oil equivalent (MTOE) during the financial year 2008-09 [112]. Energy resources like natural gas, oil, hydro & nuclear, coal, and liquefied petroleum gas (LPG) contribute to 48.3%, 32.1%, 11.3%, 7.6%, and 0.6% of the primary energy supplies respectively [112]. The share of the primary energy supplies by various sources is shown in Figure 12.

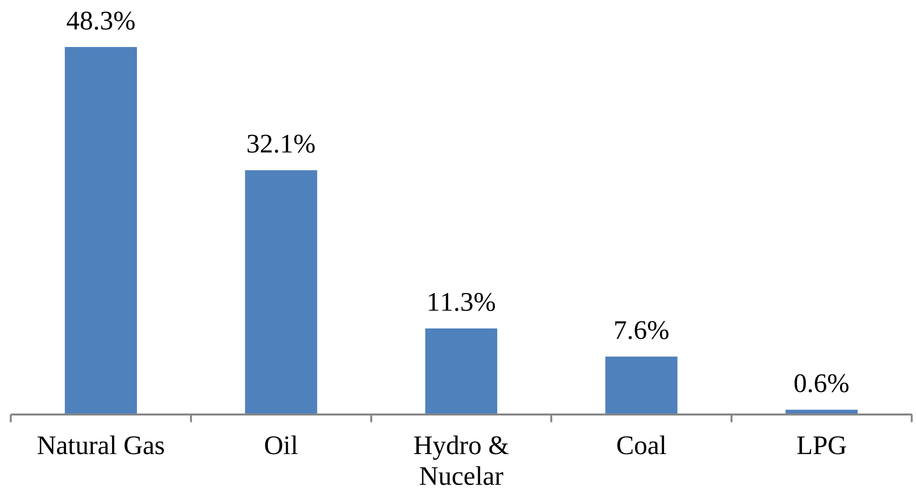

Figure 12: Share of Pakistan's primary energy supplies by various sources during financial year 2008-2009 [112].

Pakistan has a very limited fossil resource base, and the country's indigenous energy resources are insufficient to provide its economy with the necessary energy supplies [351]. Oil is the key resource of energy for electricity generation, and its import has put a heavy burden on the national economy [306, 329]. The national energy sector is heavily dependent on imported fossil-fuel. Presently, large hydropower dams are the only major renewable energy resource in the country for electricity generation. Usually, construction of large hydro dams results in a major relocation of people and changes in land use for the areas in which the dams are built. These projects have become controversial in Pakistan in recent years due to water shortages and significant impacts on the rivers, ecosystems, and surrounding communities. The large dams were developed in the 1970s, but the pace of new hydropower generation facilities has significantly slowed down over the last three decades due to the above-mentioned reasons [15]. The share of emerging renewable energy resources such as the use of wind energy for electricity generation is negligible in the country. It is shown in Figure 13 that the share of electricity generated from wind energy is around 0.2%, with the installed capacity of only 40 MW by the end of 2011 [1].

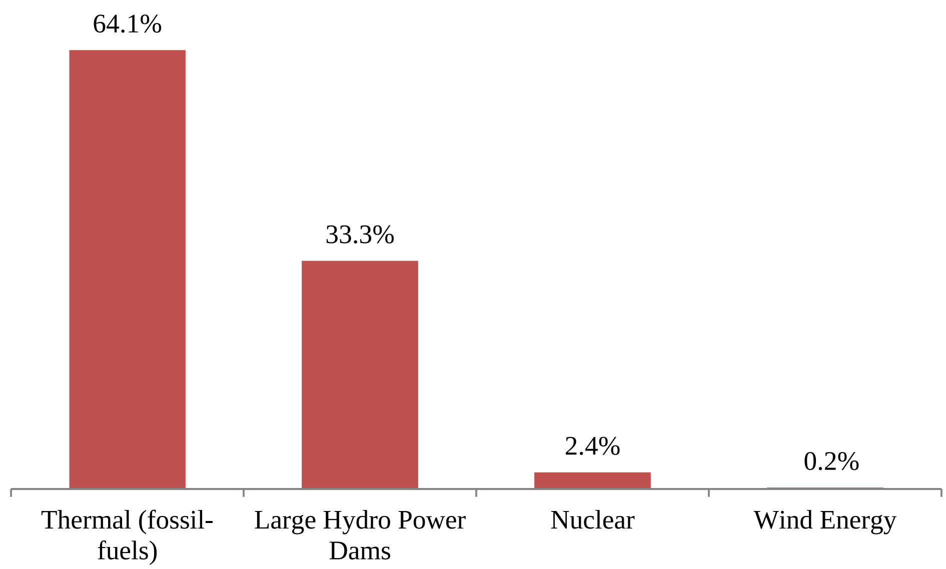

Figure 13: Share of Pakistan's electricity from various sources [1].

The residential sector consumes almost 50% of electricity produced in the country, followed by the industrial sector (26.7%), agriculture sector (13.0%), and the commercial sector (7.5%) [329]. Given the current growth trends, it is expected that the demand of the domestic sector will further increase in the near future. There has been an increase in electricity consumers due to rapid urbanization and extension of the national grid to include rural areas.

The power sector of Pakistan is dominated by two vertically integrated giants: Water and Power Development Authority (WAPDA) and Karachi Electric Supply Corporation (KESC). These two entities control the national electricity transmission and distribution network and generate almost 70% of the country's power. Independent Power Producers (IPPs) produce 30% of the country's electricity. In order to introduce a competitive environment and attract the private sector participation, in the year 2000 WAPDA was restructured and unbundled into the following 12 separate units [329, 351]:

- Eight Distribution Companies (DISCOS);
- Three Thermal Generation Companies (GENCO); and
- National Transmission and Dispatch Company (NTDC).

4.3 Energy Crisis in the Country

Pakistan is an energy deficient country facing problems due to a shortage of energy, especially electricity. The country's electric sector is in a crisis because electricity demand continues to exceed supply, and it results in extended periods of blackouts ("load shedding"). It is widely recognized as a severe obstacle to growth and poverty reduction in the country [329]. The electricity deficit of the country was over 4000 MW in the year 2008, and it is estimated to reach over

8000 MW by the end 2011 [15]. Therefore, rotating blackouts throughout the country are also necessary to overcome this shortage. The load-shedding has caused significant damage to the national economy and the closure of industry; resulting in loss of production and jobs.

An increase in the electricity demand is directly linked to the growth of the country's economy. Research indicates that every one percent of GDP growth in Pakistan requires an increase in electricity supply of 1.25%. Keeping in view the sustained growth in all sectors of the economy in the coming years, it is expected that the future demand for electricity will be more than 20,000 MW in the near future. Thus, an increase in electricity supply is required to sustain the economic growth [351]. This problem of electricity shortage will be further aggravated in the future because the national energy demand is also increasing at an average annual rate of 5.67% [112].

The electricity crisis has forced the government to make decisions like early market shutdown, power cutoff to the industry, and two holidays per week for all businesses. These measures are negatively affecting all economic and business activities in the country. The extended periods of blackouts almost suspend the social life of people. There were also some riots over the power shortages in Pakistan. The per capita electricity consumption for Pakistan is 475 kWh, which is almost six times less than the average electricity consumption in the world [140]. Access to electricity is essential to provide modern health services, improve agricultural productivity, obtain the full benefits of improved educational systems, and build an economic base that can participate in today's globalized economy [351]. The shortage of electricity and frequent blackouts constrain economic development and disrupt health, education and other services. Moreover, unreliable electricity service also undermines the cold chain vital to the distribution of medicines and perishable foods, and negatively affects public health.

Due to the shortage of electricity in Pakistan, the industrial sector has been badly affected and overall exports of the country have been reduced. Unreliable power supplies and frequent blackouts have encouraged the industries and businesses to install their own power supplies such as diesel generators. However, high operating costs of these generators raises the cost of local products and erodes their competitiveness within the region [351]. The shortage of conventional energy resources in Pakistan, when coupled with hiking energy prices worldwide, highlights a need to explore wind power in order to overcome the energy crisis in the country. Therefore, it is crucial for the country to formulate a diverse energy strategy and increase the share of sustainable energy resources by exploiting renewable energy technologies.

4.4 Importance of Wind Energy

Renewable energy technologies (RETs) are the fastest growing energy resources in the world and various projections indicate that these resources will have a huge contribution in the future [81, 150]. Pakistan mainly depends upon the conventional energy resources and there is not much effort for the exploitation of RETs for electricity generation. Due to over dependence on imported fossil-fuel, more than 60% of the foreign exchange is spent for the import of energy [306]. Oil import is a significant burden on the national exchequer and foreign reserves.

The government is trying to increase the indigenous energy supplies and renewable energy sector has been identified as an important target area. Renewable resources have enormous potential and can meet many times the current national energy demand. These resources can enhance diversity in the national energy mix, secure long-term sustainable energy supplies, reduce atmospheric emissions, create new employment opportunities, and offer possibilities for growth of the domestic manufacturing industry [222].

Among all RETs, wind is the most mature, rapidly deployable, clean, and affordable energy resource. In the decade leading up to 2009, there has been an average annual growth rate of 30% for the installed wind energy capacity in the world [46]. According to the World Wind Energy Association (WWEA), the global market for wind energy is gaining momentum and 40.5 GW of new wind capacity was installed in the year 2011 in more than 50 countries [361]. It indicates that wind energy is a rapidly growing, mature, and proven technology. Electricity is being generated from wind energy at a cost around 8 US cent/kWh in some Asian countries [225]. International Energy Agency (IEA) estimates that the investment cost of wind power is expected to further reduce in future as a result of technology development and economies of scale by 23% for onshore and 38% for offshore projects [46]. Therefore, wind energy is a technically feasible alternative of renewable energy available for Pakistan at a competitive cost. The country's 1100 km long coastline is ideal for the installation of wind farms to generate electric power. The growth of wind energy in the neighboring countries like China and India has been remarkable during the last decade. Pakistan is sharing the same coastal line of the Indian Ocean with India. Concerns about the security of energy supplies have led many countries in this region to diversify their energy mix through their indigenous wind resources.

It has been estimated by the U.S. Energy Information Administration (EIA) that the cost of electricity generation from the onshore wind projects will be competitive with conventional power plants based on coal and natural gas by the year 2016 [80]. Table 17 presents a comparison of the average levelized system cost of onshore wind power projects against the coal and natural gas based power plants.

Table 17: Comparison of the average levelized system cost in 2016 [80]

Power Plant Type		**Average System Levelized Cost ($/MWh)**
	Wind Farms (Onshore)	97.0
Coal	Conventional Coal	94.8
	Advanced Coal	109.4
	Advanced Coal with Carbon Capture and Storage	136.2
Natural Gas	Conventional Combined Cycle	66.1
	Advanced Combined Cycle with Carbon Capture and Storage	89.3
	Conventional Combustion Turbine	124.5

Import of natural gas could be seen as a viable resource to overcome the depleting domestic reserves. However, the natural gas import has significant issues such as need of substantial capital investment in the infrastructure, security issues in the region, and physical terrain concerns. Moreover, it will further increase dependence on imported energy and there is also price uncertainty over the future supply. Thus, wind energy has the potential of becoming a strong contributor in the national electricity mix.

A recent economic survey by the government indicates that more than 40,000 villages in the country do not have access to electricity [111]. Wind energy can be utilized to provide electricity to those villages. The deployment of wind energy projects can electrify these villages, improve living standards of the communities in those areas, and contribute to the national economic growth [214].

Utilization of wind energy can significantly help the country to overcome the energy shortage crisis, improve living standards of the society, diversify the national energy mix, contribute to the national economic growth, improve rural economy, reduce the energy import bill, and ensure environment sustainability. Therefore, it is critical to develop a national level wind energy roadmap in order to identify the objectives, targets, barriers, and action items of the roadmap to exploit the enormous potential of wind energy resources available in the country.

4.5 Institutional Support from the Government

In order to provide an effective institutional support for the development and deployment of renewable energy projects, the government has established two main departments: Alternate Energy Development Board (AEDB) and Pakistan Council of Renewable Energy Technologies (PCRET). The AEDB provides the institutional support, develops policies, and facilitates deployment of renewable energy projects in the country. The PCRET conducts the R&D activities, develops pilot projects for demonstration purposes, and train human resources so that they can operate and maintain the RETs based projects. Moreover, National Electric Power Regulatory Authority (NERPA) is the national electricity regulatory agency and National Transmission and Dispatch Company (NTDC) operates the national grid. The responsibilities of these departments are mentioned below:

The AEDB was established in the year 2003, to act as the central national body on the renewable energy sector and it is responsible to implement the renewable energy policies, programs, and projects in the country [1]. It is also responsible for developing the national renewable energy policy and establishing the policy goals. The country's first RE policy was announced in the year 2006. This policy established the mid-term and long-term targets including generation of 1,700 MW of electricity from renewable energy resources by the year 2015, and generation of 9,700 MW of electricity from renewable energy resources by the year 2030 [1, 110]. The AEDB also acts as a one-window facility for processing renewable power generation projects in order to ensure their smooth execution and implementation by the private sector and foreign investors. In order to facilitate renewable energy projects, the AEDB has drafted the standard power purchase agreement and other project implementation documents.

The PCRET was established in the year 2001 and it has been assigned to conduct research and development activities in the field of renewable energy technologies to promote these technologies in Pakistan [235]. It also coordinates the overall R&D activities related to the RETs in the country. It has initiated some pilot projects and deployed wind turbines, photovoltaic cells, solar water heaters, solar cookers, solar dryers, solar desalination systems, and biomass plants on a small scale to demonstrate their performance in the local environment [306]. It also provides training for operations and maintenance of the RETs.

The NERPA was established in the year 1998, in order to ensure fair competition and consumer protection. Its primary responsibilities include the issue of licenses for power production, transmission and distribution, specification of electricity tariffs, and consumer pricing [329, 351]. In addition, the NERPA is responsible for approving the tariffs negotiated in connection with the bilateral agreements between the power producers, distribution companies, and major customers [351]. It also defines the licensing requirements.

The NTDC was established in the year 1998 to take over all of the national grid stations, transmission lines, and network. It operates and maintains the

220kV and 500kV grid stations, and transmission lines. The NTDC is also entrusted to acts as:

- Central Power Purchasing Agency;
- System Operator;
- Transmission Network Operator; and
- Contract Registrar and Power Exchange Administrator.

4.6 Wind Energy in Pakistan

Wind power has been used from the ancient times for grinding grains, sailing ships, and pumping water for irrigation purposes. Wind power technology is the fastest growing renewable energy resource in the world [46]. The worldwide installed capacity of wind farms reached 254 GW by the end of June 2012, out of which 16.5 GW are new installations added in the first half of 2012 [361]. Several European countries are obtaining 10 percent or more electricity from wind power [46, 140]. It indicates that wind power technology is a rapidly growing, mature, and proven technology. The capacity and height of wind turbines have increased with time [46]. Generally, wind speed is higher and more stable at height. Increased height of the wind turbine allows increasing length of the turbine blades, so it capture more power due to larger area through which the turbine can extract energy (known as swept area of the rotor). Additionally, the rotor can be installed higher to take advantage of the higher wind speed.

Pakistan has a tropical desert climate with yearly precipitation of less than 250 mm. It is hot and dry in most of its areas, with a relative high average annual temperature. The country is under a great influence of monsoon from the Indian Ocean, which brings both precious rain and abundance of wind energy resources. The thermal depression of South Asia and monsoon winds shape the country's southern coastal areas and northern mountain areas into a land rich in wind resources.

Various studies indicate that there is a good potential for generating electricity from wind energy along the coastline and many other regions of Pakistan [47, 213, 214, 216, 305, 306]. Pakistan Metrological Department (PMD) has installed several wind data collection centers along the coastline and northern areas of the country. The wind data is obtained from 47 towers along the coastline. The collected wind data indicates that wind speeds from 5 m/s to 7 m/s persist in the coastal regions and many valleys in the Northwest region of the country at a height of 50m [250].

In an effort to access the global potential of wind resources, the US National Renewable Energy Laboratory (NREL) and 3TIER Environmental Forecast Group developed 50m wind map of Pakistan shown in Figure 14. This high-resolution wind map also indicates that many regions of country have good potential for generating wind energy [229]. Sheikh mentioned that many potential sites for wind energy generation in Pakistan have capacity factor of more than 25%, which is internationally considered suitable for the installation of economically viable commercial wind farms [305]. Multiple studies indicate 50,000 MW of wind energy potential along the coastal areas of the country with an average wind speeds of more than 7m/s at 80 m height [104, 213]. Therefore, the coastal areas of Pakistan, especially the wind corridor around Gharo region is ideal for generating electricity from wind energy.

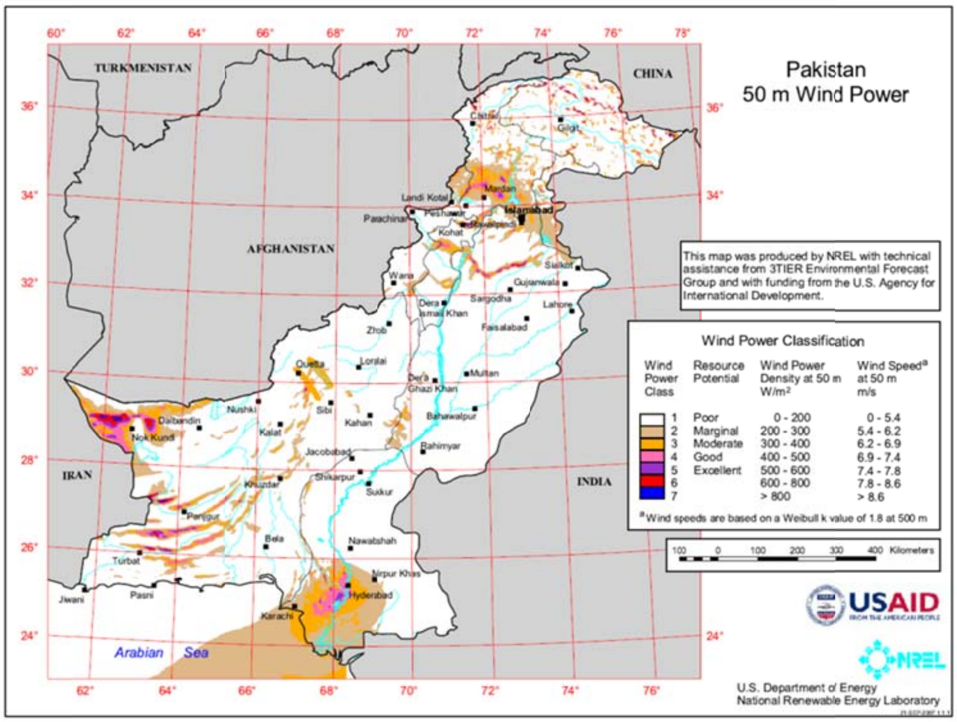

Figure 14: Wind map of Pakistan [229]
(Reprinted with permission from USAID Pakistan)

An in-depth analysis of the wind data is very useful to identify the best prospective areas and screen out less promising areas. The following areas in several regions of the country have good-to-excellent wind resources [82]:

- Southeastern Pakistan especially:
    - o Hyderabad to Gharo region in southern Indus Valley;
    - o Coastal areas south of Karachi; and
    - o Hills and ridges between Karachi and Hyderabad.
- Northern Indus Valley especially:
    - o Hills and ridges in northern Punjab; and
    - o Ridges and wind corridors near Mardan and Islamabad.
- Southwestern Pakistan especially:
    - o Near Nokkundi and hills and ridges in the Chagai area; and
    - o Makran area hills and ridges.
- Central Pakistan especially:
    - o Wind corridors and ridges near Quetta; and
    - o Hills near Gendari.
- Elevated mountain summits and ridge crests, especially in northern Pakistan.

It is estimated that approximately 26,400 km^2 (3% of Pakistan's total area) has class 4+ (good-to-excellent) wind resource for utility-scale applications. It has a potential of generating approximately 132,000 MW of electricity from wind (assuming 5 MW/km^2) [82]. Moreover, almost 9% of the country's land area has a Class 3 or better wind resource. A summary of the wind resource at 50 m height along with potential of generating electricity from the available wind resources are presented in Table 18.

Table 18: Good-to-Excellent wind resource [82]

Wind Resource	Wind Class	Wind Power W/m^2	Wind Speed m/s	Land Area Km^2	Electricity Potential MW
Good	4	400–500	6.9 – 7.4	18,106	90,530
Excellent	5	500–600	7.4 – 7.8	5,218	26,090
Excellent	6	600–800	7.8 – 8.6	2,495	12,480
Excellent	7	>800	>8.6	543	2,720
Total				26,362	131,800

Despite the availability of wind resources in abundance, there is not much progress made for the utilization these resources in the country. Presently, the installed capacity of wind power is only 40 MW in the country [1]. In the renewable energy policy announced by the government in the year 2006, surety has been given for the purchase of electricity generated by wind farms. Moreover, a unique concept of "*wind risk*" has also been incorporated to immune the investors and project developers from the risk of variability of wind resource (wind speed). This concept has been incorporated to overcome the fear related to the reliability and accuracy of the available wind data and insulate the investor from resource variability risk. This risk is absorbed by the power purchaser (government). The wind risk concept will ensure that the government will make monthly payments for the purchase of power in accordance with the benchmark wind speed tables [110]. The benchmark wind speed is determined for each project site on the basis of the independently monitored wind data. Subsequently, electricity generation levels corresponding to the benchmark wind speed are calculated. If less power is generated in a particular month due to wind speed lower than the benchmark wind speed, the government will make monthly payments to wind farms according to the benchmark wind speed data. The principle behind the wind risk concept is to make the wind farm developers and investors immune to the wind speed variability factor, which is beyond their control. However, project developer will be fully responsible for factors within their control such as availability of the wind farms [110]. The renewable energy policy also offers other benefits including some tax exemptions and waiver of import duties for the equipment required for renewable energy projects.

4.7 Wind Energy Deployment and Integration Challenges

The slow uptake of wind energy technology in Pakistan can be attributed to numerous challenges and barriers, ranging from a lack of infrastructure to poor competition with the conventional power generation. In order to pave the way forward for a sustainable energy future, the challenges faced by the national wind energy sector must be systematically identified and addressed. Therefore, it is vital to identify and prioritize these barriers and challenges, because without identifying the critical barriers, we cannot move towards addressing them. Moreover, based on these identified and prioritized barriers, appropriate action items are proposed.

There are also integration/transmission challenges associated with the deployment of wind energy, because it is a variable power source and its output varies depending on the wind speed [77, 119]. The tremendous potential of wind resource alone does not ensure significant utilization of wind energy [281]. The variability and uncertainty of wind energy significantly impacts the grid operations and it requires to make the grid more vibrant and interactive [77, 89]. It is estimated that the impact due to a large scale integration of wind power will result in an increase of the system operating cost by $5.00/MW in the United States [77]. The wind integration cost may vary for Pakistan due to different infrastructure of the national power grid.

The integration of wind energy requires investment in the transmission system in order to increase the transmission capacity, improve grid efficiency, changes in the grid operations, availability of emergency demand response resources, creation of load balancing areas with interconnection capacity, better integrated regional planning, enhanced predictability of wind resource, dispersion of new wind installations, availability of flexible power generating units like hydro power or thermal power plants, provision of energy storage system like pumped hydro, or compressed air, and formulation of a detailed reserve requirement strategy [77, 89, 119, 131, 132, 183, 184]. However, several studies conclude that it is feasible and manageable to integrate 20% to 30% of electricity to the grid from wind [77, 131, 132, 184].

Details of the barriers and challenges towards a large scale deployment of wind energy projects in Pakistan are presented in Section 5.2.2.

5 Data Collection and Research Validation

The steps taken for data collection for building the FCM-based scenarios and technology roadmap for the wind energy sector of Pakistan are described in this section. At the end of this section, steps taken to ensure the research validation are described.

5.1 Data Collection for FCM-based Scenario Development

The following steps were taken in order to collect data for developing the FCM-based scenarios and validation of the integrated FCM model:

- Input from the individual expert to obtain their FCMs and develop an integrated FCM model;
- Scenario workshop to review and critique the integrated FCM;
- Prioritization of concepts in the FCM model;
- Develop input vectors through the morphological analysis during the scenario workshop;
- Build the scenarios through the FCM simulation; and
- FCM validation.

5.1.1 Development of the Integrated FCM

Individual FCMs were obtained from each member of the FCM EP prior to the FCM scenario workshop. The experts were asked to provide their causal maps and highlight the factors that may affect the deployment of wind energy projects on a large scale in the country. The experts were asked to look into the social, technological, economic, environmental, and political aspects while identifying the concepts.

The FCM scenario workshop agenda and handout documents were provided to the experts three weeks before the workshop (attached as Appendix A). The researcher also explained the purpose of the research and basic principles for construction of FCM. Individual FCMs were obtained from 15 experts and subsequently 12 experts attended the scenario workshop. The researcher combined these maps into an integrated FCM by taking the average of the causal weights of every concept. Some experts used different terminologies to highlight the same concept in their FCM. Therefore, it was a difficult task for the researcher to combine multiple FCMs. The researcher was able to cross check with the experts and clarify meanings of the ambiguous concepts. However, in a few cases the researcher was not able to clarify meanings and it resulted in the duplication of some concepts. Details of combining multiple FCMs are given in Appendix B. The experts also identified the most uncertain scenario drivers (concepts) in the integrated FCM by pasting red dots on the most uncertain factors (details given in the scenario workshop handout).

During the FCM workshop, the experts reviewed and critiqued the integrated FCM in detail. The definition of each concept, its impact on the objective of the map, and weights and direction of the causal links, were thoroughly discussed.

During the discussion, it became apparent that the experts had used different terms for similar concepts in their individual maps. This led to redundant concepts when their maps were integrated by the researcher. The workshop participants therefore agreed to remove three concepts (C25: Availability of technology, C40: Energy storage options, and C43: Income to land owners / farmers) from the integrated map. Moreover, they discussed implications of political intervention, fiscal incentives, public opinion and perception, and collaboration with the global community. These discussions did not result in the addition of concepts because the experts felt they were sufficiently reflected in the integrated map. Finally the FCM workshop participants agreed to keep 40 concepts in the revised FCM. Thus, the integrated FCM has more concepts than the map of any individual expert. Figure 16 shows the concepts of the integrated map (top row), as well as the concepts of each individual map, excluding the three concepts (C25, C40, and C43), that were dropped because they turned out to be redundant. Figure 15 shows the causal connections between the concepts in the integrated FCM model, which was reviewed and validated in the workshop discussions. The concept meanings they agreed on are given in Table 19.

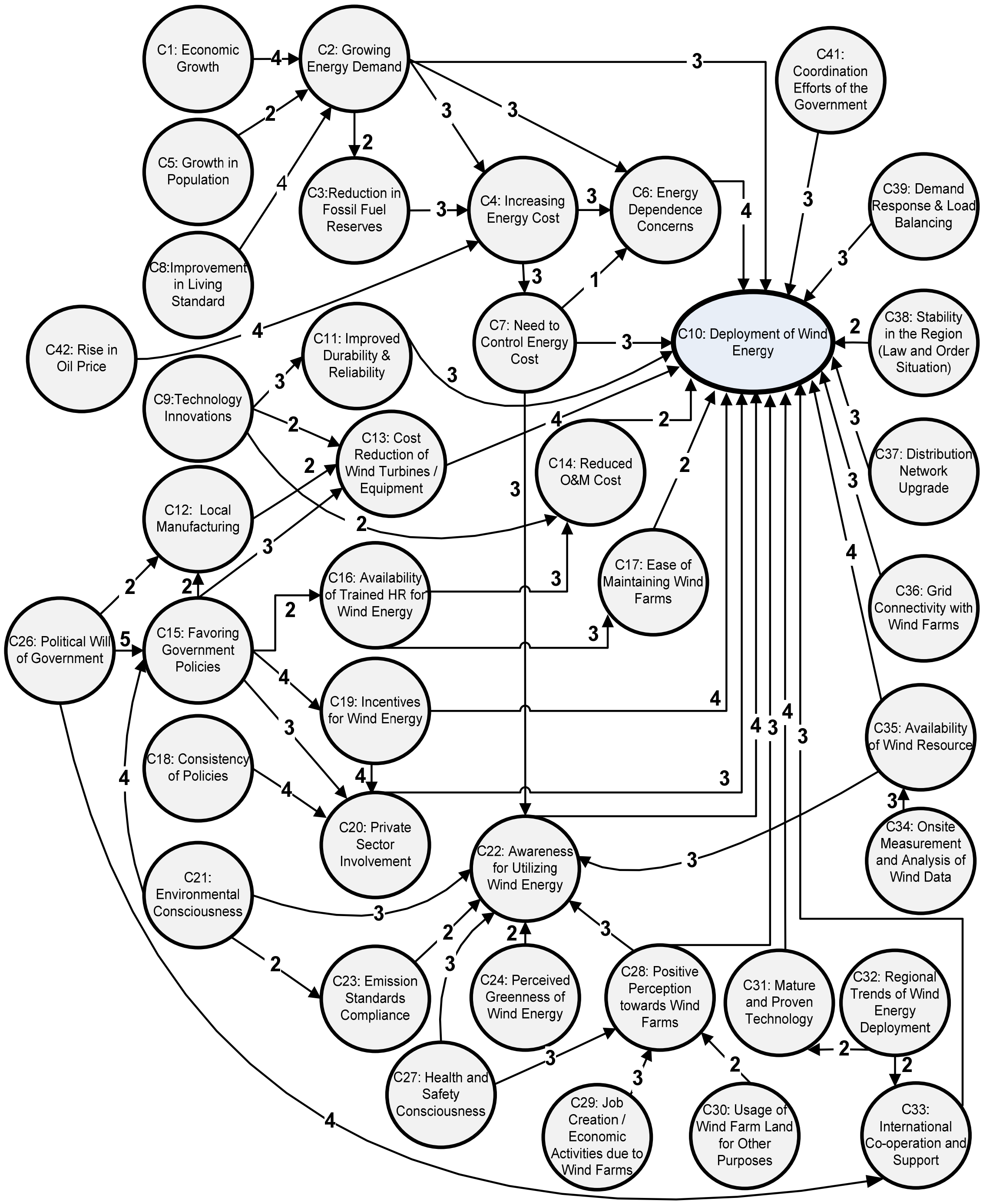

Figure 15: Revised integrated FCM for deployment of wind energy

The central objective of the FCM is to investigate the factors that will affect or cause or both the deployment of wind energy projects on a large scale in Pakistan (concept C10). A description of all the concepts in the integrated FCM model is given in Table 19:

Table 19: Description of concepts in the integrated FCM

Concept No	Concept Title	Concept Definition
C1	Economic Growth	There was good economic growth in the country during the first decade of the twenty-first century and the same trend is expected to continue in the future.
C2	Growing Energy Demand	Energy demand in the country is growing at an average annual rate of 5.67% [112].
C3	Reduction in the Fossil-Fuel Reserves	Indigenous fossil-fuel reserve of Pakistan (i.e. Natural Gas) is depleting due to growth in the energy demand.
C4	Increasing Energy Cost	The cost of electricity has significantly increased in the country, especially after the oil crisis of 2008. The national power sector is highly dependent on imported oil.
C5	Growth in the Population	The population of the country is increasing at an annual rate of over 1.55% [52].
C6	Energy Dependence Concerns	Most of the primary energy supplies are imported; thus, there is also a strong desire to reduce the energy dependence on the imported energy resources.
C7	Need to control energy (electricity) cost	The electricity cost is highly dependent on the price of fossil-fuels because 64.1% of electricity in the country is generated from the thermal resources [1]. There is a strong desire to keep the cost of electricity stable.
C8	Improvement in Living Standard	The living standard is improving due to increase in the GDP and economic growth. Moreover, there are more people living in large cities as compared to rural areas and rate of urbanization is 3.1% [52].
C9	Technology Innovations	The technology innovations and improvements in the wind turbine technology and other supporting technologies related to the wind energy sector.
C10	Deployment of Wind Energy (Objective)	Deployment of wind energy on a large scale in the country is the objective of this causal map/FCM.
C11	Improved Durability and Reliability	There have been significant improvements in the durability and reliability of the wind turbines.

C12	Local Manufacturing	Local manufacturing of the wind turbines and other supporting equipment within the country provides potential for indigenization of wind technology.
C13	Cost Reduction of Wind Turbines	Cost reduction of the wind turbines and other supporting equipment required at the wind farms for generating electricity due to local manufacturing, technology innovations, governmental support, and economies of scale. It is estimated that worldwide cost of wind turbines will reduce from by 23% to 38% [46].
C14	Reduced O&M Cost	Reduction in the operating and maintenance (O&M) cost of wind farms due to technology innovations and availability of trained workforce within the country.
C15	Favoring Government Policies	Favoring policies adopted by the government to promote the wind energy deployment in the country.
C16	Availability of Trained HR for Wind Energy	Availability of trained human resources in the country for installation of equipment and smooth operation of wind farms.
C17	Ease of Maintaining Wind Farms	Ease of operations and maintenance of wind farms, including availability of spares, technical support, and maintenance infrastructure.
C18	Consistency of Policies	Consistency and stability of the government policies towards the national wind energy sector. It also includes transparency of rules and regulations.
C19	Incentives for Wind Energy Sector	Lucrative incentives for the national wind energy sector from the government such as subsidies, tax incentives, low interest loans, import duty and levy cuts/rebates/off, and other promotional policies.
C20	Private Sector Involvement	Involvement of the private sector in the wind energy sector through favoring policies and incentives.
C21	Environmental Consciousness	Increase in pollution and emissions of CO_2 and other hazardous greenhouse gases increases the environmental consciousness and concerns.
C22	Awareness to Utilize Wind Energy	Increasing awareness for utilizing the indigenous wind energy resource among the government and public.
C23	Emission Standards	Compliance of the wind energy projects with the national emission control standards.
C24	Perceived Greenness of Wind Energy	Wind energy is considered a clean and pollution free source of energy.
C26	Political Will of the Government	Political will and determination from the government through legislative and legal cover, policies, incentives, central planning, capacity building, and institutional support.
C27	Health and Safety Consciousness	Increasing health and safety consciousness among the government and public.
C28	Positive Perception towards Wind Farms	A positive perception towards wind farms in the local communities because new wind projects create employment opportunities, generate economic activities, contribute towards cleaner climate, and avoid emissions of CO_2 and other hazardous greenhouse gases.

C29	Job Creation	Creation of employment opportunities due to establishment of wind energy projects in the local communities
C30	Other usage of Wind Farm Land	Farmers and landowners can also use the land occupied by a wind farm for other purposes such as farming, cattle grazing etc.
C31	Mature and Proven Technology	Wind is a mature and proven technology and there are several examples of successful wind projects in similar conditions and environment.
C32	Regional Trends of Wind Energy Deployment	There are regional trends of wind energy utilization on a large scale in the neighboring countries of Pakistan (China and India).
C33	International Cooperation and Support	International cooperation, support, and funding opportunities for wind energy projects. Partnerships are also vital for increasing deployment of wind energy projects and access to the wind technology.
C34	Onsite Measurement and Analysis of Wind Data	Measurement and accurate analysis of wind data at the proposed sites of the potential wind farms through installation of wind masts.
C35	Availability of Wind Resource	Availability of wind resource, including both potential and quality of wind energy resource available.
C36	Grid Connectivity with Wind Farms	Connectivity of the wind farms situated at remote locations with the national electric grid.
C37	Distribution Network Upgrade	Up-gradation and improvement of the national grid in order to increase the transmission capacity, reduce losses, and improve efficiency.
C38	Stability in the Region	The regional stability and improvement in the law and order situation in the country.
C39	Demand Response and Load Balancing	Availability of emergency demand response resources, creation of load balancing areas with interconnection capacity, and integrated regional planning in order to cater for variability and intermittence nature of wind energy.
C41	Coordination Efforts of the Government	The governmental efforts to increase coordination among various ministries, government departments, and private sector companies. Establishment of a central department to facilitate new wind energy projects and coordinate the overall national research efforts.
C42	Rise in Oil Price	Steep increase in the global oil price that results in a significant increase in the cost of electricity generation.

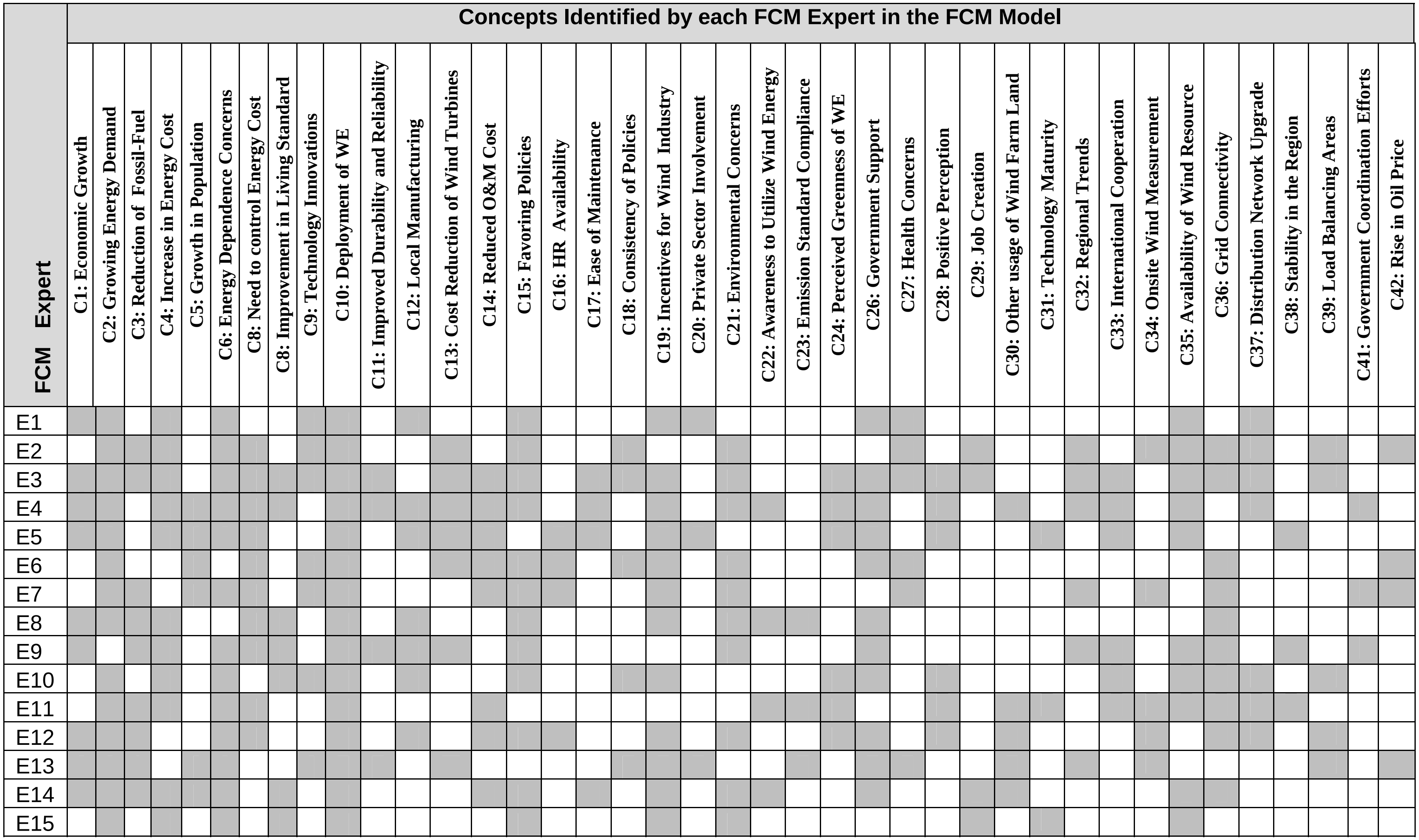

Figure 16: Concepts highlighted by each expert in their FCMs

5.1.2 Prioritization of Concepts

In the second phase of the scenario workshop, the experts identified the most important and uncertain scenario drivers (concepts) and proposed the input vectors for building the FCM-based scenarios. Figure 17 highlights the Wilson matrix created to evaluate and prioritize the impact and uncertainty of each scenario driver against two dimensions: potential impact and uncertainty. The highest priority assigned to the concepts placed in the upper right side of the matrix highlighted in blue color. The participants of the FCM workshop identified the most uncertain concepts and potential impact of the concepts is calculated based upon the weight of causal links and active scores. C2, C15, C19, C21 and C26 emerged as the most important concepts in the integrated FCM model.

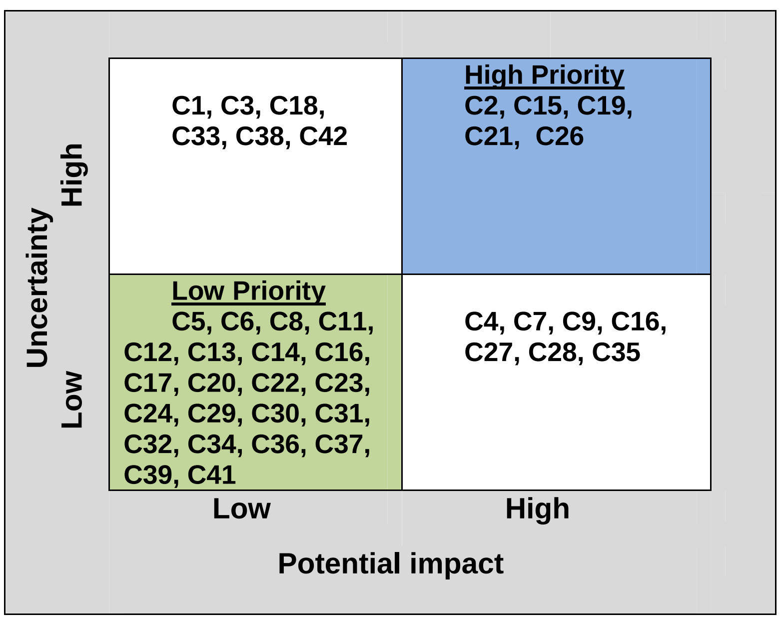

Figure 17: Wilson Matrix used to prioritize concepts (drivers)

5.1.3 Development of Input Vectors

In the FCM scenario workshop, after review of the integrated FCM, the participants were asked to highlight plausible combinations of the most important concepts (drivers) identified in the integrated FCM. The workshop moderator provided a list of the most important concepts identified through the Wilson matrix to the workshop participants. The participants were asked to highlight multiple input vectors. The input vectors consist of various plausible combinations of the important concepts. The morphological analysis was used to generate the plausible input vectors which are subsequently used to generate the FCM-based scenarios. The morphological analysis has been used for scenarios development [29, 58, 79, 269] and it can help to eliminate incompatible combinations of concepts [151].

Based upon the discussion and feedback, the workshop moderator drew five combinations of different concepts with different colors. Figure 18 highlights these input vectors shown in blue, purple, green, red, and yellow colors; they are highlighted during the scenario workshop. The morphological analysis is a useful tool because it helps to visually analyze combinations of various conceivable development variations of scenario drivers, avoids contradictions, and ensures plausibility. The following input vectors were developed in the workshop:

Input Vector 1: 2A – 15B – 19B – 21B – 26B;

Input Vector 2: 2B – 15A – 19B – 21B – 26A;

Input Vector 3: 2B – 15A – 19B – 21B – 26B;

Input Vector 4: 2B – 15B – 19B – 21A – 26B; and

Input Vector 5: 2B – 15A – 19A – 21B – 26B.

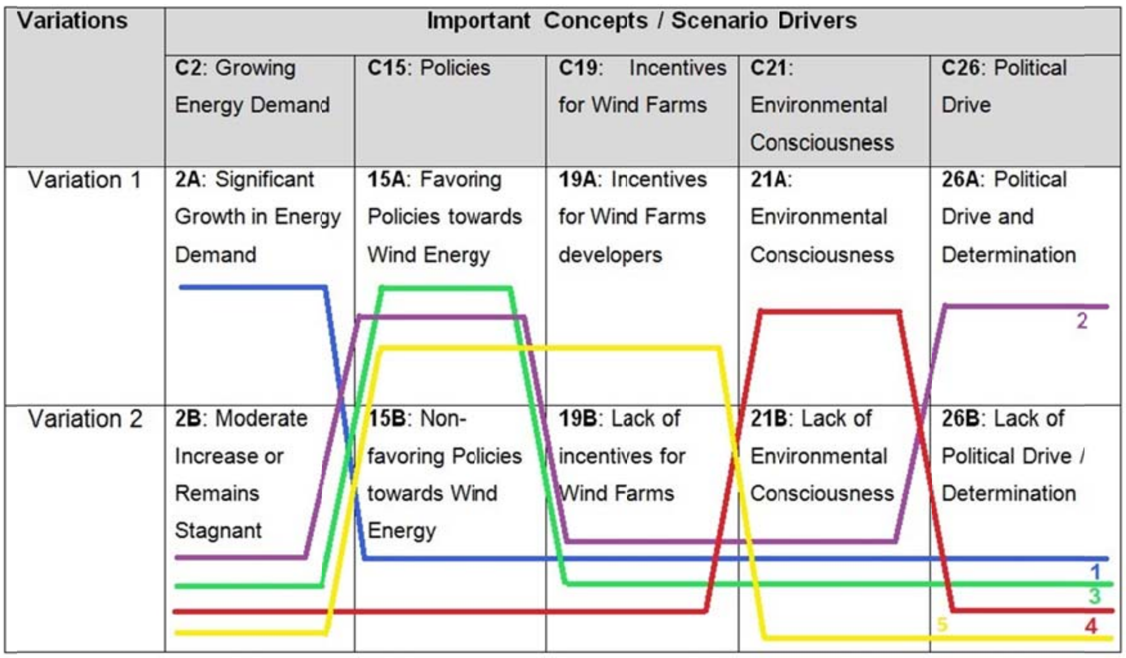

Figure 18: Morphological analysis for generating the input vectors

5.1.4 FCM Simulation and Analysis

The integrated FCM model was tested against the five input vectors. In the first scenario, the effects of economic growth and increase in energy demand were evaluated on the deployment of wind energy. In the subsequent scenarios, the effects of favoring government policies, political drive and determination of the government, incentives for the wind farms developers, and environmental consciousness were examined. In this study, the FCM model was run with a simple binary squashing function. For this squashing function, input and output values of concepts are either 0 or 1, which indicates that a concept has been turned “on” and “off”.

For the first scenario, the FCM model was evaluated against two factors: growth in energy demand and economic growth of the country. The effects of these variables on the deployment of wind energy projects in Pakistan were examined. Participants of the FCM workshop suggested combining the economic growth variable with growth in the national energy demand for the first input vector. It was suggested because both drivers (concepts) are likely to coexist. However, in both cases the FCM simulation produced similar results. For the first input, the initial states of C1 and C2 are set as 1, whereas the initial states of all other concepts are 0. The states of C1 and C2 are clamped to always be on (1). The concepts which are turned on (1) in the subsequent inference vectors are mentioned in Table 20.

Table 20: Results of the FCM simulation for the first input vector
*States of C1 and C2 are clamped to always be 1 (on).

Results of FCM Simulation for the First Input Vector	
Input Vector	C1*, C2*
First Inference Vector	C1*, C2*, C3, C4, C6, C10
Second Inference Vector	C1*, C2*, C3, C4, C6, C7, C10
Third Inference Vector	C1*, C2*, C3, C4, C6, C7, C10, C22
Fourth Inference Vector	C1*, C2*, C3, C4, C6, C7, C10, C22

For this scenario, assumptions were made that the country will continue to make an economic growth and the national energy demand will continue to increase. FCM simulation was conducted and a simple binary squashing function was applied. The output vector became stable after the fourth iteration. As a result, C1, C2, C3, C4, C6, C7, C10, and C22 were activated in the end. Details of the FCM simulation are given in Appendix I.

In the first scenario, the energy demand is growing and there is a growth in the national economy. The output vector indicates that eight concepts are turned on, which is a plausible outcome under the given input conditions. The FCM simulation results for the first scenario highlight that growth in the national economy and energy demand will result in the deployment of wind energy projects in the country (concept 10 is on). Moreover, due to these conditions, it is likely that the cost of electricity will increase because the national power sector is highly dependent on thermal resources (mainly imported oil and natural gas), local / indigenous reserves of natural gas within the country will sharply deplete, energy dependence concerns will increase, and a strong desire will emerge to reduce dependence on imported energy resources in order to control and stabilize the cost of electricity. These factors will also create or increase awareness for utilizing wind energy resource among all sectors of the society (public and government). Due to the economic growth and higher energy demand, there will be a rise in the deployment of wind energy projects on a large scale in the country. It is an interesting scenario because it indicates that despite the absence of favoring policies, wind farms will be deployed in the country.

For the second input vector, the FCM model was tested against two variables (concepts): favoring government policies and political determination from the government to promote the wind energy in the country. The results of the FCM simulation for the second input vector are shown below. The initial states of C15 and C26 are set as 1, whereas the initial states of all other concepts are 0. The states of C15 and C26 are clamped to always be 1 (on). The concepts which are turned on (1) in the subsequent inference vectors are shown in Table 21.

Table 21: Results of the FCM simulation for the second input vector
*States of C15 and C26 are clamped to always be 1 (on).

Results of FCM Simulation for the Second Input Vector	
Input Vector	C15*, C26*
First Inference Vector	C12, C13, C15*, C16, C19, C20, C26*, C33
Second Inference Vector	C10, C12, C13, C14, C15*, C16, C17, C19, C20, C26*, C33
Third Inference Vector	C10, C12, C13, C14, C15*, C16, C17, C19, C20, C26*, C33

Assumptions were made that there is a strong support and determination by the government to promote wind energy in the country, and favoring policies have been adopted in this regard. The FCM simulation was conducted again, and the simple binary squashing function was applied. On this occasion, the output vector became stable after the third iteration. The result of the simulation indicates that C10, C12, C13, C14, C15, C16, C17, C19, C20, C26, and C33 are activated.

In the second scenario, the effects of the favoring policies and government support were examined on the deployment of wind energy projects. The output vector indicates that eleven concepts are turned on, and again this is a plausible outcome under the given input conditions. The simulation results for the second scenario indicate deployment of wind energy projects in the country (concept 10 is on). Moreover, government support and favoring policies are likely to initiate manufacturing of equipment (i.e. wind turbines and supporting equipment) within the country, cost reduction of wind turbines and supporting equipment required at wind farms, reduction in operations and maintenance (O&M) cost of wind farms, availability of trained human resources for the wind industry, ease of operations and maintenance of wind farms, incentives for the national wind energy sector, involvement of the private sector in the wind energy sector, and availability of international support, cooperation and funding opportunities for wind energy projects. Due to this favorable and conducive environment, there will be a rise in the deployment of wind energy projects in the country.

For the third input vector, the FCM model was tested against one concept, i.e. favoring government policies to the national wind energy sector. However, the FCM simulation results for the third input vector were similar to the second input vector. Therefore, it is not useful to use raw scenario developed from the third input vector.

For the fourth input vector, the behavior of the FCM model is examined against the environmental consciousness. The simulation results for the fourth input vector are shown in the following table. The initial state of concept C21 is set as 1, whereas the initial states of all other concepts are 0. Moreover, the state of C21 is clamped to always be 1 (on). The concepts which turned on (1) in the subsequent inference vectors are mentioned in Table 22.

Table 22: Results of the FCM simulation for the fourth input vector
*State of C21 is clamped to always be 1 (on).

Results of FCM Simulation for the Fourth Input Vector	
Input Vector	C21*
First Inference Vector	C15, C21*, C22, C23
Second Inference Vector	C10, C12, C13, C15, C16, C19, C20, C21*, C22, C23
Third Inference Vector	C10, C12, C13, C14, C15, C16, C17, C19, C20, C21*, C22, C23
Fourth Inference Vector	C10, C12, C13, C14, C15, C16, C17, C19, C20, C21*, C22, C23

An assumption is made that the environmental consciousness is growing among the public and government due to increases in pollution, emissions of CO_2 and other hazardous gases. Again, the FCM simulation was conducted and the simple binary squashing function was applied. The output vector became stable after the third iteration. The result of the simulation indicates that C10, C12, C13, C14, C15, C16, C17, C19, C20, C21, C22, and C23 are activated.

Participants of the FCM scenario workshop recommended that the environmental concerns and health & safety concerns are interlinked and recommended combining these two variables. For the FCM simulation, the initial states of concept C21 and C27 are set as 1, whereas the initial states of all other concepts are 0. The states of C21 and C27 are clamped to always be 1 (on). The concepts which turned on (1) in the subsequent inferences are shown in Table 23.

Table 23: Results of the FCM Simulation for the modified fourth input vector
*States of C21 and C27 are clamped to always be 1 (on).

Results of FCM Simulation for the Modified Fourth Input Vector	
Input Vector	C21*, C27*
First Inference Vector	C15, C21*, C22, C23, C27*, C28
Second Inference Vector	C10, C12, C13, C15, C16, C19, C20, C21*, C22, C23, C27*, C28
Third Inference Vector	C10, C12, C13, C14, C15, C16, C17, C19, C20, C21*, C22, C23, C27*, C28
Fourth Inference Vector	C10, C12, C13, C14, C15, C16, C17, C19, C20, C21*, C22, C23, C27*, C28

In this scenario, the effects of the growing environmental, health, and safety concerns are studied for the deployment of wind energy. The output vector indicates that fourteen concepts are turned on. This outcome is also plausible under the given input conditions. The simulation results for the third scenario indicate widespread deployment of wind energy projects in the country (concept 10 is on). Moreover, growing environmental, health, and safety concerns will result in the formulation of favoring policies towards the wind energy sector, initiate manufacturing of equipment (i.e. wind turbines and supporting equipment) within the country, cost reduction of wind turbines and supporting equipment required at wind farms, reduction in the O&M cost of wind farms, availability of trained human resources to support the wind industry, ease of operations and maintenance of wind farms, incentives for the wind energy sector, involvement of the private sector in the national wind energy sector, awareness of utilizing the indigenous wind energy resources, and strict compliance with emission standards. Due to these factors, a positive perception towards wind farms will be created in the country, and there will be a rise in the deployment of wind energy projects in the country.

For the fifth input vector, the FCM model was tested against two concepts, i.e. favoring government policies and incentives for wind farm developers. Again, the FCM simulation for the fifth input vector generated the results similar to the second and third input vectors.

As a result of FCM simulation, all the scenarios highlighted a positive trend toward deployment of wind farms, but each scenario indicated different barriers, challenges, and deployment paths. Moreover, all the developed scenarios are quite plausible. The scenario planning literature also emphasizes the need to identify weak signals, surprises and unexpected futures. Thus, this research has not been able to create heterogeneous scenarios. This limitation might be due to the participants of the FCM expert panel and their feedback. The researcher tried to balance the expert panels and the experts were selected from the government departments, universities, utilities, and private companies working in the wind energy sector of Pakistan. However, despite this limitation, the developed scenarios provide a detailed overview of the probable future landscape of the national wind energy sector. Thus, the scenarios are useful for the long-term strategic planning and developing technology roadmaps.

5.1.5 Discussion

The approach taken in this study - the capture of individual causal maps, their mathematical integration, and the discussion of the integrated map in a workshop setting - resulted in a usable FCM model that the workshop team was able to agree to. The resulting model contains each expert's partial model of the subject matter and thus preserves diversity of opinion. However, the model has some potential limitations, namely missing links, definitional relationships, lack of feedback cycles, and different time frames [153, 156].

Missing links occur when concepts remain unconnected even though the experts believe them to be interdependent. For example, in Figure 15, experts are likely to agree that economic growth (C1) will result in improved living standards (C8), yet the concepts are unconnected. Definitional relationship occur when experts use concepts and causal links to elaborate on a concept meaning, rather than to model causality [156]. For example, the link between Rise in Oil Prices (C42) and Increasing in Energy Costs (C4) shows two facets of the identical phenomenon, not true causality in that sense that C4 rises because and after C42 increases. Lacking feedback cycles are commonly understood as an indicator of limited system knowledge in complex dynamic systems. For example, given the constraints that current energy shortages put on the Pakistani economy, most experts would agree that increased wind energy deployment (C10) will positively impact economic growth (C1). Through multiple pathways, C1 is linked to wind energy deployment, thus potentially generating a virtuous cycle until some level of saturation is reached. These feedback loops are not visible in the integrated FCM [300]. Different timeframes characterize a situation when the time lag to activation between some concepts is very short (e.g. minutes or days) and between others is very long (e.g. years or even decades). This is problematic because in FCM computation, each arrow responds to one iteration. One such example is the link between improved living standards (C8) and increased energy demand (C2) which happens with such little time lag that standard of living is sometimes measured in per capita energy consumption. On the other hand, the time it takes for political will of the government to translate into improved domestic manufacturing may be years.

These potential problems with the expert generated map are partially owed to the workshop situation. A significant amount of workshop time was consumed in defining the meaning of all the concepts, and less time was available for the experts to review the FCM. The FCM literature therefore proposes standard approaches to reducing the effort needed for concept [156, 231]. It furthermore provides a variety of approaches to pre-process FCM models before actual FCM simulations in order to identify missing links, delete definitional variables, standardize timeframes and improve experts' awareness for interdependencies [76, 156]. Many FCM studies, however, chose to accept FCM as a "quick and dirty" approach to modeling the worldviews of experts, which are inherently subjective and limited. FCM in this context are used as communication tool to guide the discussion and structure the scenario planning process [334]. By using the results of the FCM simulations solely as an input for in-depth scenario discussions, this study follows this approach.

The input vectors used for conducting simulation consist of the important concepts based on their potential impact and uncertainty. It was revealed that some concepts that are endogenous to the model also emerged as the critical scenario drivers. For example growing energy demand (C2) is dependent on economic growth (C1), population growth (C5), and improvements in living standards (C8). However, these problems were avoided by clamping an exogenous concept with the important endogenous concepts. For example C1 was clamped with C2 in the first input vector and C26 was clamped with C15 in the second input vector.

One general concern with the FCM simulation results in this study is that all scenarios led to an increase in the deployment of wind energy in the country, even though scenario studies commonly result in more heterogeneous outcomes. There are two alternative explanations for this result, namely (1) the FCM method is to granular and therefore incapable of generating diverse scenarios for the relatively small input vector variations considered feasible by the experts, and (2) the participating experts' believe so strongly in the future deployment of wind energy that their mental models do not allow different overall outcomes, but only variations with regard to the barriers, challenges, and the wind energy deployment paths. To investigate if the similarity of scenario outcomes is an inherent limitation of the FCM method, two additional studies were undertaken.

In the following sections the integrated FCM model is further analyzed by applying a different squashing function and introducing wild cards in order to generate some heterogeneous scenarios. Hyperbolic tangent function is applied to the model as a squashing function. Research indicates that use of a different squashing function leads to different model outcomes [152, 156]. In section 5.1.5.2, wild cards are applied to the FCM model. Wild cards are often used to augment the scenario planning exercise; they help in identifying weak signals and unexpected futures. Thus, wild cards can help to identify a radically different scenario from this FCM model.

5.1.5.1 Hyperbolic Tangent Function

The FCM simulation is conducted again with a different squashing function to examine the behavior of the integrated FCM model. A bipolar sigmoid function, hyperbolic tangent function (*tanhx*), is used. The hyperbolic tangent function is a mathematical function, and it is recommended in the literature for conducting the FCM simulations [35, 152]. It gives values of the concepts in the range of -1 to 1 [35]. One advantage of using the hyperbolic tangent function is that it also highlights the degree or extent: a concept is on or off such as “slightly on”, “slightly off”, etc. A hyperbolic tangent function drawn for values between -1 to 1 is shown in Figure 19.

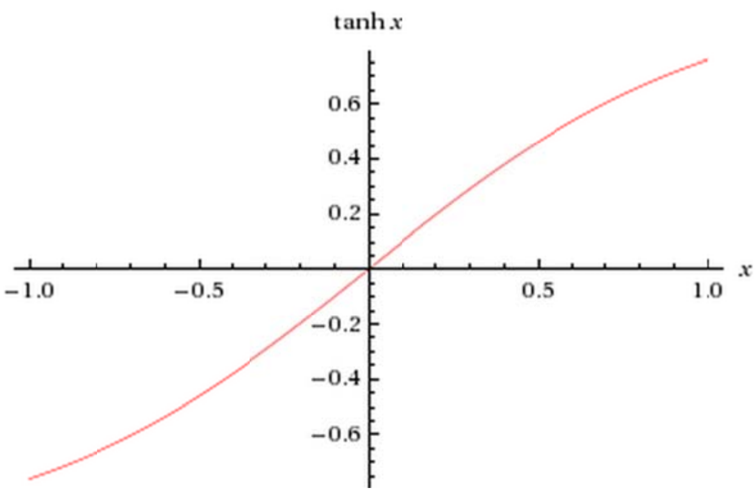

Figure 19: Hyperbolic Tangent Function drawn for values between -1 to 1

The input vectors presented in Section 5.1.3 are again used to conduct the FCM simulation. Simulation begins with the definition of the input vector, which represents a proposed situation. The simulation results for the first input vector are shown in the following table. The initial states of C1 and C2 are set as 1, whereas the initial states of all other concepts are 0. The states of C1 and C2 are clamped to always be on (1). FCM simulation is conducted and the hyperbolic tangent function is applied as a squashing function. The output vector became stable after the fourth iterations. C1, C2, C3, C4, C6, and C10 are activated in the end. C7 and C22 are slightly off, and all other concepts are off.

Table 24: Results of the FCM simulation for the first input vector
*States of C1 and C2 are clamped to always be 1 (on).

Results of FCM Simulation for the First Input Vector								
Input Vector	C1*	C2*						
	1	1						
First Inference Vector	C1*	C2*	C3	C4	C6		C10	
	1	1	0.54	0.54	0.54		0.54	
Second Inference Vector	C1*	C2*	C3	C4	C6	C7	C10	
	1	1	0.54	0.77	0.73	0.31	0.77	
Third Inference Vector	C1*	C2*	C3	C4	C6	C7	C10	C22
	1	1	0.54	0.77	0.81	0.43	0.88	0.18
Fourth Inference Vector	C1*	C2*	C3	C4	C6	C7	C10	C22
	1	1	0.54	0.77	0.82	0.43	0.93	0.25

In this scenario, assumptions are made that the energy demand is growing and there is a growth in the national economy. The output vector indicates that six concepts are turned on. The FCM simulation results highlight that growth in the national economy and energy demand will result in the deployment of wind energy projects in the country. Moreover, due to these conditions, it is likely that the cost of electricity will increase, the indigenous reserves of natural gas in the country will deplete, and energy dependence concerns will increase a strong desire to reduce dependence on the imported energy resources. In this case, unlike the simulation results with the binary squashing function, C7 (need to control energy/electricity cost) and C22 (awareness for utilizing wind energy resource among all sectors of society) are slightly off. The simulation results also indicate a rise in the deployment of wind energy projects on a large scale in the country.

Similarly, for the second input vector, the FCM model was tested against two variables (concepts): favoring government policies and political will and determination from the government to promote wind energy in the country. The initial states of C15 and C26 are set as 1, whereas the initial states of all other concepts are 0. The states of C15 and C26 are clamped to always be 1 (on). The FCM simulation results for the second input vector using the hyperbolic tangent function are shown in Table 25.

Table 25: Results of the FCM simulation for the second input vector
*States of C15 and C26 are clamped to always be 1 (on)

Results of FCM Simulation for the Second Input Vector											
Input Vector					C15*					C26*	
					1					1	
First Inference Vector		C12	C13		C15*	C16		C19	C20	C26*	C33
		0.66	0.54		1	0.38		0.66	0.54	1	0.66
Second Inference Vector	C10	C12	C13	C14	C15*	C16	C17	C19	C20	C26*	C33
	0.93	0.66	0.7	0.22	1	0.38	0.22	0.66	0.81	1	0.66
Third Inference Vector	C10	C12	C13	C14	C15*	C16	C17	C19	C20	C26*	C33
	0.97	0.66	0.7	0.22	1	0.38	0.22	0.66	0.81	1	0.66
Fourth Inference Vector	C10	C12	C13	C14	C15*	C16	C17	C19	C20	C26*	C33
	0.97	0.66	0.7	0.22	1	0.38	0.22	0.66	0.81	1	0.66

For this scenario, assumptions are made that there is a strong support and determination by the government to promote the wind energy technology in the country, and favoring policies have been adopted in this regard. The hyperbolic tangent function is applied and the output vector became stable after the fourth iteration. The results of the simulation indicated that C10, C12, C13, C15, C19, C20, C26 and C33 are on.

In this scenario, the effect of the favoring policies and government support is examined using the hyperbolic tangent squashing function. The output vector indicates deployment of wind energy in the country. Moreover, favoring policies by the government are likely to initiate local manufacturing of wind turbines and supporting equipment, cost reduction of wind turbines and supporting equipment required at wind farms, incentives for the national wind energy sector, involvement of the private sector, and availability of international support, cooperation, and funding opportunities for wind energy projects.

In this case, as a result of using a different squashing function, C14 (reduction in operations and maintenance cost of wind farms), C16 (availability of trained human resources for the wind industry), and C17 (ease of operations and maintenance of wind farms) are slightly off. However, due to an overall favorable and conducive environment, there will be a rise in the deployment of wind energy projects on large scale in the country.

Again, for the third input vector, FCM simulation generated similar results for the second input vector.

Similarly, for the fourth input vector, the behavior of the FCM model was tested against environmental consciousness using the hyperbolic tangent function. Thus, the initial state of concept C21 is set as 1, whereas the initial states of all other concepts are 0. The state of C21 is clamped to always be 1 (on). The results of the FCM simulation for the fourth input vector are mentioned in Table 26.

Table 26: Results of the FCM simulation for the fourth input vector
*State of C21 is clamped to always be 1 (on)

Results of FCM Simulation for the Fourth Input Vector												
Input Vector										C21*		
										1		
First Inference Vector					C15					C21*	C22	C23
					0.66					1	0.54	0.38
Second Inference Vector	C10	C12	C13		C15	C16		C19	C20	C21*	C22	C23
	0.41	0.26	0.38		0.66	0.26		0.49	0.38	1	0.64	0.38
Third Inference Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23
	0.89	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.64	0.38
Fourth Inference Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23
	0.95	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.64	0.38
Fifth Inference Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23
	0.95	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.64	0.38

An assumption is made that the environmental consciousness is growing among the public and government due to increases in pollution and emissions of the hazardous greenhouse gases. FCM simulation is conducted and the hyperbolic tangent squashing function is applied. On this occasion, the output vector became stable after the fourth iteration. The result of the simulation indicates that C10, C15, C19, C20, C21, and C22 are activated. However, as a result of using a different squashing function, C12, C13, C14, C16, C17, and C23 are slightly off. These concepts also turned on when the binary squashing function was applied.

Finally, the hyperbolic tangent squashing function is applied again to the modified fourth input vector. In this case, the initial states of concept C21 (environmental concerns) and C27 (health & safety concerns) are set as 1, whereas the initial states of all other concepts are 0. The states of C21 and C27 are clamped to always be 1 (on). Table 27 highlights the simulation results.

Table 27: Results of the FCM Simulation for the modified fourth input vector
*States of C21 and C27 are clamped to always be 1 (on)

Results of FCM Simulation for the Modified Fourth Input Vector														
Input Vector										C21*			C27*	
										1			1	
1st Infere-nce Vector					C15					C21*	C22	C23	C27*	C28
					0.66					1	0.83	0.38	1	0.54
2nd Infere-nce Vector	C10	C12	C13		C15	C16		C19	C20	C21*	C22	C23	C27*	C28
	0.76	0.26	0.38		0.66	0.26		0.49	0.38	1	0.93	0.38	1	0.54
3rd Infere-nce Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23	C27*	C28
	0.96	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.93	0.38	1	0.54
4th Infere-nce Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23	C27*	C28
	0.98	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.93	0.38	1	0.54
5th Infere-nce Vector	C10	C12	C13	C14	C15	C16	C17	C19	C20	C21*	C22	C23	C27*	C28
	0.98	0.26	0.46	0.15	0.66	0.26	0.15	0.49	0.66	1	0.93	0.38	1	0.54

In this scenario, the effects of the growing environmental, health and safety concerns are studied on the deployment of wind energy. The output vector indicates that eight concepts are turned on. The simulation results for this scenario also indicate a positive trend towards the deployment of wind energy projects in the country. Moreover, growing environmental, health and safety concerns will result in the formulation of favoring government policies towards the national wind energy sector, and incentives will be offered to the wind farm developers resulting in involvement of the private sector. It will also increase awareness of utilizing the wind energy resource, create a positive perception towards the wind farms, and subsequently it will result in the deployment of wind energy projects on a large scale in the country.

However, as a result of using a different squashing function, C12 (manufacturing of wind turbines and supporting equipment within the country), C13 (cost reduction of wind turbines and supporting equipment required at wind farms), C14 (reduction in operating and maintenance cost of wind farms), C16 (availability of trained human resources for the local wind industry), C17 (ease of operations and maintenance of wind farms), and C23 (compliance with the national emission standards) are slightly off. These concepts turned on when the binary squashing function was applied. However, in both cases there will be a rise in the deployment of wind energy projects on a large scale in the country. Similarly, for the fifth input vector, FCM simulation again generated similar results for the second and third input vector.

Although the simulation results indicate a positive trend towards wind energy deployment when hyperbolic tangent function is applied; there are several differences with the use of different functions summarized in the following table.

Table 28: Differences in the simulation outcome with different squashing functions

Differences in the Results with Different Squashing Functions		
Scenario	**Simple Binary Function**	**Hyperbolic Tangent Function**
Scenario A	C7 turned on	C7 turned off
	C22 turned on	C22 turned off
Scenario B	C14 turned on	C14 turned off
	C16 turned on	C16 turned off
	C17 turned on	C17 turned off
Scenario C	C12 turned on	C12 turned off
	C13 turned on	C13 turned off
	C14 turned on	C14 turned off
	C16 turned on	C16 turned off
	C17 turned on	C17 turned off
	C23 turned on	C23 turned off

As mentioned earlier, the hyperbolic tangent function also highlights the degree or extent, a concept is on or off. The following table highlights the simulation results for concept C10 (wind energy deployment) against all scenarios. Among these scenarios, the deployment of wind energy trend is highest against scenario C. However, in all scenarios there is a positive trend towards the deployment of wind energy projects in Pakistan.

Table 29: Results of the FCM simulation for concept C10

Results of FCM Simulation for C10	
Scenario A (First Input Vector)	0.93
Scenario B (Second Input Vector)	0.97
Fourth Input Vector	0.95
Scenario C (Modified Fourth Input Vector)	0.98

5.1.5.2 Use of Wild Cards

Through the use of wild cards, the experts can foresee unexpected futures and identify the weak signals. The wild card refers to sudden and unique incidents that can constitute turning points in the evolution of a certain trend [205]. A list of wild card events is developed to augment a scenario planning exercise. These events have very low probability, but if they were to occur they would have a very high impact on the future [128, 204]. The wild card scenarios are developed to make robust plans in turbulent environments [205]. The wild cards also help strategic planners to develop signposts for indicating that an assumption is being violated [74].

It has been recommended to analyze the wild cards (possible disruptive events) and their subsequent effects on the subject under study in order to develop preventive measures and reduce the worst effects of these events [344]. Generally, the wild cards result in the creation of a disruptive or worst-case scenario and help to analyze the effects of these events. Some commonly used wild cards are: technological breakthroughs in a specific area, an ecological disaster, a stock exchange crash, a financial crisis, a sudden regional war or nuclear war, and massive terrorism attack [73, 344].

The following wild card events are created for this research:

- Discovery of gigantic reserves of natural gas and oil in the country; and

- Technological breakthroughs in nuclear power resulting in generation of electricity at a very low price through nuclear power plants.

These wild cards are added to the FCM model, and necessary changes are made to accommodate these wild cards in the model. These two variables have similar influences on the other concepts highlighted by causal links. The modified FCM is shown in Figure 20.

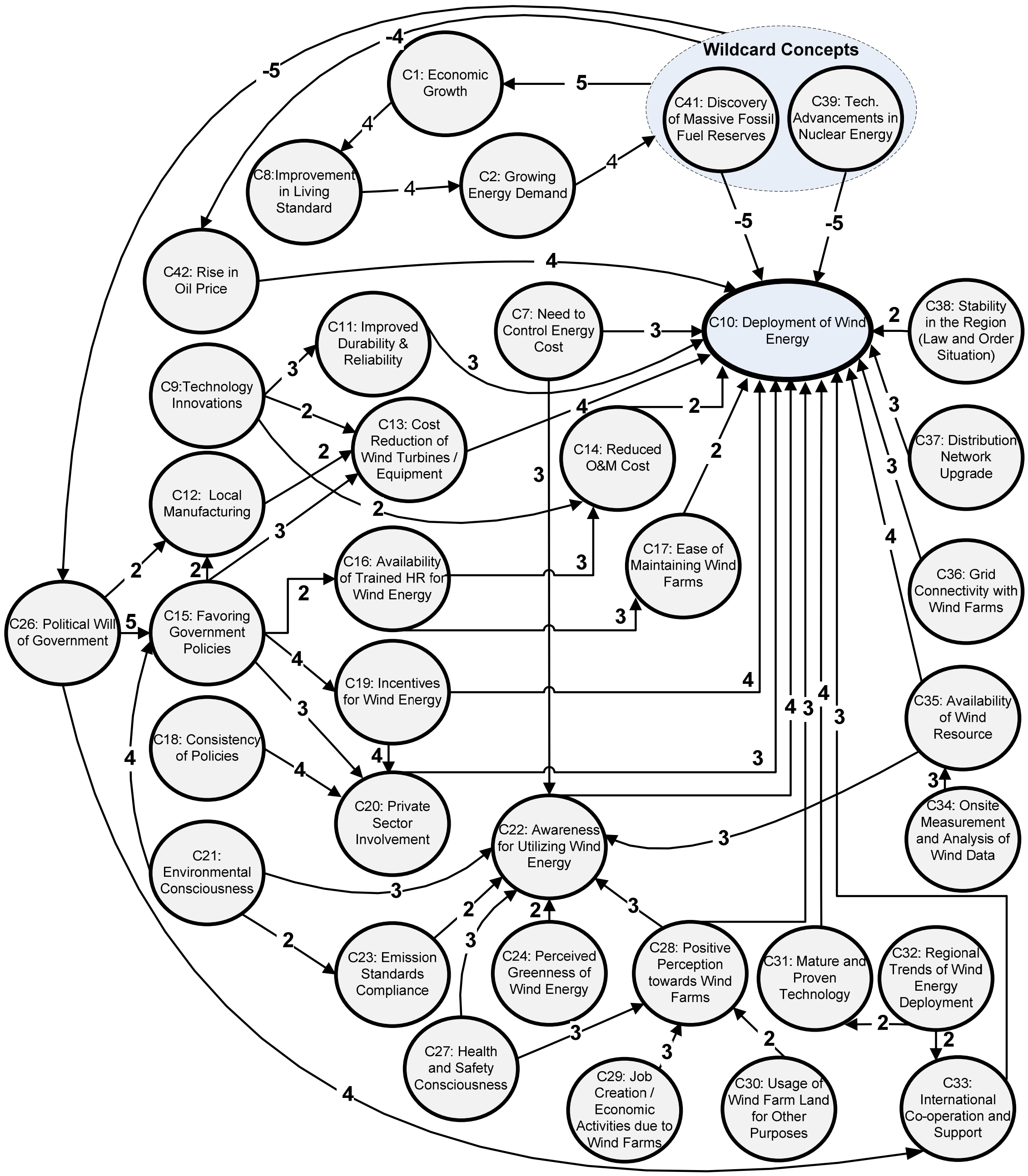

Figure 20: Integration of the wild cards in the FCM model

The FCM modified through the wild cards is evaluated against two factors: discovery of massive amount natural gas and oil in the country (Concept 41); and technological breakthroughs in nuclear power resulting in generation of electricity at a very low price (Concept 39). The effect of these wild card variables on the deployment of wind energy projects in Pakistan is examined.

The results of FCM simulation for this scenario are shown in the following table. The initial states of C39 and C41 are set as 1, whereas the initial states of all other concepts are 0. The states of C39 and C41 are clamped to always be on (1). The simple binary squashing function is applied. The concepts which are turned on (1) in the subsequent inferences are mentioned in Table 30.

Table 30: Results of the FCM simulation with the wild cards
*States of C39 and C41 are clamped to always be 1 (on)

Results of FCM Simulation for FCM modified with the Wild Cards	
Input Vector	C39*, C41*
First Inference Vector	C1, C39*, C41*
Second Inference Vector	C1, C8, C39*, C41*
Third Inference Vector	C1, C2, C8, C39*, C41*
Fourth Inference Vector	C1, C2, C8, C39*, C41*

Assumptions are made that there have been technological breakthroughs in nuclear power resulting in generation of electricity at a very low price and discoveries of massive amounts of natural gas and oil reserves in the country. The simple binary squashing function is applied to the FCM simulation. On this occasion, the output vector became stable after the fourth iteration. C1, C2, C8, C39, and C41 are activated in the end. Moreover, there will be a negative effect on the deployment of wind energy projects in the country. There will be a lack of political will from the government to promote the wind energy sector, absence of policy measures to support the wind energy sector, and the price of oil will reduce or remain stable in the country.

This is a worst-case scenario for the national wind energy sector. The output vector indicates that five concepts are turned on. The FCM simulation results indicate that discovery of massive amounts of fossil fuel reserves and technological innovations in nuclear energy will have a very positive impact on the national economy, improve the living standards, and subsequently it will raise the energy demand in the country. However, this scenario indicates a negative tendency towards deployment of wind energy projects in the country (concept 10 is off). Moreover, due to these conditions, there will be a lack of political support from the government for the wind energy sector, and an absence of favoring policies and incentives for the deployment of wind energy projects.

Energy security, financial limitations, environmental consciousness, and the need to control energy cost were the major concerns in the developed scenarios presented in Section 5.1.4. But in this scenario, due to abundance of energy resources available at low cost, wind energy is not a promising alternative. The lack of political will from the government and unavailability of favoring policies are the major challenges faced by the national wind energy sector in this scenario. The civil society and environmental pressure groups have to take a proactive approach and push hard to promote renewable energy resources in the country.

Due to economic growth in the country, financial constraints will not hinder the deployment of wind energy projects on a large scale. However, significant efforts are required to persuade the government to formulate favoring policies and offer lucrative incentives to the wind farm developers. In this scenario, it will be vital to highlight the environmental degradation caused by the growing energy utilization and emission of greenhouse gases and hazardous materials from the fossil-fuel based power plants. It is also required to highlight the benefits of the renewable energy resources such as wind energy. Moreover, it is critical to highlight the impact of environmental damage and pollution on human health and wellbeing. Due to improvements in the living standards, people will be more concerned about their health and environmental issues.

It is an interesting scenario and significantly different from the other three scenarios developed in the previous section. This scenario indicates a negative trend towards the deployment of wind energy projects in the country. It also demonstrates that the FCM-based scenario development approach has the capability of developing multiple and radically different scenarios. Moreover, development of this type of worst-case scenario will allow the important stakeholders to foresee and envisage different strategies for the deployment of wind energy projects in a challenging environment and with the absence of favoring government policies.

5.2 Data Collection for Technology Roadmap Development

A series of three workshops and two follow-up surveys were conducted to obtain the expert judgment and develop the technology roadmap. A separate workshop was conducted to ascertain the roadmap objectives and targets, identify the roadmap barriers, and propose the roadmap action items. After the roadmap barriers workshop, two follow-up surveys were conducted to rank and prioritize the roadmap barriers against each scenario. In the third workshop, the TRM EP2 members also assigned responsibilities for the roadmap action items to the major stakeholders.

5.2.1 Roadmap Objectives and Targets Workshop

This workshop was conducted to identify and establish the strategic objective and national targets of the wind energy roadmap for the next 20 years. It was the first workshop for the roadmap development. The national renewable energy policy of Pakistan was used as a baseline document for establishing the objective and national targets of the wind energy roadmap [110]. The workshop agenda and handout documents highlight the purpose of the workshop and focus questions were provided to the participants (members of the TRM EP1) three weeks prior to the workshop (attached as Appendix C).

During the workshop, the participants discussed, deliberated, and identified the strategic objectives of the roadmap in accordance with the national renewable energy policy. The workshop participants used the worksheets developed for the roadmap objectives and targets workshop. The following strategic objectives were identified for the roadmap:

- **Energy Security**

  The country can ensure national energy security by increasing the share of the indigenous energy resources like wind energy in the national energy mix. It will reduce the national dependence on imported fossil-fuel and help to achieve the national targets of electricity generation from renewable resources.

- **Economic and Social Benefits**

  Pakistan has very limited fossil-fuel reserves, and it is estimated that approx. 60% of the foreign exchange is spent for the import of energy [306]. Moreover, increasing and fluctuating global energy prices impact the economic stability and put extra burden on the national economy. Deployment of wind energy on a large scale will provide numerous economic and social benefits. The major benefits are savings from energy imports, empowerment and income generation amongst the deprived sections of society, creation of new business opportunities, and development of local wind industry to support renewable energy technologies. In addition, development of a wind energy manufacturing base in the country will not only reduce the cost of equipment, but it will also create employment opportunities and contribute to the national economy. More than 70% of the population in Pakistan lives in the rural areas, where access to electricity is limited [280]. Wind technology can provide a promising solution to the electricity shortage problems. It will improve living standards of the communities living in those areas.

- **Environmental Sustainability**

  Deployment of the wind energy projects in the country will help to reduce the environmental pollution, emission of greenhouse gases, and other environmental degradation risks. Research studies indicate that one wind turbine of 1.5 MW capacity can reduce 2700 tons of CO_2 emission per year [16]. Presently over reliance on fossil-fuels is negatively affecting the environment and it makes energy use unsustainable.

In the second phase of this workshop, the participants established the national targets for the wind energy sector for the next 20 years. Again, the national renewable energy policy of Pakistan was used as a baseline document for establishing the national targets. The following national targets were established in the workshop:

- Generation of 1700 MW of electricity from wind energy by the year 2015;
- Generation of 9700 MW of electricity from wind energy by the year 2030;
- Development of the local wind industry and domestic manufacturing base;
- Reducing national dependence on imported fossil-fuel by utilizing the indigenous wind energy resources.

5.2.2 Roadmap Barriers Workshop

In order to systematically identify and address the barriers and challenges faced by the wind energy sector of Pakistan, the roadmap barriers workshop was conducted. In this workshop, the experts were asked to deliberate, identify and explore barriers and challenges towards the deployment of wind energy projects in Pakistan. Based on the literature review on the wind energy and renewable energy sector of Pakistan, and integrated FCM model; critical barriers and challenges to the widespread use of wind energy technology were identified. This information was given to the members of TRM EP2 through the roadmap barrier workshop agenda and handout documents, three weeks before the workshop. During the roadmap barrier workshop, the experts were asked to add additional barriers and challenges if they think that some important barriers are not included in the handout. The agenda and handout documents for the roadmap barrier workshop are attached as Appendix D.

Numerous barriers and challenges were identified during the workshop, ranging from absence of suitable policies to lack of infrastructure required to support the national wind energy sector. The workshop participants also deliberated the meaning of the roadmap barriers. In the next roadmap workshop, appropriate action items were proposed to overcome the roadmap barriers. Therefore, it was vital to identify and prioritize roadmap barriers. The major barriers and challenges identified during the workshop, which hinders the deployment of wind energy projects in Pakistan, are discussed below:

a. Policy Barriers [6, 47, 169, 214, 216, 265, 281, 306]

The lack of supportive legislations, absence of effective national renewable energy policies, and inconsistencies of the government policies are the major policy barriers. These policy barriers hinder development of wind energy projects and effective policies can significantly increase wind energy penetration in the country. Suitable policy instrument covers power purchase agreements, well-defined policies for the private sector participation, guidelines for land allotments, speedy clearance process for the wind farms, subsidies, and incentives for power generation from wind energy. The government has not implemented any mandatory renewable portfolio standards mechanism or voluntary targets. The favoring policies offer attractive incentives which may nurture the wind industry.

b. Lack of Competition with Conventional Power Generation

This is one of the principal reasons for the slow uptake of the wind energy technology in Pakistan. Despite some tax exemption to the national wind energy sector, wind technology has high capital investment cost as compared to the other technologies based on fossil-fuels. Unavailability of the domestic manufacturing industry results in import of wind turbines and other related equipment, which drives the cost of a wind power project up even further. Moreover, heavy furnace oil is heavily subsidized as compared to wind power technology, which further hinders the deployment of wind power technology in Pakistan.

These factors, taken together, result in wind power sector being unable to compete with conventional means of power generation. Therefore, the incentives and subsidies given for the wind energy sector in the current National Renewable Energy Policy are not enough to stimulate significant growth of the wind power sector in Pakistan.

c. Institutional Barriers [169, 214, 216, 217, 305]

Institutional support plays a critical role for the identification, promotion and implementation of wind energy technology. There is a lack of institutional support and only a few institutes are working to promote renewable energy technologies in Pakistan. Moreover, there is a lack of coordination and cooperation within and between various ministries, agencies, institutes and other stakeholders. Institutional inertia also results in resistance on the part of officials from different organizations / departments to share their knowledge / information with others. Pakistan has a history of poor coordination and cooperation between governmental agencies.

Absence of a central body for the overall coordination of all activities in the national wind energy sector also results in duplication of the efforts. This lack of coordination and cooperation among the government agencies, institutions, ministries and stakeholders result in procedural delays in the approval process and subsequent deployment of wind power projects. There was even no governmental body responsible for the planning and development of renewable energy policies in Pakistan prior to the founding of the Alternative Energy

Development Board (AEDB). These institutional barriers delay and restrict the progress in the wind energy development and commercialization.

Due to these institutional barriers, the process of obtaining approval for the wind energy projects is very lengthy. There was much emphasis during the roadmap barriers workshop on streamlining and simplifying the approval process. These lengthy procedures result in lots of delays and cause frustration for the project developers and investors. The following figure highlights the approval process for the wind farms in Pakistan.

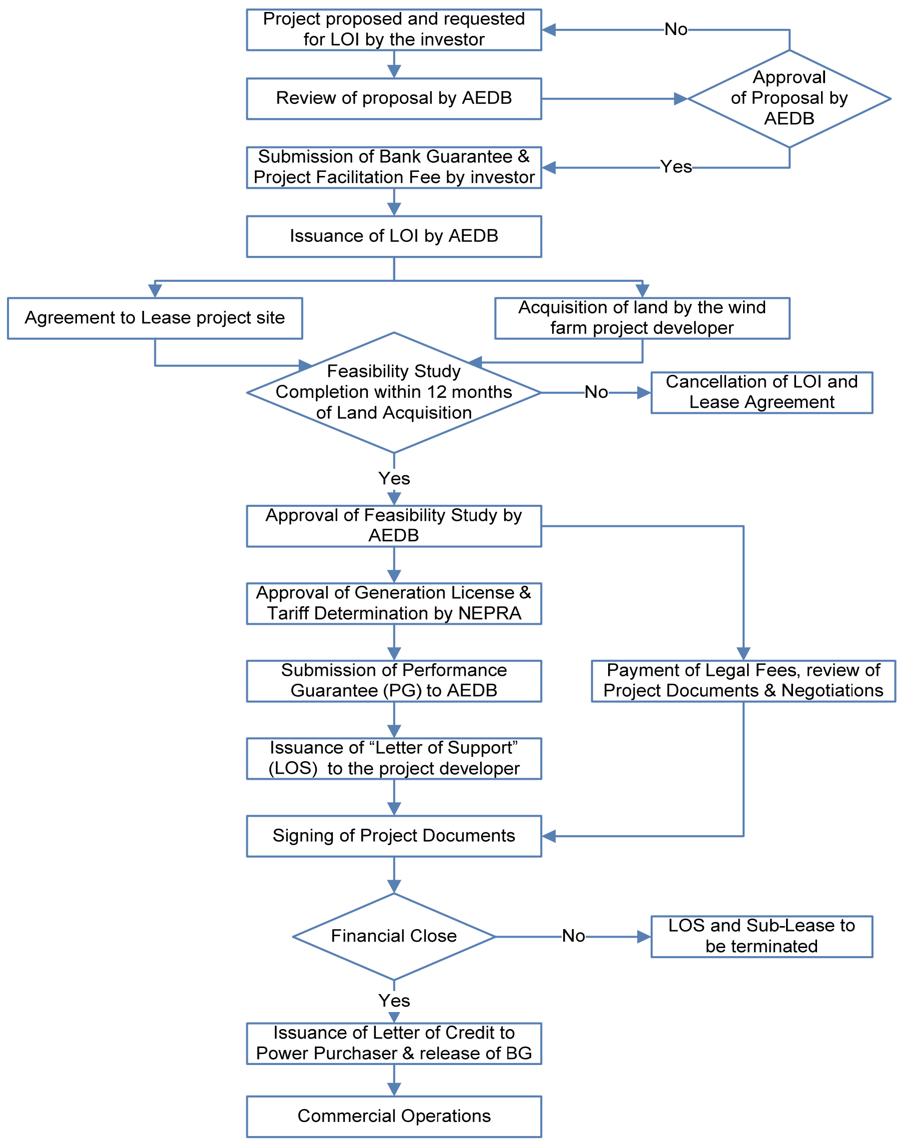

Figure 21: Approval process for a new wind farm in Pakistan

d. Financial Barriers [169, 214, 216]

There are difficulties and barriers in obtaining a competitive form of finance from the local, national and international levels to implement the wind energy projects in Pakistan. There are many reasons for this barrier including a lack of familiarity with wind technology, high risk perception, uncertainty regarding the resource assessment and reliability of wind speed projections, intermittent power generation from wind energy, and the site-specific nature of every project. These risks potentially discourage the financers to invest in this sector. Moreover, there is a lack of financial resources and proper lending facilities, particularly for the small-scale wind projects.

e. Circular Debt Barriers

The circular debt is an important problem for the power sector of Pakistan. A lot of circular debt has been caused by the government entities, including the provincial and federal government departments, by not paying their utility bills. It creates a liquidity problem for the power generation companies, and these companies are unable to pay for the fuel for their power plants. The circular debt and the resulting liquidity crunch in the power sector are acting as a bar to the new investment, especially in the renewable energy sector. As a result, the power companies are not able to pay their fuel bills, and they are unable to invest in the power sector or attract outside investment.

f. Economic Barriers [169, 217]

The current power generation cost from wind energy is high due to high capital cost (cost of wind turbines and supporting equipment), taxes and custom duty on equipment imports, low capacity factor, and government subsidies given to conventional power plants. External costs such as health and environmental costs associated with air pollution through fossil-fuel consumption are not factored into the energy price. At the same time, social and environmental benefits of non-polluting wind power technology are not accounted for either. Therefore, energy prices do not reflect environmental costs and damage, and mask the striking environmental advantages of a new and clean wind energy option. Subsidies give an unfair advantage to the fossil-fuel based power plants over wind farms, and these reasons make the wind energy projects un-economical in the country. These factors negatively affect commercialization of wind technology in Pakistan.

g. Technical Barriers [4, 169, 214, 216]

A limited access to the accurate technical information of wind technology is also a big obstacle towards the development of wind energy technology in the country. The technical barriers include limited R&D infrastructure in the country, availability of low quality products available in the local market, and lack of standards in terms of durability, reliability, and performance for these wind energy products. There is no manufacturing industry for the wind turbines, and as a result, the technology must be imported at a higher cost; and there is a lack of domestic knowledge about these turbines as well. There are also very limited R&D activities and lack of technical experts in the country to support the wind energy projects. This lack of an overall technically encouraging environment hinders the development of wind power technology in Pakistan.

h. Capacity Building [15, 47, 169, 214]

There is a requirement of capacity building for the key institutions (policy makers, planners, regulators, facility managers, and project implementers). Shortage of maintenance infrastructure and skilled human resources required to operate, maintain, and support the local wind farms also represent a critical challenge. Furthermore, maintenance facilities for the wind sector are inadequate, leading to low operational reliability and customer confidence. Skilled manpower can provide the essential services such as installation, operation, maintenance, and troubleshooting of the equipment required for development of a wind power project. At present, there is lack of both trained personnel and training facilities for the development, installation, and maintenance of the wind power projects. The skilled professionals are also required for conducting research and development activities in this sector. A shortage of proper training facilities also increases this challenge. Inadequate servicing and maintenance infrastructure would lead to poor performance of the equipment installed in the field. It results in limited market penetration of wind technology.

i. Transmission Barriers [214]

Integration of wind energy with the national grid is a challenge. Wind energy resources are often located at remote and dispersed locations, not connected with the transmission and distribution networks. Thus, investments and modifications are required in the grid to integrate the wind power. Non-availability of a distribution network at the potential sites for wind farms is a major challenge.

Moreover, wind energy is a variable and uncertain power resource, and its deployment on a large scale requires significant changes in the power grid to make it more vibrant and interactive. Low reliability in grid operations also creates problems in integrating power from the wind farms.

j. Wind Resource Assessment Barriers [47, 193, 213]

The lack of reliable and sufficient wind data and inadequate wind energy resource assessments are also very important barrier. The development of wind power projects requires a detailed assessment of the wind regime of the area under consideration. The international practice is to analyze the historical wind data (10 to 20 years) with at least one year of on-site data, recorded according to international standards, for the purpose of power output estimation from the wind farms. The analysis of the long-term wind data helps in predicting more reliable annual wind characteristics and wind speed averages, resulting in an accurate estimation of wind power generation capacity. This is an important factor for making the wind power projects bankable. The long-term wind data serves the purpose of risk mitigation from the lender's point of view, whereas short-term or less reliable wind data increases the risk factor for the estimated energy production, which in turn increases the lender's risk perception of the project. In Pakistan, many suitable areas in remote locations have not been assessed properly for the implementation of wind energy projects. In this case, the private investors are finding it very difficult to attract lenders for their projects and were not prepared to risk their own capital on the available short-term and unreliable wind data.

k. Wind Speed Variation Challenges

Some studies support the theories that climate change could affect surface wind speeds. Pryor et al. found that wind speeds across the United States have decreased since the year 1973 [258]. There are other scientific investigations that have reported a decline of surface wind speeds in many regions of the world [203, 331, 342, 348]. The power output of a wind turbine is proportional to the cube of wind speed [301]. Thus, modest variations in the surface wind speed can have significant implications on the generation capacity. However, there is no study conducted to analyze changes in the surface wind speed in Pakistan. The variations in the wind speed and wind energy density have great importance for the financial viability of a wind farm [257]. Therefore, a decline in the wind speed is a potential concern for the wind energy sector. It may become a critical barrier in future and affect power output from the wind farms.

l. Lack of Awareness/ Information [47, 169, 215, 216]

There is a considerable lack of awareness regarding the wind technology and its benefits for the country and local communities. There is very limited information available regarding the practical issues in the implementation and maintenance of wind energy projects. Information regarding wind energy projects is not easily available and it deters implementation of wind energy projects in the country. Availability of information will trigger entrepreneurs to invest in wind energy projects, and it is vital for wind power generation. Therefore, it is needed to increase availability of the technical information in order to increase the deployment of wind power projects in the country.

m. Market Barriers [47, 169, 214]

Small size of the local market, limited involvement of the private sector, monopoly of the giant conventional power generation companies, lack of marketing infrastructure with promotion campaigns, low level of after-sales service and quality control measures for the wind energy related products available in the local market are the major market barriers. Absence of successful and replicable business models also hinders the market penetration. All these factors hinder the market penetration of the wind energy technology in Pakistan.

n. Lack of Social Awareness and Acceptance [169, 214, 281]

Finally, there are several social challenges which affect the national wind energy sector. The lack of social acceptance and local participations in the wind energy projects also restricts large scale deployment of wind energy projects. The participation of the local communities is restricted to just a few demonstration projects and it restricts the deployment of wind energy projects on a large scale in the country. Moreover, land acquisition is sometimes very difficult and it takes long negotiations with the local community and significant compensation in order to acquire the land for a wind farm. The production of wind power generates several environmental and social benefits, such as emission reductions, power portfolio diversity, and local employment opportunities. Wind power is labor intensive relative to conventional fossil-fuel based power plants. Thus, it generates employment opportunities which are considered as a significant social benefit. All of these socio-economic benefits are valuable, but the value of these positive attributes is not well recognized.

5.2.3 Prioritization of the Roadmap Barriers against each Scenario

In the second phase of the roadmap barriers workshop, the experts were asked to rank and prioritize the most important roadmap barriers and challenges for each scenario on the basis of their importance and impact on the roadmap targets. In the first session, the experts identified and validated 14 critical barriers towards the deployment of wind energy projects in Pakistan, mentioned in the previous section. Then, members of the TRM EP2 discussed importance of these roadmap barriers against each scenario. As a first step, the experts assigned priority weights to the roadmap targets. Then the experts ranked the roadmap barriers on the basis of their impact on the roadmap targets and assigned scores. The weighted sum method (WSM) was used to prioritize the roadmap barriers, which is a commonly used technique for ranking. The questionnaire used to rank and prioritize the roadmap barriers against each scenario is attached as Appendix E.

At the end of the roadmap barriers workshop, attendees were asked to complete a questionnaire to prioritize the roadmap barriers for each scenario. The workshop moderator collected the responses from the participants and compiled the results. The results of the first survey were provided to the workshop participants and another follow-up Delphi survey was conducted. The experts were asked again to prioritize the roadmap barriers for each scenario. This approach gave an opportunity to the experts to freely express their opinions in an independent and anonymous way without any undue social pressures.

Analysis of the data from the roadmap barrier workshop and the follow-up surveys revealed that for most of the roadmap barriers, consensus was achieved in the first or second Delphi round and/or experts confirmed their previous responses. However, in a few cases there was some difference of opinion among the experts, but majority of the participants responded the same reply. Guidelines given in the literature (presented in Section 3.2.5) to deal with the disagreement and termination of a Delphi study were followed.

After the second Delphi round, chi-squared test was used to determine the stability of responses obtained from the TRM EP2 members between the first and second round. The results of the chi-square test concluded that individual stability has been achieved. Details of the chi-square test used to measure the stability of group responses in the follow-up Delphi surveys to prioritize the roadmap barriers are attached as Appendix G.

The scores assigned to the roadmap barriers by the experts were normalized. Then k-means clustering technique was used to group the roadmap barriers [88, 138, 262]. Cluster analysis is a generic name for a class of techniques used to classify cases into groups that are relatively homogeneous within themselves and heterogeneous between each other [273]. Thus, data clustering technique allows objects with similar characteristics to be grouped together for further analysis. Cluster analysis has been extensively used in numerous applications ranging from strategic management and marketing research to information technology and climatology [88, 124, 138, 168, 259, 273]. The k-means method aims to minimize the sum of squared distances between all points and the cluster center [262].The elbow method was used to define the number of clusters [168]. The details of the cluster analysis performed for all scenarios are given in Appendix H. The results of the cluster analysis of the roadmap barriers against each scenario are shown in Table 31. The most important roadmap barriers having a greater impact on the roadmap targets against each scenario are also highlighted.

Table 31: Cluster analysis to group the roadmap barriers for each scenario

Barriers	Scenario B		Scenario B		Scenario B		Worst-Case Scenario	
	Normalized Value	Cluster	Normalized Value	Cluster	Normalized Value	Cluster	Normalized Value	Cluster
Policy	100	1	0	1	9	1	86	1
Competitiveness	93	1	23	1	20	1	21	2
Institutional	76	1	19	1	41	3	21	2
Technical	52	3	46	2	74	2	60	2
Capacity	41	3	15	1	48	3	93	1
Awareness	41	3	8	1	7	1	14	3
Financial	24	2	100	3	100	2	7	3

Economic	15	2	85	3	7	1	33	2
Transmission	20	2	71	3	41	3	35	2
Wind Resource	9	2	38	2	11	1	21	2
Social	0	2	29	2	0	1	21	2
Market	24	2	8	1	30	3	100	1
Circular Debt	9	2	15	1	20	1	0	3
Speed Variation	9	2	19	1	15	1	21	2

Ranking of the roadmap barriers against each scenario is shown in Figure 22. The most critical roadmap barriers identified through cluster analysis for each scenario are highlighted in this figure by a small circle.

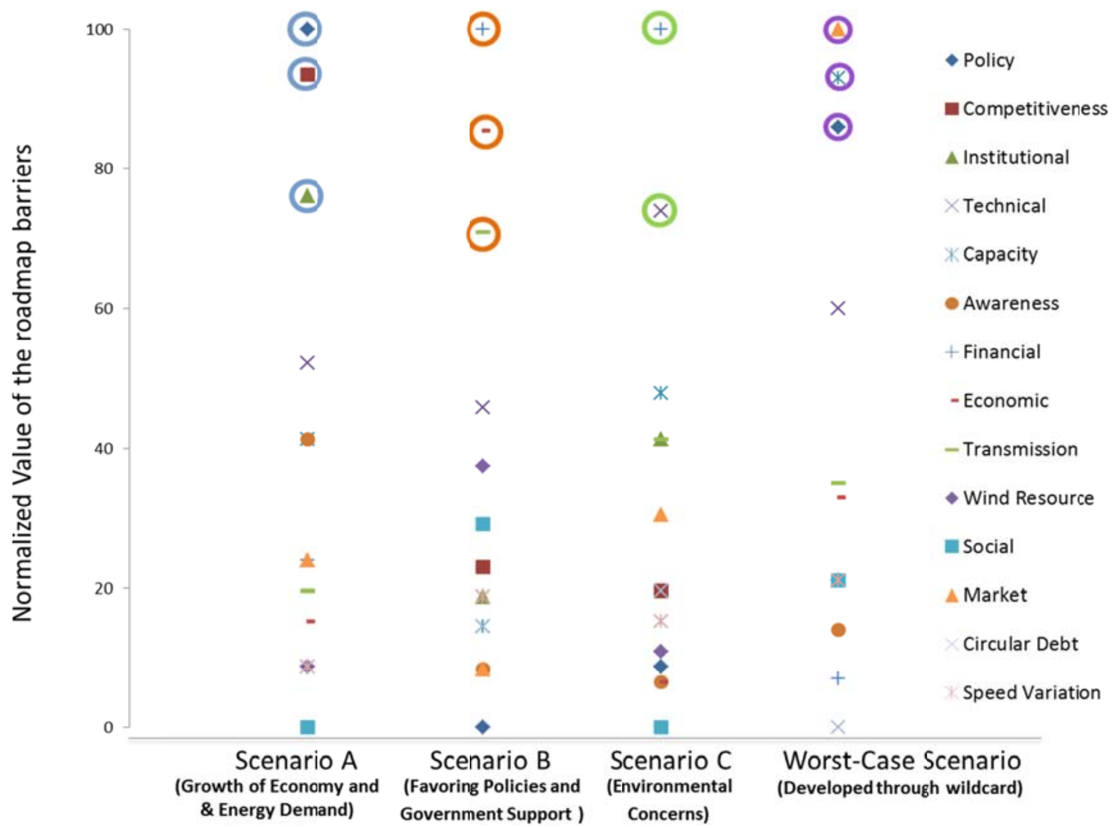

Figure 22: Ranking of the roadmap barriers against each scenario

5.2.4 Roadmap Action Items Workshop

The roadmap action items workshop was conducted, and the TRM EP2 members were asked to propose suitable action items required to overcome the roadmap barriers and challenges hindering the deployment of wind energy projects in Pakistan. Members of the TRM EP2 earlier participated in the roadmap barriers workshop and the follow-up surveys. Therefore, all the experts in this workshop were familiar with the roadmap barriers. The workshop agenda and handout documents highlighting the purpose of the workshop, focus questions, important tasks, and examples were provided to the members of TRM EP2 three weeks prior to the workshop (attached as Appendix F).

During the workshop, the experts proposed and discussed the appropriate action items required to overcome the roadmap barriers for each scenario. Moreover, the experts tried to translate the roadmap targets into the roadmap action items. Earlier the most critical roadmap barriers were identified against each scenario. Some barriers were identified against two scenarios due to their importance and impact. In the first step, the experts proposed suitable action items followed by discussion on their usefulness to overcome the roadmap barriers against each scenario. A list of critical action items was created for each roadmap barrier. The experts also specified the estimated timeline for the proposed roadmap action items as given below:

- Short-term: To be taken immediately
- Medium-term: Between the year 2015 to 2020
- Long-term: After the year 2020

5.2.4.1 Identification of Roadmap Action Items

The following action items are proposed by the members of TRM EP2, which are required in order to overcome the roadmap barriers. In some cases, the experts proposed that the same action item would help to overcome two or more roadmap barriers. These action items are crucial for the successful deployment of wind power projects in Pakistan:

a. Policy Barriers

i. Legislations to enforce the mandatory Renewable Portfolio Standards (RPS) in order to promote deployment of renewable and wind energy technologies in the country;

ii. Implementation of the feed-in tariffs (FITs) mechanism to increase the deployment of wind power generation and improve their competitiveness. The FIT framework guarantees payment to project developers at a set rate for electricity production over a given period of time (usually 15 to 20 years);

iii. Incorporate the wind risk concept in the Power Purchase Agreements (PPA**),** to cover the power producer from abnormal wind speed variations;

iv. Provide the tax incentives, subsidies, and Production Tax Credit (PTC) to the wind energy sector by the government;

v. Complete removal of the custom duty on the import of wind turbines and related equipment;

vi. The government should ensure consistency in policies towards the wind energy sector for the next twenty years;

vii. The government should establish the definitive policy targets and implementation plan for the national wind energy sector;

viii. Regulate, standardize, streamline and simplify the processes required for:

- Clearance from the federal government for a wind energy project;
- Grant of no objection certificate (NOC) from the local government;
- Power purchase agreements (PPA) for electricity purchase from the wind;
- Finalize the PPA within the stipulated time; and
- Land allocation process for the wind farms.

b. **Lack of Competition with Conventional Power Generation**

i. Transfer the subsidies from fossil-fuel based power plants to renewable energy technologies like wind power technology in order to bridge the competitive gap between these technologies;

ii. Cost burdens and gains of transferring the subsidies are to be shared by both consumers and producers;

iii. Promote the domestic manufacturing industry of wind turbines and associated equipment to reduce their capital cost; and

iv. Reflect cost of carbon and other hazardous emissions in the energy price.

c. **Institutional Barriers**

i. Creation of a central body to support the national wind energy sector and ensure coordination and cooperation within and between various ministries, government agencies, research institutes, and other stakeholders;

ii. Reduce the procedural delays and duplication of efforts in the national wind energy sector of the country;

iii. Information sharing between various entities from the public and private sector to increase efficiency and progress of the wind energy sector; and

iv. Promote the joint research and development programs of wind energy technology among various organizations through the central controlling and coordinating body.

d. **Financial Barriers**

i. Provision of financing arrangements to support investment in the wind energy sector in order to encourage and facilitate the deployment of wind energy projects in Pakistan;

ii. Creation of an innovative funding program for the small and medium scale wind power projects;

iii. Initiation of investment tax credit (ITC) for the wind energy projects;

iv. Increase familiarity with the wind technology through seminars, workshops, and conferences to attract the potential investors; and

v. Ensure reliability of the wind resource assessment and wind speed projections to gain confidence of the potential investors and financers.

Economic Barriers

i. The social, environmental, and health-related benefits of the non-polluting wind power technology are not accounted for. These factors reduce the cost of the wind power technology when taken in comparison with the negative external cost of greenhouse gas emissions and health hazards from the conventional fossil-fuel based power plants. Therefore, it is required to devise a mechanism to factor the environmental degradation cost and health cost into the conventional energy prices to reflect their environmental damage and pollution;

ii. Establishment of the local manufacturing industry within the country to reduce the capital cost of wind energy projects;

iii. Improve the supply chain and installation strategies for the national wind industry; and

iv. Remove or significantly reduce the subsidies given to the fossil-fuel based power plants in the country.

e. Technical Barriers

i. It is vital for the government to invest in the R&D activities, increase the R&D infrastructure, and establish a wind energy research institute. The investments by the government in the R&D activities would improve the technology access;

ii. Obtain the best practices from the countries having large scale deployments of wind farms;

iii. Provide easy access to accurate technical information related to the wind energy technology;

iv. Initiate courses related to wind energy in the local engineering universities, technology colleges, poly-technique institutes, and schools; and

v. Ensure quality control and standardization (in terms of durability, reliability, and performance) for the wind energy related products developed by the local manufacturing industry or available in the local market.

f. Capacity Building Barriers

i. Create skilled work force through formal courses and on job trainings for the purpose of capacity building to support the wind energy sector;

ii. Development of educational facilities to promote the wind technology and development of skilled professional for this sector;

iii. Establishment of maintenance infrastructure to support the national wind energy sector and ensure smooth operation of wind farms; and

iv. Establishment of manufacturing industry to sustain the wind energy sector and reduce the dependence on foreign import of technology and knowledge.

g. Transmission Barriers

i. Initiate plans to upgrade the transmission grid in order to support the integration of wind energy;

ii. Start building new transmission facilities to access the remote locations having good wind resources, especially the locations where land has been allocated for the development of wind farms;

iii. Reduce the transmission and distribution losses of the grid;

iv. Use advance tools to forecast the wind speed in order to improve the grid operations;

v. Plan geographic dispersion of new wind farms to mitigate the impact of wind speed variability;

vi. In order to respond quickly to wind shortfalls, ensure provisions of standby emergency demand response resources;

vii. For each potential wind farm project site, study the existing grid in the vicinity and perform load flow, short circuit, and dynamic analysis; to investigate that the grid in the vicinity of a wind farm can absorb power generated by that wind farm;

viii. Start practicing new approaches for grid operations to support wind energy:

- Create the electric load balancing areas to support the integration of wind power; and
- Increase the grid efficiency, reliability, and interoperability.

h. Wind Resource Data Barriers

i. Establishment of the benchmark wind speeds at different hub heights for the regions and locations identified for establishing wind farms;

ii. Install metrological masts with anemometers, at the potential wind farm locations for on-site wind speed measurement in order to generate reliable wind data;

iii. In order to improve access to the wind data, establish a comprehensive, reliable, and easily accessible central information system and database;

iv. Use advanced modeling techniques to produce detailed wind resource maps; and

v. Develop the 50 m and 70 m wind resource maps of the country and obtain the best practices from the developed countries.

i. **Lack of Awareness/ Information Barriers**

i. Initiate campaigns to educate general public on the benefits of wind technology to raise public awareness, particularly in the context of current power crisis;

ii. Conduct seminars and workshops to highlight the availability and abundance of wind energy resources in the country, and attract the potential investors and donors agencies for investment in the wind energy sector;

iii. Use the print and electronic media by the government to increase awareness and create a positive perception towards wind energy;

iv. Availability of an information system will also help to spread general awareness, acceptance, and interest regarding the wind power technology; and

v. Conduct workshops and conferences to spread the information regarding the practical issues in implementing and maintaining the wind energy projects.

j. **Market Barriers**

i. Promote and market the successful wind projects in Pakistan and the neighboring countries as a replicable business model;
ii. Promote involvement of the private sector through various incentives; details of the incentives are given in the policy related to action items;
iii. Break monopoly of the giant conventional power generation companies through transfer of the subsidies by the government; and
iv. Ensure the quality and after-sales service support of the small to medium range of wind energy turbines and related equipment available in the local market through regulations and quality control measures.

k. **Lack of Social Acceptance**

i. Initiate the programs to educate the general public about the social, economic, and environmental benefits obtained from the wind energy projects. These socio-economic benefits are valuable, but their value is not well recognized. It is important to educate the local communities regarding the following benefits of the wind energy projects to gain their support and acceptance:

- Creation of employment opportunities and preference is given to the workforce living in the local communities;
- Generation of business activities in the region;
- Reduction of the GHGs and other harmful emissions;
- Appreciation of the land prices due to wind farms in the region;
- Opportunities of additional income for the land owners as a rent for the installed wind turbines on their properties; and
- Electrification of the local area, in case that area is not connected with the national grid.

ii. Participation of the wind farm developer in the regional fairs and other social activities in order to engage with the local community. It will increase a positive perception and social acceptance of the wind farms.

iii. Soft measures by the wind farm developers to support the local community by helping a public school or a basic health center of the local government. These measures will significantly increase social acceptance of the wind farms.

5.2.4.2 Classification of Roadmap Action Items

In the second phase of the roadmap action items workshop, the experts were asked to classify the proposed action items into the following three categories:

- New action items (gaps/needs) that required to overcome the roadmap barriers and achieve the roadmap targets;
- Action items already undertaken by the stakeholders (government, regulators, utilities, power distribution companies, and wind energy sector) to address the roadmap barriers; and
- Action items that are already undertaken by the stakeholders, but that require significant modification, adjustments, and/or reforms in order to become effective and overcome the roadmap barriers.

The action items classified by the experts in these three categories are color coded in the graphical technology roadmap shown in Section 6. The required action items are shown in blue color, the action items undertaken are shown in green color, and the action items needed significant modification, adjustments, and/or reforms are shown in purple color. The experts also specified the estimated timeline for the roadmap action items.

In the end, the experts were asked to assign the respective leading role and responsibility for each action item to the major stakeholders. In several cases, the expert assigned the responsibility for an action item to two or more stakeholders. The responsibilities for the roadmap action items with the estimated timeline are shown in Section 6.

5.3 Research Validation

Generally, validity refers to "the extent to which an empirical measure adequately reflects the real meaning of concept under consideration" [17]. In order to ensure a credible research, three major types of validity must be considered: content, construct, and criterion-related. Therefore, validation of the results of this research case was successfully conducted from these three major aspects. Moreover, details of the specific steps taken to ensure validation of the integrated FCM model and technology roadmaps are also explained in this section.

5.3.1 FCM Validation

It is very difficult to establish validity of a model. Some researchers argue that all models are wrong and reject the notion that models can be validated [318]. However, the literature suggests focusing on the modeling process because it leads to the creation of better models [91, 317, 318]. Moreover, participation of a wide range of people in the modeling process and model review by the critics also helps to develop a useful model. Involvement of stakeholders in the modeling process helps to develop a deeper understanding of the system under consideration. Researchers also emphasize focusing on creating useful models

[318]. This research has also indicated that through a series of workshops, this research approach can be successfully implemented.

In the context of the FCM modeling, it has been recommended in the literature that test and validation should be ongoing activities [156]. Therefore, it is important that every step should be validated through the experts, who have to agree that their mental models are correctly and adequately captured, and/or through other forms of available data [156, 317]. It is very important to accurately reflect the experts' knowledge and properly design the FCM [156]. Weak or poor translation of knowledge in the causal maps/FCM and weak facilitation may lead to poor quality of the model [109]. By strictly following the FCM modeling guidelines, the modeler would be able to reflect the experts' knowledge and adequately translate it into the FCM model [155, 156]. Therefore, it is important for the modeler to ensure model validity through a high quality modeling process. Participation of the experts helps to address the validity and acceptability aspects of the model [133]. Jetter devised test and validation criteria for FCMs [156], which were followed during the development process of this FCM model. Moreover, the following steps recommended in the literature were strictly followed to ensure validity of the FCM model [154-156]:

- Identification and selection of the knowledgeable experts;
- Ensuring proper knowledge capture with the help of stimuli;
- Cross checking of the knowledge capture process; and

- Proper interpretation and translation of experts' knowledge in the causal maps and FCM models.

In this research, knowledgeable experts were very carefully identified and selected. The researcher obtained individual FCMs from every expert and asked the experts to review their FCMs at the end of each session. Then, the integrated FCM model was critically reviewed and cross-checked by the experts during the FCM workshop. The experts thoroughly analyzed and discussed the impact of each concept; and weights and directions of the causal links. They also deliberated the meaning of all the concepts in the FCM, so that there was no ambiguity in the meaning. In order to provoke creative thinking of the experts, example of an integrated FCM developed in a pilot study project was also used as a stimulus [11]. In order to ensure validity, the integrated FCM model was also presented to three additional reviewers / experts. These reviewers were not included in the FCM EP, but they were familiar with the wind energy sector of Pakistan. These reviewers were also asked to review and critique the integrated FCM and they agreed with the structure of the FCM model. They analyzed impacts of all the concepts on the objective of the map and their associated causal links. The reviewers suggested that the concepts are relevant to the objective of the FCM and the causal links indicate a logical connection among various concepts. Through the above-mentioned activities, the integrated FCM model was validated and no contradiction or major flaw was found by this diverse group of experts and reviewers.

Moreover, after conducting the FCM simulation, the simulation results / raw scenarios were further refined through a few experts from the FCM EP in a follow-up session. During this session, the experts discussed the future scenario narratives and evaluated potential implications of these scenarios.

5.3.2 Roadmap Validation

It is also critical to employ a validation process in order to develop a credible technology roadmap. For the roadmap validation purposes, assistance from the TRM EP1 and TRM EP2 members was obtained. This process is important because during the roadmap development process, it is not possible to derive a definitive form of the roadmap before it has been completed, even for the experts who are participating in the TRM workshops [174]. Moreover, an expert group of four members, outside from the TRM expert panels; further validated the adequacy of the information in the technology roadmap. These new experts also had a good knowledge and experience in the renewable energy sector of Pakistan and they were also selected according to the expert selection criteria presented in Section 3.2.1. The literature highlights the importance of involving both internal and external experts to verify and validate the technology roadmaps [173].

In a follow-up session, the developed technology roadmap was presented to the experts for the roadmap validation purposes. This process enabled a wider participation and engagement of both the internal and external experts. Their feedback was used to improve the quality of the developed roadmap. The experts confirmed that the roadmap objectives and targets are rational, classification of the roadmap barriers and challenges is accurate without any ambiguity, and the roadmap action items are appropriate and adequate. The experts also confirmed the assigned responsibilities for the roadmap action items and the estimated time frame to undertake these action items.

5.3.3 Content Validity

Content validity is used to confirm that the research scope is broad enough and it adequately reflects an entire universe of items in a certain topic under study [17]. The expert judgment was used to confirm the content validity and ensure that the research instruments include the range of all possible outcomes and all appropriate content is included. The content validity was conducted during the preparation phase of the research instruments.

In order to ensure validity, the research instruments were developed based on the literature review and research questions. The instruments were validated using the literature, a pilot study, and the expert panels. In this case study, three steps were taken to check the validity of the research instruments. As a first step, the research instruments (workshop handouts, agenda documents, and follow-up survey questionnaires) were initially validated by a group of doctorate students from the Engineering and Technology Management department of Portland State University. The purpose of the research instruments was explained to them and they analyzed all of the questions and pointed out if there were any ambiguity or confusion. Based upon their comments and suggestions the questionnaires were modified.

Then a pilot study project was conducted and based on the feedback from the experts, the research instruments were revised.

Finally, the research instruments were presented to a small group of experts, who were serving on the TRM EPs and FCM EP. These experts reviewed the revised instruments and checked the relevance and ease of answering all of the questions. Based on their feedback, the research instruments were finalized. These experts confirmed the readiness and sufficiency of all the instruments used for data collection.

5.3.4 Construct Validity

Construct validity reflects the degree to which the structure of the model is correct and appropriate. It reflects the ability to measure what we are interested in measuring. The construct validity assesses how well one measure correlates with another measure purported to represent a similar underlying construct. It is based on the logical relationship among variables [17]. The experts can be used to test the construct validity [230].

In this research, the key factors (scenario drivers) that may affect deployment of wind energy on a large scale in the country were highlighted in the integrated FCM model. Every expert reviewed the FCM to ensure that their knowledge is properly captured and reflected in the model. Then the integrated FCM model was presented to all the experts in the FCM workshop and they validated the FCM model. The participants in the workshops discussed and agreed with the structure of the FCM model. The causal relationships among various scenario drivers (concepts) of the model were also critically reviewed and validated by the experts.

Moreover, after the FCM workshop, the integrated FCM model was again presented to three additional reviewers, who were not part of the FCM expert panel. They also agreed with the structure of the FCM model. These activities ensured that the integrated FCM model has been validated since no contradiction or flaw was highlighted by any member of the expert panel and outside reviewer.

Through the above-mentioned activities, the integrated FCM model and the definition of the concepts were validated.

5.3.5 Criterion-Related Validity

Criterion-related validity measures the degree to which the predictor is adequate in capturing the relevant aspects of a criterion. It is judged by determining the similarity between a judgment about the future and its real value [335]. Usually the criterion-related validity is determined by correlating the research results with some other measure that is already valid and assesses the same set of abilities.

In this research, it was very difficult to measure the criterion-related validity because the outcomes of the research are the scenarios and technology roadmap developed for the national wind energy sector for the next two decades. However, when the research was completed, a group of experts was used for this validation and they reviewed the research outcomes and confirmed their agreement. Thus, feedback from the experts was obtained through a follow-up meeting and e-mail correspondence. All the experts agreed upon the research outcome and confirmed the research results. The experts were also impressed from this research methodology because it clarified their understanding about the energy future of Pakistan and provided a comprehensive action plans against different scenarios. Some of the quotes obtained from the members of the expert panels are given below:

- “An innovative approach that has broadened my horizon regarding technology planning”
- “A comprehensive and thorough analysis of the barriers and challenges faced by the national wind energy sector”
- “An interesting way of getting an overview of different energy futures”
- “This TRM exercise has brought more knowledge in my decision making process”
- “It has highlighted the required strategies to achieve the targets of electricity generation from wind”
- “It has clarified my understanding about the energy future of Pakistan”

In order to further ensure validity, a comparison was made of the findings of this research with some other technology roadmaps developed by some prestigious international agencies and national organizations. In this research, the roadmap objectives and targets were established in accordance with the national renewable energy policy of Pakistan as a baseline document. That was followed by identification of the critical roadmap barriers. Policy concerns, lack of competition with conventional power plants, financial constraints, and technical limitations emerged as the most critical roadmap barriers. The results of this research are similar with other studies conducted by some international agencies and national organizations, shown in the following table. Therefore, we can conclude that the research findings are in accordance with the roadmaps developed by these reputable organizations.

Table 32: Comparison of the roadmap barriers

Most Important Roadmap Barriers	**Research Case**	**AWEA [1] Roadmap [21]**	**EWEA [2] Roadmap [89]**	**IEA [3] Roadmap [46]**	**NREL[4] Roadmap [228]**	**NRC [5] Roadmap [227]**
Policy Barriers	✓	✓		✓		✓
Financial Barriers	✓	✓		✓		✓
Technical Barriers	✓	✓			✓	✓
Lack of competition with conventional power plants	✓	✓		✓		
Institutional Barriers	✓		✓	✓	✓	
Capacity Building Barriers	✓					✓
Awareness Barriers	✓	✓				✓
Transmission Barriers	✓		✓	✓		
Economic Barriers	✓					
Social Acceptance Barriers	✓		✓	✓		
Wind Resource Assessment Barriers	✓	✓				✓
Market Barriers	✓	✓		✓	✓	

This research has also proposed appropriate action items required to overcome the roadmap barriers against different scenarios. In the case of roadmap action items, some similarities are also observed with other technology roadmaps. Thus, these comparisons also indicate validity of the research outcome.

[1] American Wind Energy Association
[2] European Wind Energy Association
[3] International Energy Agency
[4] National Renewable Energy Laboratory
[5] Natural Resources Canada

Table 33: Comparison of the roadmap action items

Critical Groups of Action Items	Research Case	AWEA Roadmap [21]	EREC [6] Roadmap [85]	ERI [7] Roadmap [87]	IEA Roadmap [46]	NRC Roadmap [227]
Policy and Regulation	✓	✓	✓	✓	✓	✓
Technology and Industry	✓	✓	✓	✓	✓	✓
Awareness and Engagement	✓	✓		✓	✓	✓
Finance and Economic Aspects	✓				✓	✓
Wind Integration and Resource Assessment	✓	✓	✓	✓	✓	✓
Infrastructure and Capacity Building	✓	✓	✓	✓	✓	✓

Finally, we can conclude that all three aspects were validated qualitatively through the expert reviews. Table 34 highlights the summary of above-mentioned validity aspects.

[6] European Renewable Energy Council
[7] Energy Research Institute, China

Table 34: Research validation [17, 252, 283]

Validity type	Application	Method	Validity time	Validation results
Content validity	Content validity ensures that research scope is broad enough and it covers an entire universe of items within the topic under study	Through expert judgment by asking experts to ensure that the research instruments include the range of all possible outcomes	During the preparation phase of the workshop handouts, research instruments, and background material	Added clear instructions, focus questions, and examples in the handouts. Designed sticky notes.
Construct validity	It reflects the ability to measure what we are interested in measuring	Through expert judgment by asking experts to validate structure of the FCM model and other research findings	After developing the FCM model (Proper translation of expert opinion in the integrated FCM)	Three redundant concepts were removed from the integrated FCM model
Criterion related validity	It measures the degree to which the predictor is adequate in capturing the relevant aspects of criterion	Through expert judgment by asking experts to review the complete results and confirm their agreement	After compiling the research results (Experts reviewed the scenarios and multi-scenario roadmaps)	Experts reviewed the roadmap and confirmed its outcome. Results were also compared with other RE TRMs.

6 Analysis and Discussion

The FCM-based scenario development approach has helped us to identify and model the concepts (factors) that affect wind energy deployment in Pakistan. The complex causal relationship among these concepts is also portrayed in the model. Despite some limitations, the resulting FCM model offers a visual medium and provides insight into the factors and barriers towards the deployment of the wind energy projects in the country. This approach also provides a good structured description of the system. The aim of this study was to provide a rich insight into the wind energy sector. There are 40 concepts in the revised FCM model. These concepts are drivers of change (from the social, technological, economic, environmental, and political aspects) and are likely to influence the future of the wind energy sector of Pakistan. Analysis of the integrated FCM revealed that the concepts/drivers identified in the model can be grouped into the following seven major clusters:

- Policy and Political Support;
- Financial and Economic Factors;
- Demographic Changes;
- Public Attitudes and Perceptions;
- Technology Changes and Requirements;
- Infrastructure Requirements; and
- Environmental Changes.

Based on a literature review of 27 studies, it was found that these seven clusters of drivers are adequate for the future-oriented research related to sustainable energy management [117]. Thus, the concepts identified in the integrated FCM are aligned with findings of other research studies focused on energy management with a futures perspective.

Initially, three scenarios were developed based on the integrated FCM model. Then another scenario was created by introducing wild cards to the integrated FCM model. Earlier in Section 2.3.5, it was revealed by the literature review that development of three to five future scenarios is considered appropriate by most of the futurists and researchers.

6.1 Scenarios and Important Barriers

The following four FCM-based scenarios were created through the FCM simulation. It was noticed that a small change in the input vectors resulted in different stable states of the FCM model, which are used as scenarios. The set of output vectors contain a pattern of the FCM model and the underlying causal relationships. Thus, FCM is a powerful modeling technique and an attractive tool to improve the quality of the scenario outcome. The developed scenarios represent four alternative futures, and it was concluded that this method can be used to create a set of plausible future scenarios. The quality of the FCM-based scenarios significantly depends upon the quality of the underlying causal map. Therefore, the experts were carefully selected, input was obtained from multiple experts, their input was carefully translated into the map, and the integrated FCM was validated by the experts.

The results of the FCM simulation (raw scenarios) were further refined through the members of the FCM EP. In this follow-up session, the experts discussed the future scenario narratives and explored their potential implications.

6.1.1 Scenario A: Economic Growth & Growing Energy Demand

In the first scenario, it was assumed that there is growth in the national economy and the national energy demand is also increasing; therefore, it is likely that the cost of electricity will increase because the national power sector is highly dependent on thermal power generation, the indigenous reserves of natural gas in the country will sharply deplete, energy dependence concerns will increase, awareness for utilizing indigenous wind energy resources will also increase, and a strong desire will emerge to reduce dependence on the imported energy resources and to control or stabilize the cost of electricity in the country. All of these factors will result in the deployment of wind energy projects on a large scale in Pakistan. This is an interesting scenario, because despite the absence of a favoring government policy, wind farms will be deployed in the country.

Securing energy supplies / energy security is the dominant concern in this scenario. Moreover, increasing energy costs, driven by rising demand, and shrinking supplies of fossil-fuel based energy supplies are also significant concerns. Pakistan follows a path of improving its energy security, both by reducing the energy demand and by increasing the alternative supplies. This scenario indicates that by the year 2030, there will be large scale deployment of wind energy projects in the country. The scenario results indicate that organizational type of barriers will be important in a growing economy with increasing energy demand. New policies supporting wind industry, institutions such as a central agency and mechanisms enabling competition are indicated by the experts as areas to focus. The most critical barriers identified against scenario A are mentioned below:

- Policy Barriers;
- Lack of Competition with Conventional Power Plants; and
- Institutional Barriers.

6.1.2 Scenario B: Favoring Policies and Government Support

The second scenario is based on the assumptions that there is a strong support and determination by the government to promote the wind energy projects in Pakistan and that the government has also formulated favoring policies in this regard. These favoring policies adopted by the government are likely to establish the wind manufacturing industry within the country, reduce cost of the wind turbines and supporting equipment required at wind farms, reduce O&M cost of wind farms, provide incentives to the wind energy sector, and encourage involvement of the private sector. Moreover, in this scenario trained human resources will be available to support the wind energy sector, and international support, cooperation, and funding opportunities will be available for the wind energy projects. Due to this favorable and conducive environment, there will be a positive trend towards the deployment of wind energy projects in Pakistan.

The favoring government policies are the focal point of this scenario. It is assumed that the government has formulated the favoring policies to promote the national wind energy sector along with a strong and consistent political support. However, since the country is not making good economic growth, scarcity of financial resources is an important concern.

This radical transition towards the widespread deployment of wind technology has also resulted in international collaboration and direct foreign investment. Lucrative incentives have been offered to the private investors and wind farm developers. There have been huge investments for the widespread deployment of wind technology by the government and private sector. By the year 2030, around 9700 MW of electricity will be generated from the wind resources. For scenario B, following are the most critical roadmap barriers:

- Financial Barriers;
- Economic Barriers; and
- Transmission Barriers.

6.1.3 Scenario C: Environmental Concerns

In the third scenario, climate change and health and safety issues are the serious concerns. It is assumed that the environmental consciousness is growing among the political leadership, government, and public due to increases in pollution, emissions of CO_2, and other hazardous gases. In this scenario, growing environmental, health, and safety concerns will result in incentives for the wind energy sector, involvement of the private sector, and the formulation of favoring policies by the government towards the wind energy sector. The local wind manufacturing industry will be developed resulting in cost reduction of wind turbines and associated equipment, reduction in O&M cost of wind farms, and availability of trained human resources to support the national wind industry. Moreover, there will be awareness of utilizing the indigenous wind resources. The government will ensure strict implementation of the national emission control standards. Due to all these factors, a positive perception towards wind farms will emerge in the country, and there will be rise in the widespread use wind technology in Pakistan.

Climate change and environmental degradation are the dominant concerns in this scenario. Public health has also become a concern due to the harmful effects of hazardous emissions from the fossil-fuel based power plants. The climate change and health concerns have translated in the adoption of wind energy technology in order to effectively reduce the emissions. Moreover, there is also emphasis on reducing both the energy losses and emissions. There will be widespread deployment of wind technology in the country. Moreover, technical knowhow and financing to develop the infrastructure and acquire the knowhow become critical. Following are the most critical roadmap barriers against scenario C:

- Financial Barriers; and
- Technical Barriers.

6.1.4 Worst-case Scenario for Wind Energy Deployment

Two wild cards were added in the integrated FCM model to create a worst-case scenario for wind energy deployment in the country. It was assumed that there have been technological breakthroughs in nuclear power resulting in generation of electricity at a very low price and discoveries of massive amounts of natural gas and oil reserves in the country. This scenario indicated a positive impact on the national economy, improvement in the living standards, and subsequent rise in the energy demand. However, this scenario indicates a negative tendency towards deployment of wind farms in the country. Moreover, due to these conditions, there will be a lack of political support from the government for the wind energy sector, and an absence of favoring policies and incentives for the deployment of wind energy projects.

In this scenario, due to abundance of energy resources available at a low cost, wind energy is not a promising alternative. Market and capacity building barriers emerged as the most significant barriers in this scenario. Moreover, the lack of political will from the government and unavailability of favoring policies are the major challenges faced by the national wind energy sector in this scenario. However, due to economic growth in the country, financial constraints will not hinder the deployment of wind farms.

The most critical barriers identified against this scenario are mentioned below:

- Market Barriers;
- Capacity Building Barriers; and
- Policy Barriers.

6.2 Analysis of the Research Approach

In this section a detailed analysis has been performed on the strengths of the FCM-based scenario development approach and weaknesses of the integrated FCM model developed in this research case. At the end, some recommendations have been made for improvement of this research approach.

6.2.1 Strengths of FCM-based Scenario Development Approach

It has been observed that the FCM-based scenario development approach has resulted in the following benefits:

- This research has demonstrated that the FCM-based scenario development approach has proved to be a useful tool for the engagement of the stakeholders. A group of key stakeholders from the government departments, research organizations, universities, independent power producers, and private companies worked together in the FCM expert panel. These experts identified and prioritized the scenario drivers. Thus, they actively participated in the creation of FCM-based scenarios.

- In this research, the integrated FCM was used to represent the knowledge in a symbolic manner and the mapping process helped to analyze the influence of various scenario drivers on each other. The experts were able to easily highlight and map the scenario drivers that may affect the deployment of wind energy projects in the country. Thus, it was relatively easy to use FCMs for representing the structured knowledge in a short time. It also helped to increase the creativity and structure of the scenarios and made the knowledge acquisition relatively easy. Moreover, different techniques can be used to capture the knowledge. For this research, the knowledge was captured from the literature, through interviews, and through group sessions of the scenario workshop.
- This approach enabled the researchers to quickly observe behavior of a system without the requirement of an expensive and proprietary software tool and the inferences were computed by numeric matrix operations. A spreadsheet created in Microsoft Excel was used to perform the calculations. Moreover, this technique was very useful to answer what-if questions and the researcher was able to assess how various changes impacted the model outcome and resulted in different scenarios. For example, the model outcome was observed against the presence and absence of the favoring policies and economic growth in the country.

- This technique has a high-level of integration because the causal maps and the resulting FCMs were modified and the views of additional experts were integrated into the model. Individual FCMs were obtained from the FCM EP members and the model was extended by adding new concepts and causal links, and changing the causal weights assigned to the existing links. Thus, this technique has the potential to reflect views of many respondents in one integrated FCM model.
- The quantitative analysis of causal cognitive maps has helped to improve the overall quality of the developed scenarios and overcome the indeterminacy problem. FCMs provided a simulation environment and the use of various input vectors have allowed the researcher to foresee consequences of these vectors resulting in different scenarios. Five different input vectors were used in this research. Moreover, the use of different input vectors have also allowed the researcher and experts to better reflect their anticipated concerns.
- All the scenario drivers (concepts) and their complex causal relationships in the integrated FCM model were considered during the scenario development process (FCM simulation). Finally, there were 40 concepts in the revised integrated FCM model after the scenario workshop. Therefore, this process has resulted in the creation of comprehensive scenarios rather than creating scenarios based on a few hypothetical assumptions and scenario drivers.

- This research has also demonstrated that FCM-based scenario development approach can be used with other techniques such as wild cards to augment the scenario building process. In order to develop heterogeneous scenarios, two wild cards were introduced to the integrated FCM model. It resulted in the creation of a significantly different scenario, which indicates a negative trend towards the deployment of wind energy projects in the country. It demonstrates that the FCM-based scenario development approach has the capability of developing heterogeneous scenarios. Moreover, development of this type of worst-case scenario will allow the policy and decision makers to foresee and envisage different strategies in a challenging environment.

A summary of the observed strengths of the FCM-based scenario development approach demonstrated in this research is presented in Table 35.

Table 35: Strengths of the research approach

Strengths of FCM-based Scenario Development Approach	
1.	Involvement of stakeholders in the scenario building process
2.	Ease of use to represent structured knowledge in a short time
3.	Quick observation of the model outcome, computation of inferences, and answer what-if questions
4.	High-level of integration to combine multiple FCMs
5.	Quantitative analysis of causal cognitive maps
6.	Creation of comprehensive scenarios
7.	Can be applied with other techniques to augment the scenario building process

6.2.2 Weaknesses of the integrated FCM Model (Research Case)

Some of the envisaged benefits of the FCM-based scenario development approach were not observed during this research. It has happened due to certain limitations of the integrated FCM developed in this research case. Therefore, the limitations, implementation challenges, and observed weaknesses are described in this section:

- Initially, as a result of FCM simulation, all scenarios led to an increase in the deployment of wind energy projects in the country. Although the barriers, challenges, and the wind energy deployment paths are different against each scenario, there is a positive trend towards wind technology. Thus, this research has not been able to create heterogeneous scenarios. This limitation might be due to the members of the FCM expert panel. Their feedback represents linear thinking, without considering a surprisingly different or unexpected trend (concept) in their FCMs. A cognitive bias may have deviated judgment of some experts in this particular situation. In order to overcome this problem, it is recommended to ensure a wider participation of experts in the expert panels. Moreover, it is also important to carefully balance the expert panels. However, through the use of wild cards a significantly different scenario was also developed in this research.
- Some weaknesses were also observed in the integrated FCM model. The integrated FCM model was not refined before actual FCM simulation in

order to identify missing links and definitional variables. There are several concepts in the model having only a direct effect on the objective of the FCM model (widespread deployment of wind energy in the country). However, these concepts may also affect other concepts in the FCM model, but in some cases it is not highlighted by causal links. For example the direct effect of international cooperation (C33) has shown on the deployment of wind energy projects. However, it may also affect the other concepts such as availability of trained HR (C16), measurement and better assessment of wind resources (C34), local manufacturing (C12), and involvement of the private sector (C20) are not shown in the model. Similarly, the effect of economic growth (C1) on the improvement of living standards (C8) is not shown. It indicates that the experts were focused on the deployment of wind technology and they may have missed some causal links among various concepts. The integrated FCM model also has some definitional relationship highlighted in section 5.1.5. During the scenario workshop, significant amount of time was consumed in defining meaning of all the concepts in the model. As a result, less time was available for the experts to critically review the integrated FCM model. It is recommended to define the meaning/description of all the concepts before the workshop to overcome this problem. It is especially important when there are many concepts in the integrated FCM model.

- At the start of this research, it was difficult to get input from some of the experts in the form of a causal map. The experts were not familiar with the causal maps and FCMs. Thus, the researcher translated their feedback in the form of a causal map/FCM and asked them to review it to ensure that their judgment was properly translated in it. However, the use of stimuli significantly helped to capture the experts' knowledge. A casual map developed in a pilot study project was used as a stimulus during the process of obtaining feedback from each expert [11]. It helped the experts to understand the FCM and provide meaningful feedback.

- In this research, it was a difficult task for the researcher to combine the individual FCMs of all the experts in one integrated FCM model because some experts used different descriptions and terminology to highlight the same concepts. Therefore, it was a challenge to remove the redundant concepts and causal links from the integrated FCM model. The scenario workshop provided a suitable platform where the experts reviewed the integrated FCM and removed the redundant concepts. Clear definition of the meanings of all the concepts helped to overcome this challenge. This standardization is also very helpful when multiple experts are reviewing the integrated FCM.
- There is lack of consideration of time lags in the integrated FCM model and simulation. It has been explained in section 5.1.5 that the expert highlighted causal links with very different timeframes in the integrated FCM model. However, these time frames were not synchronized through "dummy concepts".

A summary of the observed weaknesses and implementation challenges is presented in the following table:

Table 36: Weaknesses and implementation challenges

Weaknesses and Implementation Challenges	
1.	In this research case, it was difficult to create heterogeneous scenarios
2.	Due to limited time of scenario workshop, the integrated FCM is not very comprehensive and some causal links are missing
3.	Sometimes experts are not familiar with the causal maps
4.	Difficulties to combine multiple FCMs due to different description/terminology of concepts
5.	Lack of consideration of time lags

6.2.3 Recommendations

This research has indicated that through a series of workshops, this research approach has been successfully implemented. However, there were some process related problems and implementation challenges, which are described in this section. Moreover, recommendations are also presented to overcome these problems.

- It was observed that there was limited time available for the experts in the scenario workshop. Therefore, it is recommended to increase time of scenario workshop and conduct two workshop sessions. It would ensure that the experts have ample amount of time to review and critique the integrated FCM model. A case study indicates that multiple workshops were conducted to create the FCM-based scenarios [334].

- It is recommended to pre-process FCM models before actual FCM simulations in order to identify missing links, delete definitional variables, standardize timeframes and improve experts' awareness for interdependencies [76, 156].
- It is important to consider time lags in the integrated FCM model and simulation. It has been observed that the experts drew several causal links with very different timeframes. For example the political will of the government (C26) will take some time (in months) to translate into formulation of favoring policies (C15) and subsequent improvements in domestic manufacturing (C12) may take even years. The FCM literature highlights to synchronize these time frames through incorporation of "dummy concepts". These concepts help to break the more long-term causal links into several causal links with shorter time-frames [156, 233].
- This research framework was primarily focused on the workshops. However, there are many other participation modes possible such as online discussions, online modeling etc. that could be used. It would facilitate the experts to join the expert panels from different geographical locations. Several researchers have highlighted that the online discussions make it possible for the experts to participate from anywhere in the world [42, 114, 189, 316].
- It was difficult for some of the participants to easily understand the FCM. This increases the responsibility of the researcher and workshop moderators to guide the workshop participants through the process and

explain the research outcome. In order to overcome this problem, some researchers have also conducted a training workshop for the experts to provide background information of the scenario development theory and FCM theory [334].

- It was observed that the expert panel members had a tendency to break into small groups of 5-6 experts during the workshops. Therefore, it would be critical to make sure that at least two workshop moderators are available for each workshop session.
- It is strongly recommended to clarify the meaning and description of all the concepts in the FCMs obtained from every expert. This would facilitate the researcher to easily combine multiple FCMs obtained from all the experts and remove the redundant concepts. The FCM literature also suggests that clear names of the key concepts is helpful to integrate multiple FCMs into one [156].
- The researcher should also ensure to use standard terminology for various concepts highlighted in the FCM model. This would help to ensure clear communication without any ambiguity and confusion. The literature on expert judgment [127, 335] and FCM [156] also highlight the importance of using clear and standardized terminology.
- It is recommended to explore software tools to facilitate the map building process and creation of a FCM Adjacency matrix. A software tool can facilitate the modeler to read, edit, and combine multiple maps and

translate them into FCM models [156]. This would also significantly reduce the time and effort required for conducting FCM simulation.

- The researcher and workshop moderators should encourage some brainstorming in the start of every workshop. It helps to get people into a creative mood and generate useful ideas [30, 211, 322].
- It is also recommended to use stimuli during the knowledge capture process from the members of an expert panel. The FCM literature also highlights the importance of using stimuli [155, 156].
- Finally, the researcher should try to include more policy and decision makers working in key government organizations and experts that can also assess the usefulness of the action items. This would ensure the creation of a comprehensive and detailed FCM model and technology roadmap.

6.3 Wind Energy Technology Roadmap

In this research, a systematic top-down approach was used for the development of this technology roadmap, and separate workshops were conducted for various layers of the roadmap. The strategic objectives of the roadmap were identified by the experts using the national renewable energy policy of Pakistan as a baseline document. Then, the experts established the national targets of the wind energy roadmap for the next 20 years.

In the next roadmap workshop, the experts identified and explored the critical barriers towards the deployment of wind energy projects in Pakistan. In this workshop, the experts also ranked and prioritized the most important roadmap barriers against each scenario on the basis of their impact on the roadmap targets. In the last roadmap workshop, the experts proposed appropriate action items required to overcome the roadmap barriers for each scenario. Moreover, the roadmap objectives and targets were translated into the roadmap action items. Figures 23, 25, 27, and 29 highlight the action items required to overcome the roadmap barriers against the all scenario. The action items already taken by the stakeholders (government, power regulators, utilities, power distribution companies, and national wind industry) to address the roadmap barriers are shown in green color. Whereas, the action items which are already taken by the stakeholders but require significant modification or reforms are highlighted in purple color. The new action items (gaps/needs) that are required to overcome the roadmap barriers and achieve the roadmap targets are shown in blue color. Most of the action items proposed by the experts are in the category of new action items. In these roadmaps, the responsibility for the key action items is assigned to the major stakeholders. In several cases, the expert assigned the responsibility for an action item to two or more stakeholders.

The experts also specified the estimated timeline for the proposed roadmap action items against each scenario as shown in Figures 24, 26, 28, and 30. In these roadmaps, the key action items are highlighted with a timeline. The roadmap is developed for the wind energy sector of Pakistan and it is based on the multiple FCM-based scenarios. This research approach has helped us to develop robust and flexible roadmaps. These multiple scenario technology roadmaps will be useful against a wide range of alternative future outcomes. These roadmaps would also help the stakeholders to visualize the appropriate action items against different circumstances and scenarios. The most critical roadmap barriers and challenges are identified against each scenario, and the appropriate action items are proposed to overcome these barriers and achieve the roadmap targets.

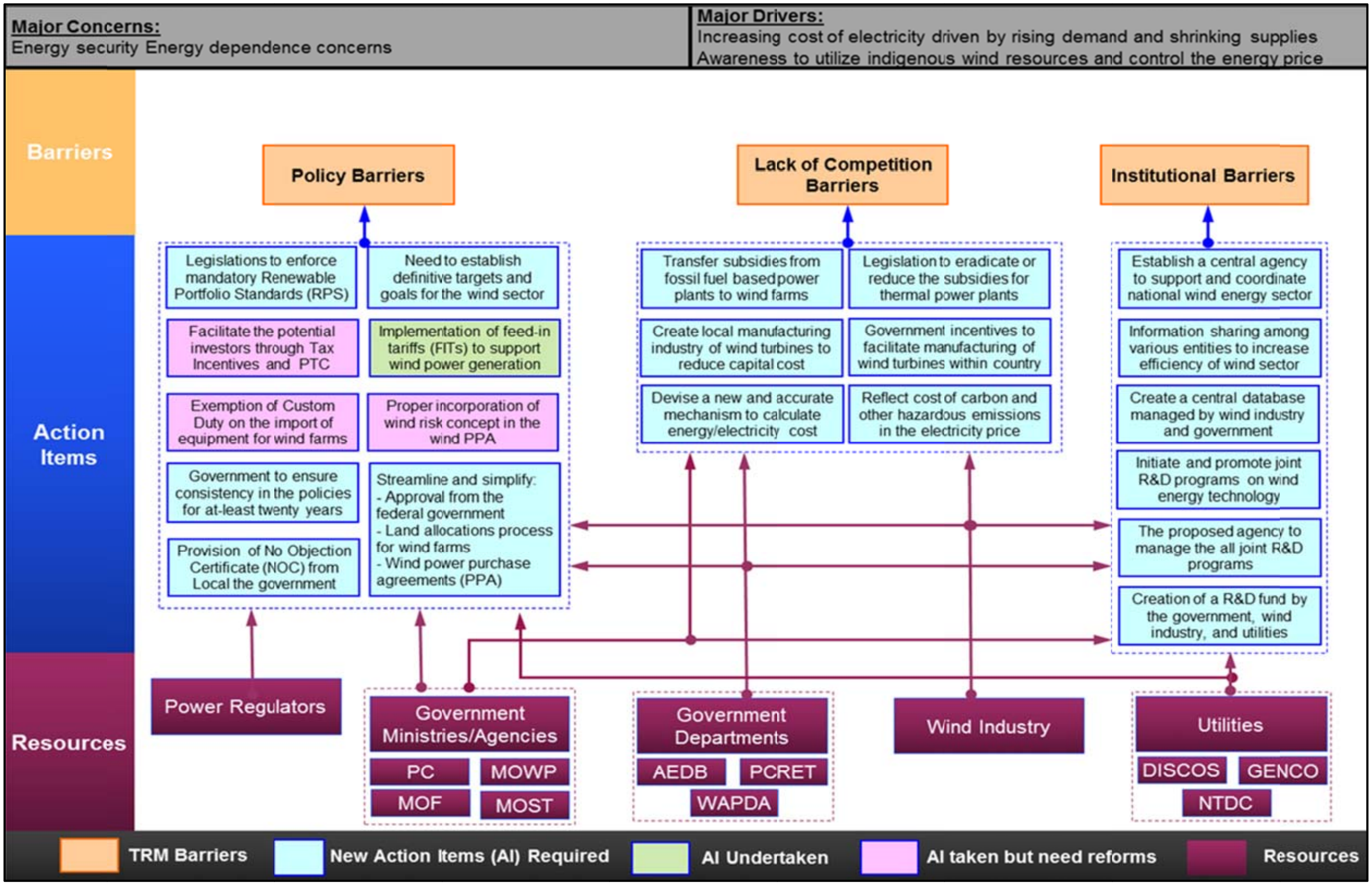

Figure 23: Action items required to overcome the barriers for scenario A: Growth of Economy and Energy Demand

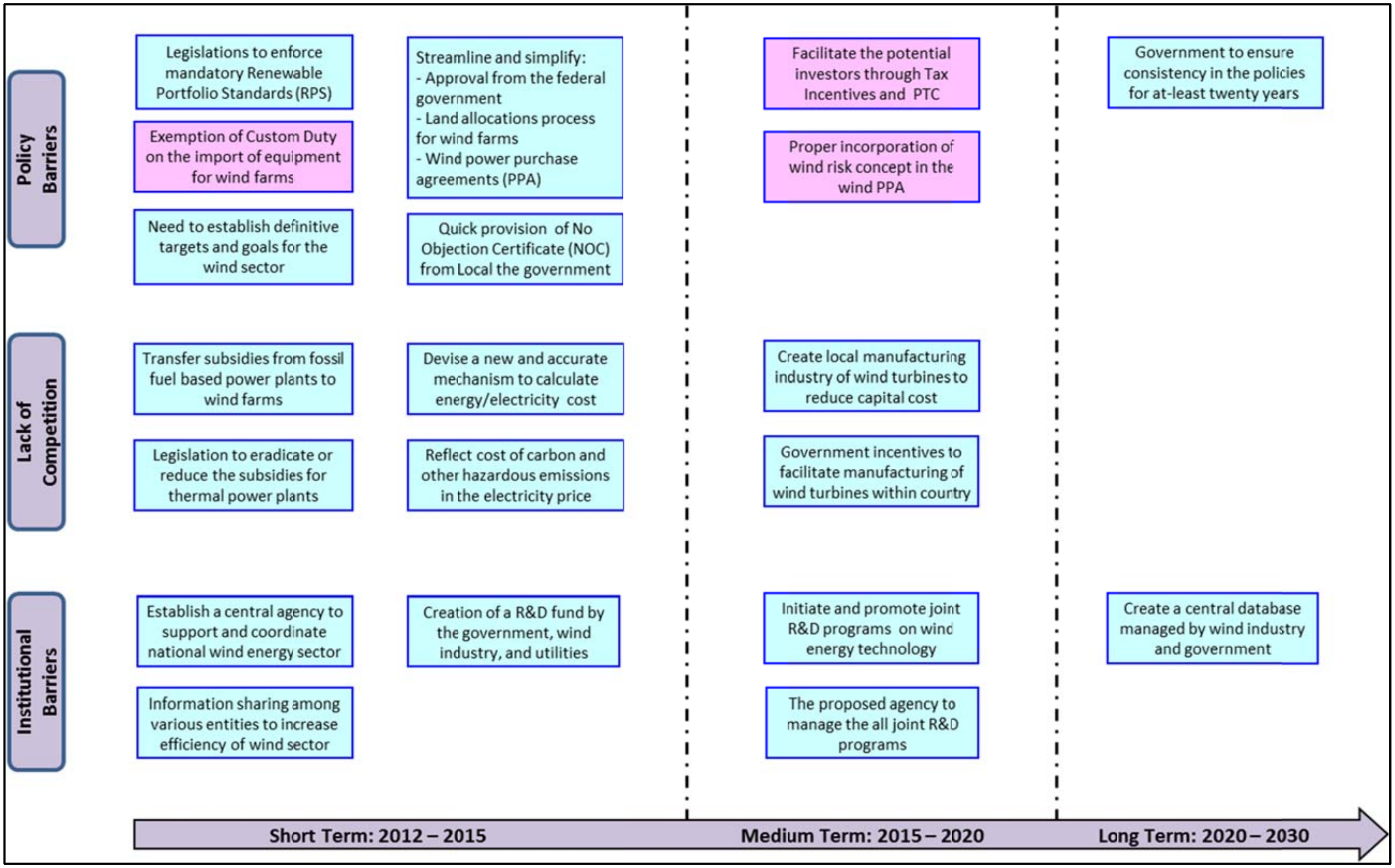

Figure 24: Key roadmap action items with timeline for scenario A: Growth of Economy and Energy Demand

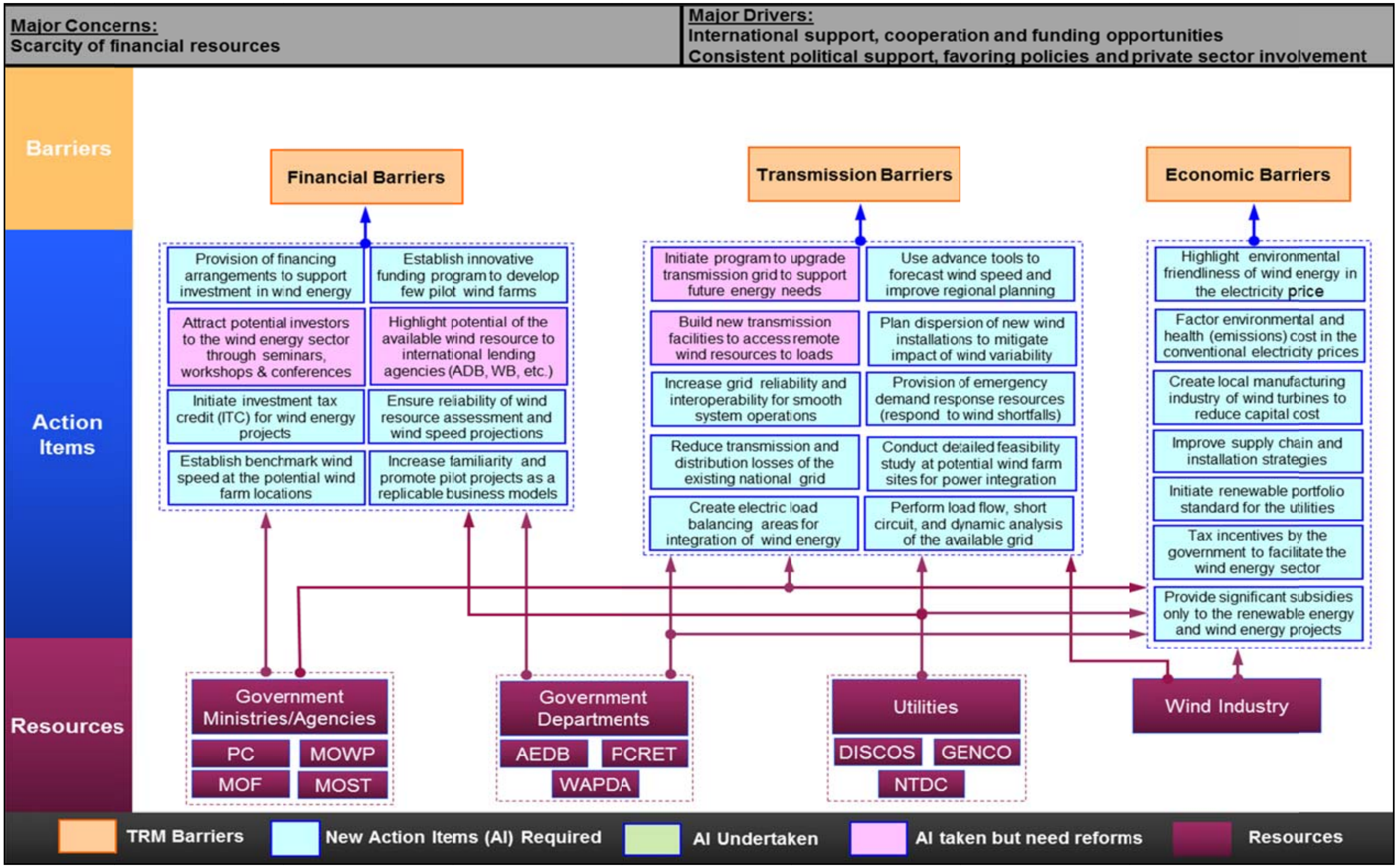

Figure 25: Action items required to overcome the barriers for scenario B: Favoring Policies and Government Support

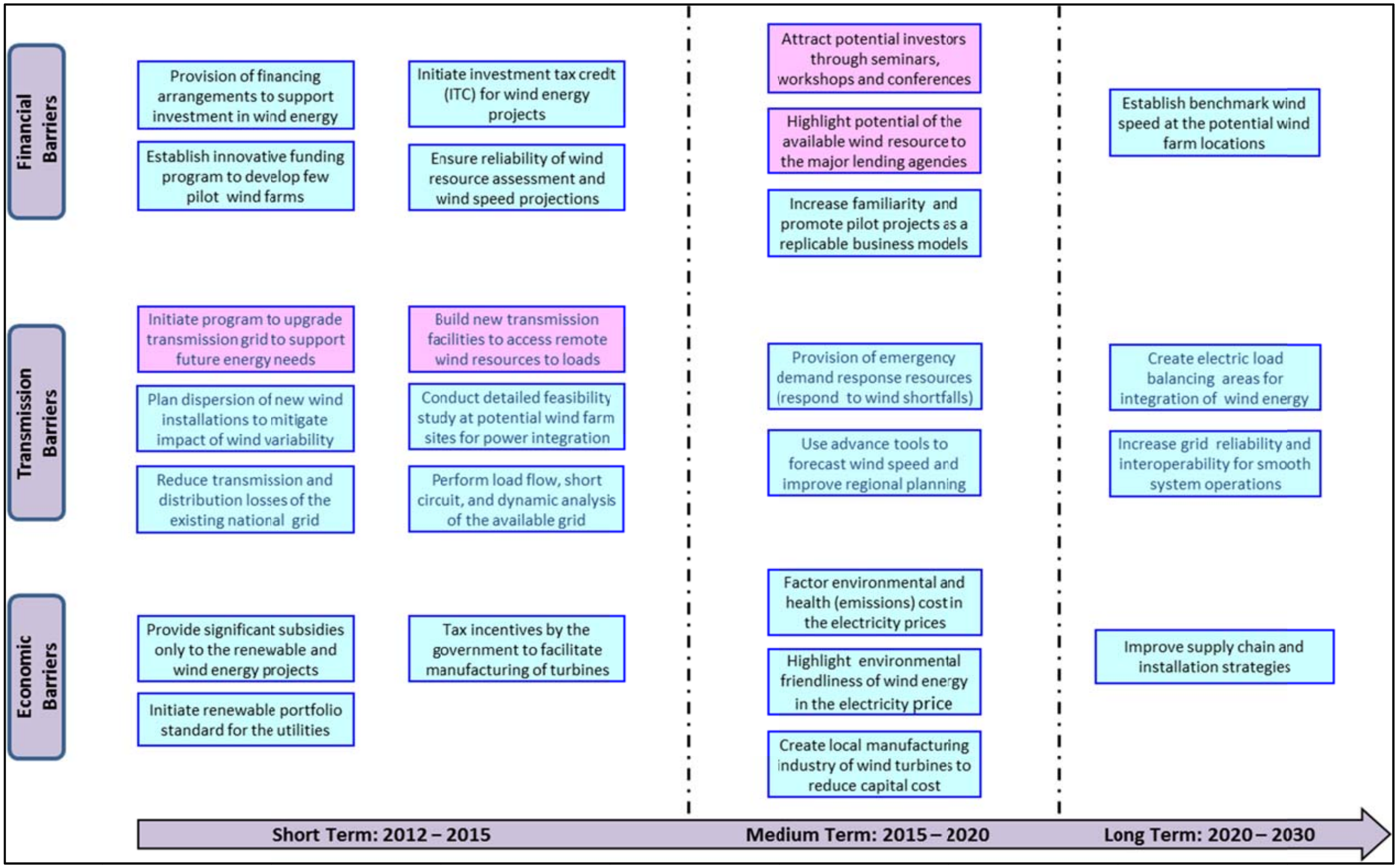

Figure 26: Key roadmap action items with timeline for scenario B: Favoring Policies and Government Support

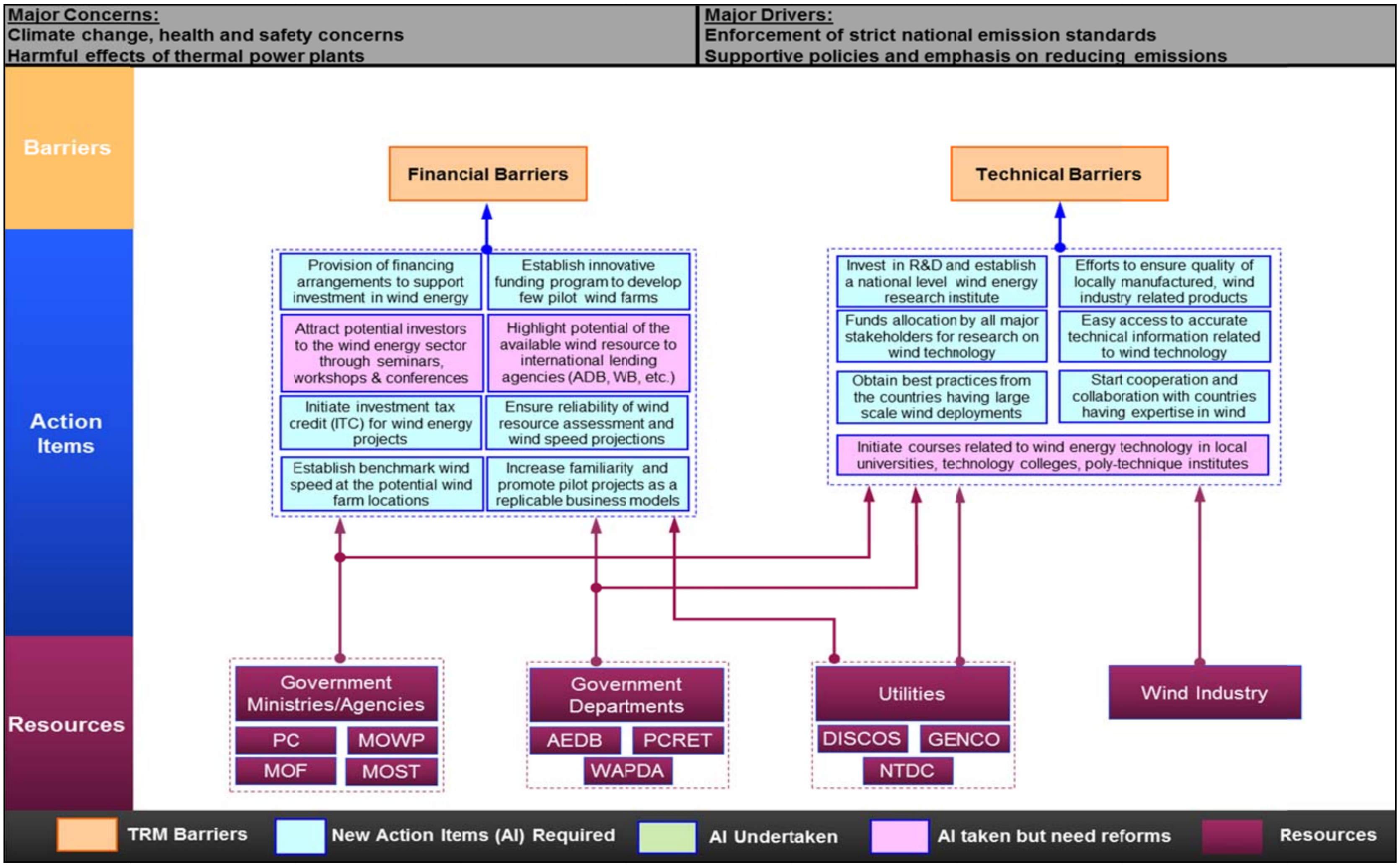

Figure 27: Action items required to overcome the barriers for scenario C: Environmental Concerns

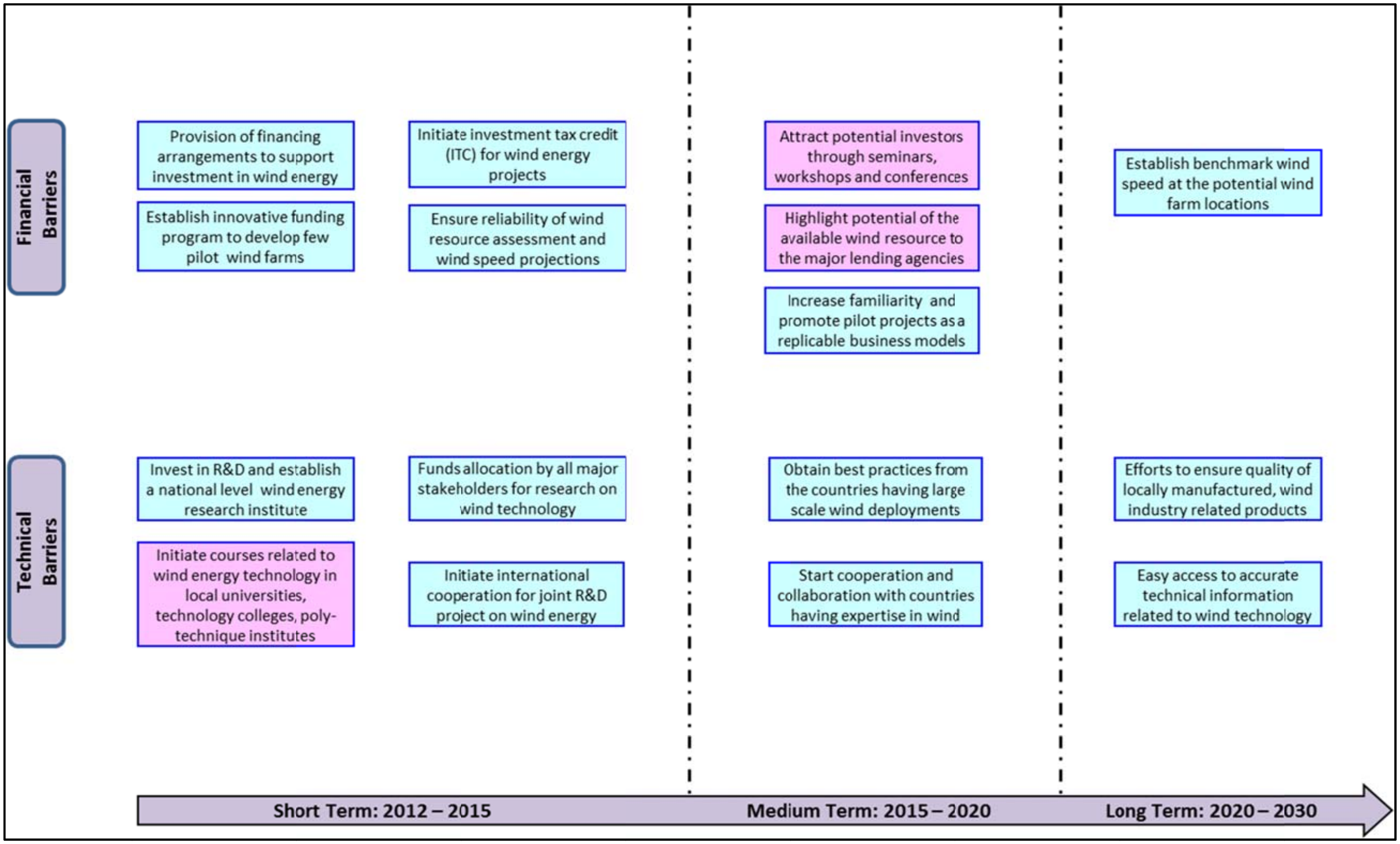

Figure 28: Key roadmap action items with timeline for scenario C: Environmental Concerns

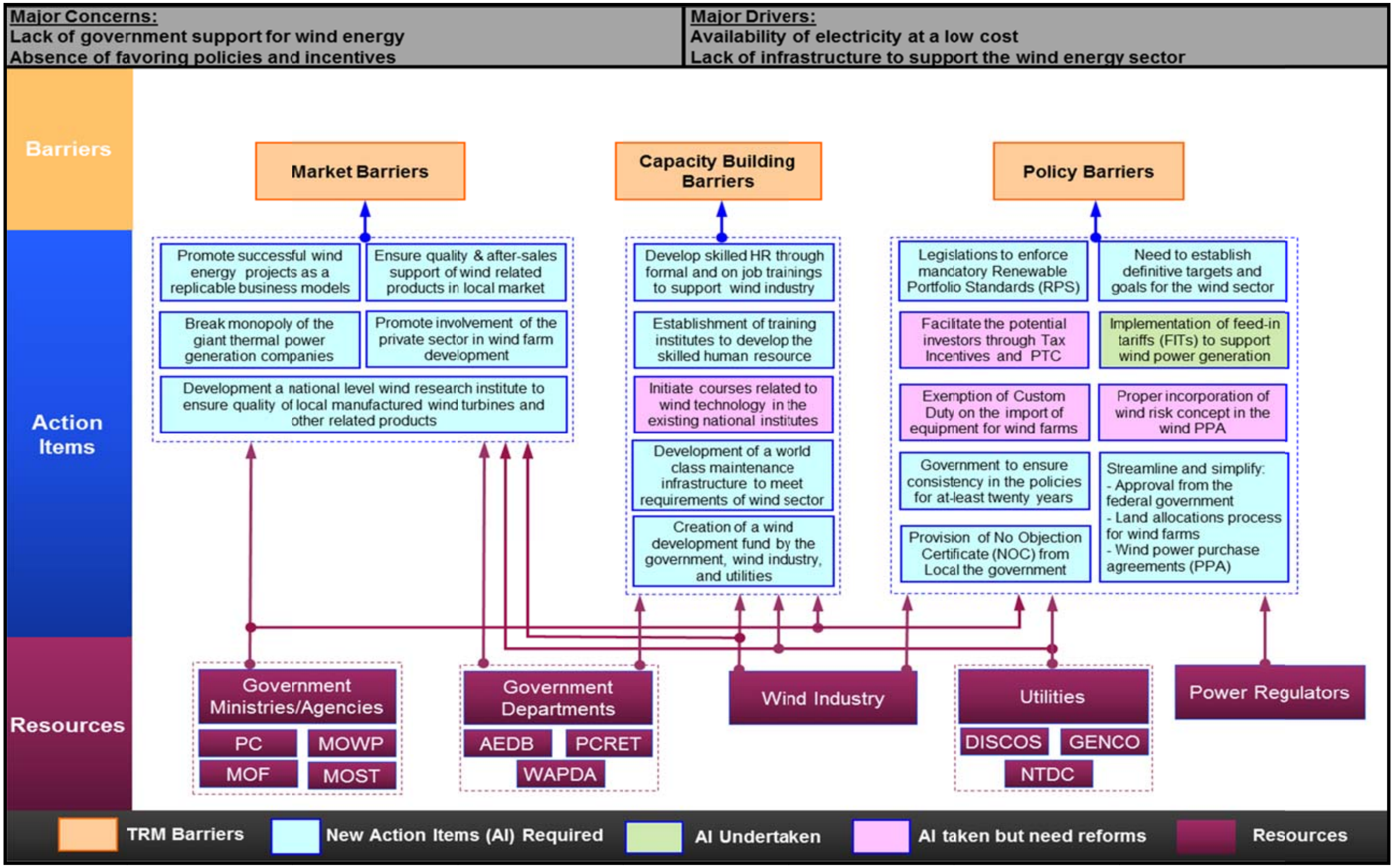

Figure 29: Action items required to overcome the barriers for the worst-case scenario

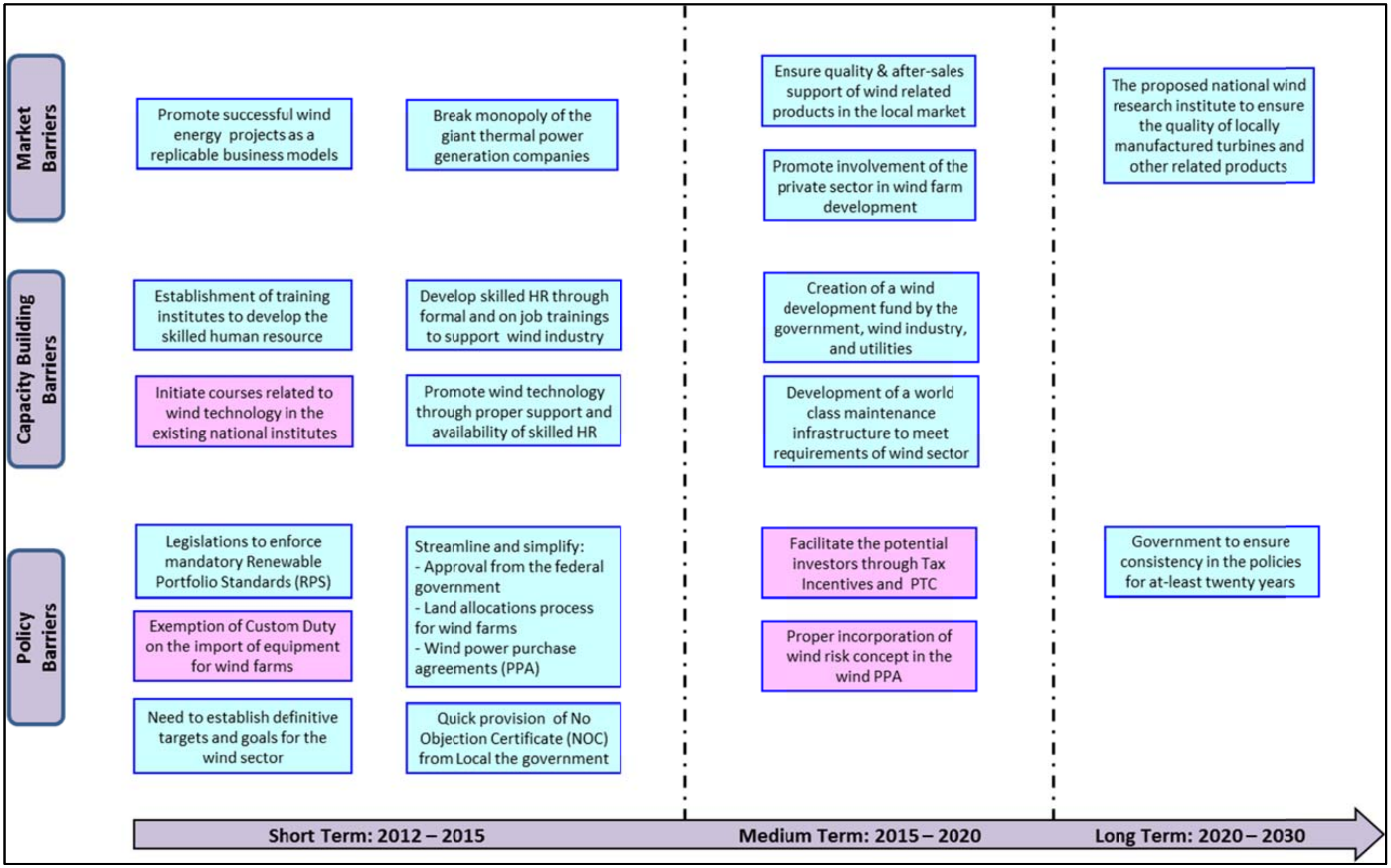

Figure 30: Key roadmap action items with timeline for the worst-case scenario

7 Conclusion

In this section, the research outcome and research contributions are discussed. Research limitations and recommended future research are also described in this section.

7.1 Research Outcome

The outcome of this research is the national level wind energy technology roadmap for Pakistan based on multiple FCM-based scenarios. Energy is a key element required for sustainable development and prosperity of a society. These roadmaps have been developed for the next two decades. The roadmap has four layers and it has highlighted the objectives, national targets, barriers and challenges, and recommended action items with assigned responsibilities for the deployment of wind energy projects in Pakistan. The objectives and national targets of the roadmap are established in accordance with the national renewable energy policy. Then, the important barriers and challenges towards the deployment of wind energy projects against each scenario are identified through the experts, literature review, and integrated FCM model. These barriers and challenges are prioritized on the basis of their impact on the roadmap targets. In the last tier of this roadmap, after detailed deliberations among the domain experts, appropriate action items are proposed to overcome the roadmap barriers and achieve the roadmap targets. These roadmaps for multiple scenarios also help all major stakeholders (government, wind industry, regulators, and power distribution companies) to envisage the required action items against different circumstances and scenarios.

7.1.1 Use of FCM to Develop Scenarios for Wind Energy

This research has demonstrated development of the FCM-based plausible scenarios for the wind energy sector. These scenarios are developed through expert judgment representing different plausible futures. This research has demonstrated a new approach for developing scenarios and conducting future studies. Despite some limitations, the integrated FCM model offers a visual medium and provides insight into the factors supporting and hindering the deployment of wind energy projects in Pakistan. The FCM-based scenario development approach has helped us to identify and model both qualitative and quantitative factors and their complex causal relationships in the context of wind energy deployment in Pakistan.

Four FCM-based scenarios have been developed. These scenarios help to establish a future vision of the wind energy sector and facilitate development of a robust technology roadmap. In the economic growth scenario, security of energy supplies emerged as a significant driver and dominant concern, leading towards utilization of the indigenous wind power. In the favoring policies scenario, scarcity of financial resources is an important concern because the country is not making good economic growth. The climate change and emissions of greenhouse gases are the dominant concerns in the third scenario. Finally, market, capacity building and policy barriers are the major concerns for the worst-case scenario developed through wild cards. These scenarios provide a detailed overview of the probable future landscape of the wind energy sector. Moreover, developed scenarios provide a basis for the long-term strategic energy planning and technology roadmapping.

7.1.2 Integration of Scenario Planning with Technology Roadmapping

This research has demonstrated the integration of scenario planning with technology roadmapping. Thus, it has extended the technology roadmapping through FCM-based scenario analysis. It was revealed in the literature review that multi-scenario technology roadmap is never developed before for any renewable energy technology [8]. The combined use of scenario planning and technology roadmapping has provided a greater insight into the problem and developed a robust roadmap. The developed roadmap has taken alternate futures into account rather than only focusing on a desired future. Scenario planning has introduced thinking and planning for multiple futures and strategic options. This research has indicated that use of scenario planning has complemented the technology roadmapping process. Several roadmap barriers were also identified from the integrated FCM model. As a result, this approach has brought more knowledge into the roadmap by identifying multiple alternatives of the future states. The resulting roadmaps enable better use of public/private resources by eliminating duplication of similar efforts.

In this research, the developed scenarios have provided an overview of the multiple energy futures of the country. Moreover, incorporation of the roadmapping process has identified pathways to achieve the desired targets against each scenario. It has resulted in a robust roadmap useful against different circumstances and scenarios. Therefore, it has enhanced flexibility and vision of the roadmap, and enabled anticipation of a broader range of possible changes. Figure 31 highlights the integration of scenario planning with technology roadmapping.

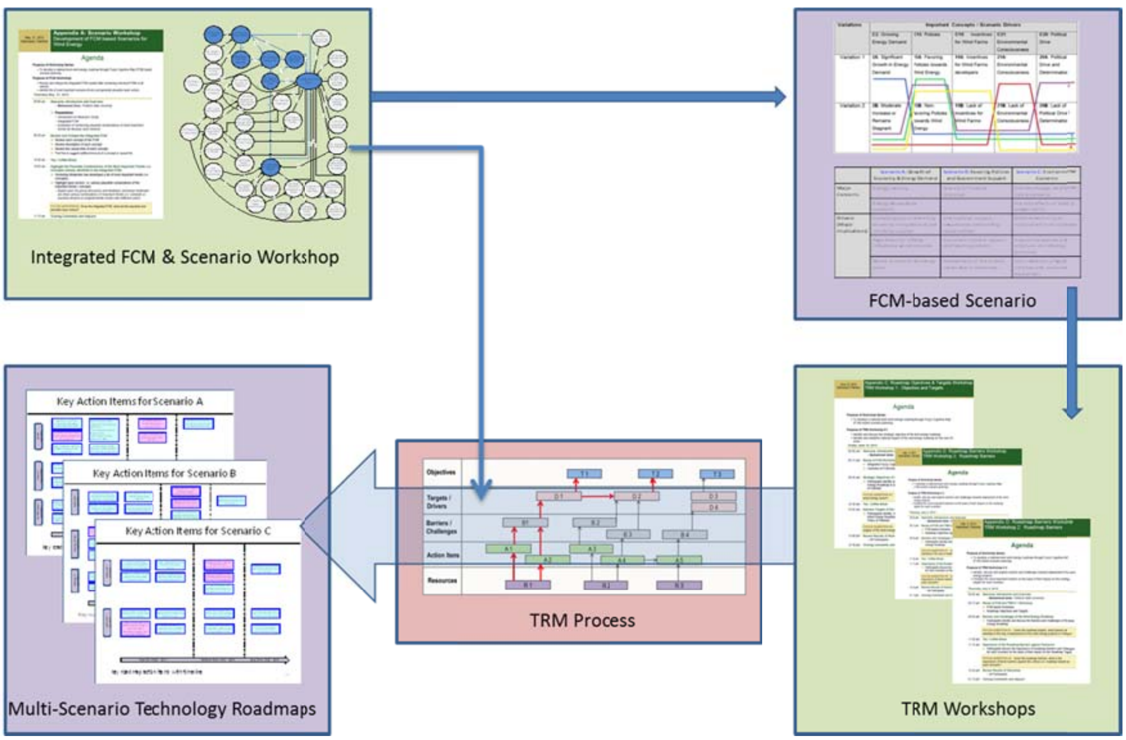

Figure 31: Integration of scenario planning with technology roadmapping

7.1.3 Barriers towards the Deployment of Wind Energy

This research has identified and prioritized the important barriers and challenges towards the widespread deployment of wind energy projects in

Pakistan. It is very important to identify the critical barriers in order to pave the way forward for a sustainable energy future in the country. The barriers and challenges faced by the wind energy sector have been systematically identified and addressed in the roadmap. There are numerous barriers and challenges, ranging from policy and legislative issues to a lack of infrastructure and financial constraints. These barriers have restricted the deployment of wind energy technology in the country.

This research is the first serious effort to systematically identify the critical barriers faced by the national wind energy sector. The research findings suggest that policy concerns, lack of competition with conventional power plants, financial constraints, and technical limitations are the most critical roadmap barriers hindering the deployment of wind energy projects in the country against these scenarios. The developed roadmap has also suggested the action items required to overcome the roadmap barriers against each scenario.

The roadmap barriers identified through this research are similar to other wind energy and renewable energy technology roadmaps. The American Wind Energy Association (AWEA) has developed a technology roadmap for the wind turbine technology for the next 20 years [21]. The AWEA's roadmap identified that the policy barriers, technology barriers, and market barriers are the major challenges to the widespread use of wind technology [21]. Another study indicated that the technical barriers, market barriers, and institutional barriers are the most critical obstacles to widespread use of renewable energy technologies [228]. Barriers related to the legislation, administration, lack of information, and institutional issues are also important [41]. Therefore, it can be concluded that other wind energy roadmaps have also resulted in similar outcome.

7.1.4 Roadmap Action Items

In this roadmap, numerous action items have been identified and proposed to achieve the roadmap targets and overcome the roadmap barriers. Implementation of these action items will help to execute wind energy projects in the country. The research has provided a framework for a national level gap analysis for large scale deployment of wind energy. The domain experts proposed these action items to address the roadmap barriers against each scenario. A list of detailed action items have been proposed by the experts against each roadmap barrier. During this process, the experts also translated the roadmap targets into these roadmap action items. The proposed roadmap action items are also classified by the experts into three categories: new required action items, action items already undertaken by the stakeholders, and action items undertaken but that require significant modification.

In the developed roadmap, responsibility for the key action items is also assigned to the major stakeholders along with the estimated time frame, when these action items are required to be undertaken. Thus, all major stakeholders can review their responsibilities in this roadmap against different scenarios. It also defines the roles and responsibilities of the major stakeholders and aligns their efforts towards the roadmap targets and eliminate duplication of resources and efforts. Implementation of these suggested action items will ensure widespread deployment of wind energy projects. For the first time, the detailed roadmap action items have been proposed for the national wind energy sector of Pakistan.

Again, it has been observed that there are similarities regarding the roadmap action items between this roadmap and some other technology roadmaps. The wind energy technology roadmap developed by the International Energy Agency (IEA) has proposed similar action items [46]. The Natural Resources Canada (NRC) has also recommended that strengthening the policy framework, expanding role of the wind industry, creating research centers, informing and engaging the community, accelerating the development activities, and demonstrating innovative projects are the most critical action items [227]. Analysis of the roadmap action items reveals that in these cases the proposed action items can be grouped into the following clusters:

- Policy and regulation related action items;
- Technology and industry related action items;
- Awareness and engagement related action items;
- Finance and economics related action items;
- Action items related to infrastructure and capacity building; and
- Action items related to integration of wind power to the national grid.

Further analysis also reveals that despite some similarities in the barriers and action items, there are significant differences in the nature of roadmap barriers and details of the action items. Due to the peculiar conditions and circumstances in different countries, there are differences in the specific nature of action items. Thus, there are similarities when analysis is performed at a broader level, but an in-depth analysis reveals that there are also differences in the action items. However, it can be concluded that the research outcomes and findings are in accordance with some other similar studies. This further validates and confirms the findings of this research.

7.2 Research Contributions

The main contribution of this research is that it extends the technology roadmapping methodology by combining it with a scenario planning approach. This research also presents a new approach for scenario development using fuzzy cognitive maps. The contribution of this research can be grouped into the following two aspects:

From technology management and methodology aspects:

- This study presents a combined use of scenario planning and technology roadmapping techniques. It extends technology roadmapping through FCM-based scenario planning. This combination has significantly improved the usefulness of the roadmap and enabled anticipation of a wide range of possible future outcomes. Both scenario planning and technology roadmaps complement each other, and it is an appropriate approach to use both techniques in a research project.

- In this research, four scenarios are developed for the national wind energy sector of Pakistan using FCM. Generation of FCM-based scenarios is a very new approach, and it has been applied to the wind energy sector for the first time. This unique approach combines the benefits of both qualitative and quantitative analysis and develops comprehensive scenarios.
- It was revealed during analysis of the public-domain sustainable energy roadmaps that, generally, scenarios are developed based on some hypothetical assumptions without much deliberation. However, in this research FCM-based scenarios, which provide logical reasoning and the causal relationship between various elements, are developed after combining individual causal maps from several experts. Subsequently, these scenarios are used for developing the technology roadmap.

From application of new methodology aspects: the wind energy sector of Pakistan as a research case:

- In this research, for the first time, a technology roadmap for the wind energy sector of Pakistan has been developed. It identifies the objectives, national targets, barriers, and obstacles towards deployment of wind energy technology in the country. It also recommends appropriate action items. The existing research related to the renewable energy sector in

Pakistan is limited to identifying the potential of renewable energy resources and highlighting some generic barriers. There is no roadmap, concrete action plan or strategy proposed or discussed in the renewable energy literature of Pakistan.

- Research has addressed the challenges and barriers associated with the deployment of wind energy on a large scale in Pakistan through the roadmap action items. These action items have been proposed to overcome the roadmap barriers identified against each scenario. Thus, the objectives and the targets of the roadmap are translated into the suggested action items.

7.3 Research Limitations

There are a number of research limitations that need to be considered. Some limitations of this research are given below:

- The outputs of this research rely on expert judgment, which is subjective data obtained from the members of the expert panels. Moreover, in some cases limited knowledge of the experts may limit the usefulness of the FCM model, scenarios, and roadmap. However, it is assumed that the members of the expert panel have a sufficient level of knowledge and experience, but biases or limitations of knowledge of the panel members can impact the research validity. Due to this reason, there is much emphasis in the literature on the careful selection of the expert panel members. However, this researcher has tried to overcome this limitation by balancing the experts in each expert panel.

- The expert opinion expressed in this research is limited by time, individuals, and context. This may yield different results due to a different time, a different group of experts, or a different country. The research is time and context dependent.
- The research case study is limited to the wind energy sector of Pakistan, which is a developing country having peculiar energy problems. Therefore, these results will not be applicable to other countries or industries. However, if a similar type of research is conducted for another country or industry, then it may give more generalized results which are applicable in other cases as well.
- This study has only considered the onshore and utility scale wind energy projects in the technology roadmap.
- All the scenario drivers (concepts) in the FCM model were prioritized based on their potential impact and uncertainty using the Wilson matrix, also known as impact-predictability matrix. During this process, some concepts which are actually endogenous to the model, such as C2 and C15 also emerged as the critical scenario drivers. However, in order to overcome this problem, combinations of endogenous and exogenous variables were used in some cases such as first and second input vectors.

- FCMs of the experts were mathematically combined by taking the average of the causal weights. It is controversial approach particularly if the experts in their FCMs connect concepts with causal links that have different weights or directions. However, in this research, some experts assigned different causal weights, but different directions of causal links were not assigned. Moreover, for scenario building purposes, this approach is considered better than the other method based on measuring the Hamming distance (bit difference) between the inference vectors of various experts and assessing the expert creditability weights for each expert as explained in Appendix B.
- In this research, the integrated FCM model has some limitations due to missing links, definitional relationships, lack of feedback cycles, and different time frames. These limitations are explained in section 5.1.5 and detailed recommendations to overcome the limitations are presented in section 6.2.
- This research has provided an overview of the roadmap action items. However, it is required to specify exact technical details of the action items especially for the medium and long-term.

7.4 Future Research

Further research is recommended in multiple areas including expanding the research application, enhancing the robustness of the FCM model, using a hierarchical decision model, monitoring the roadmap results, and assessing the state of the technology roadmap.

- Expanding the research application

  As indicated in the previous section on limitations, the outcome of this research is limited to the deployment of wind energy technology in Pakistan. However, this methodology can be extended and applied to another technology or industry. It will be interesting to apply this research approach to another renewable energy technology or wind energy sector of another country.

- Enhancing the robustness of the FCM model

  The integrated FCM model is developed after obtaining input from the members of the FCM expert panel. It is recommended that this model be presented to all major stakeholders through seminars and symposiums in order to obtain input from a wider audience. Through this process, a more robust and detailed FCM model can be developed.

- Use of a Hierarchical Decision Model

  It is recommended to use a Hierarchical Decision Model (HDM) and pairwise comparisons to establish more robust measurements of the importance weights of the roadmap targets and ranking of the roadmap barriers. A conceptual overview of the proposed Hierarchical Decision Model is shown in Figure 32.

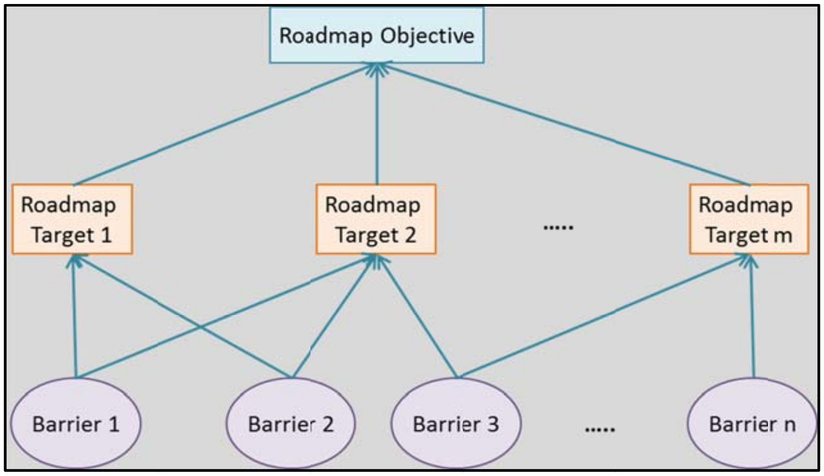

Figure 32: Overview of the proposed Hierarchical Decision Model

- Monitor and measure the roadmap results

  Various research studies have highlighted the need to analyze that actual results of the roadmap are achieved after the TRM exercise [100, 144, 145, 340]. It would be interesting to develop a framework for monitoring and measuring results from the technology roadmaps. It will help to monitor how well the roadmap initiatives are achieving their intended results.

- Assess the state of the roadmaps

  It is important to develop an approach to assess the state of the scenarios and technology roadmaps [143, 241, 340]. The practical approach proposed by Vatananan and Gerdsri [341] can be used. It determines the current state of a roadmap by analyzing changes in the key drivers and their collective effect on the roadmap. It is recommended to develop a status signal based on the elements of the roadmap. This status signal will assist the decision to maintain, update or revise the roadmap. An overview of the model for calculating the status signal of this technology roadmap is shown in Figure 33.

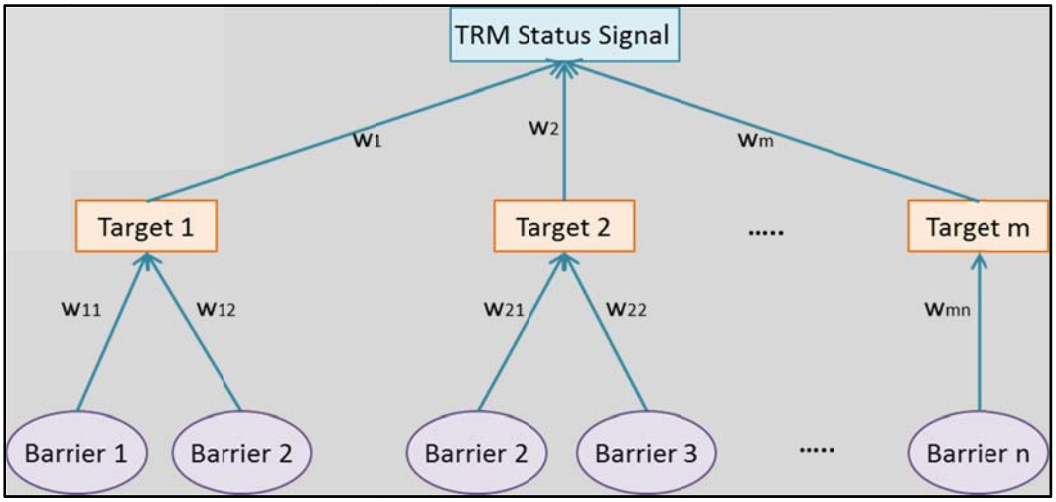

Figure 33: Model for calculating the TRM status signal [333]

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Appendices

Appendix A: FCM-based Scenario Workshop

Agenda

Purpose of Workshop Series:

- To develop a national level wind energy roadmap through Fuzzy Cognitive Map (FCM) based scenario planning

Purpose of FCM Workshop:

- Review and critique the integrated FCM created after combining individual FCMs of all experts
- Identify the of most important scenario drivers and generate plausible input vectors

Thursday May 31, 2012

09:00 am **Welcome, Introduction and Overview**

- **Muhammad Amer**, Portland State University

Presentation

- Introduction to Research Study
- Integrated FCM
- Examples of combining plausible combinations of most important trends (to develop input vectors)

09:30 am **Review and Critique the Integrated FCM**

- Review each concept of the FCM
- Review description of each concept
- Review the causal links of each concept
- Feel free to suggest addition/removal of a concept or causal link

10:30 am **Tea / Coffee Break**

10:45 am **Highlight the Plausible Combinations of the Most Important Trends (i.e. Concepts already identified in the Integrated FCM)**

- Workshop Moderator has developed a list of most important trends (i.e. concepts)
- Highlight input vectors i.e. various plausible combinations of the important trends / concepts
  - Based upon the group discussion and feedback, workshop moderator will draw various combinations of important trends (i.e. concepts or scenario drivers) on projector/white screen with different colors.

FOCUS QUESTION #1: Given the integrated FCM, what are the important and plausible input vectors?

11:15 am **Closing Comments and Adjourn**

Handout for FCM-based Scenario Workshop

Purpose of Scenario Workshop:

Prior to Workshop:

- Identify the concepts (scenario drivers) that in your opinion affect or will affect deployment of wind energy on large scale, in the form of a casual map
- Identify the causal relationship among various concepts of the map

During the Workshop:

- Review and critique the integrated FCM created after combining individual FCMs of all experts
- Identify the of most important scenario drivers and generate combination of these important drivers / trends (i.e. plausible input vectors consisting of most important scenario drivers) for developing FCM-based scenarios

Focus Questions:

- Which concepts / factors are affecting deployment of wind energy projects on large scale in the country?
- Given the concepts of FCM, what is the causal relationship among these concepts?
- Given the integrated FCM, what are the important and plausible input vectors?

Introduction and Background Information:

Objective of this research is to develop a national level wind energy roadmap through scenario planning for the next 20 years. Multiple scenarios will be developed using Fuzzy Cognitive Maps (FCM) approach. For this purpose, please provide your opinion and judgment in the form of causal cognitive maps as explained in the instruction section. Some background information is also given in order to provide a brief overview of the research problem. A causal map developed earlier for the deployment of wind energy, prepared in a pilot research project is also included in the end of instruction section [1].

Pakistan is an energy deficient country facing problems due to shortage of energy, especially electricity which is adversely affecting the economy. Country has a limited fossil resource base and there is high demand of energy to sustain economic and industrial growth. Electricity deficit of the country was over 4000 MW in 2008 [2] and import of fossil fuel has put a lot of pressure on the country's economy [3]. The per capita electricity consumption for Pakistan is 475 kWh, which is almost six times lesser than average electricity consumption in the world [4]. Due to shortage of electricity in Pakistan, industrial sector has been badly affected and overall exports of the country have been reduced. It is likely that this problem will further aggravate in the future because the national energy consumption is increasing at an average annual rate of 5.67 percent [5]. Therefore, it is crucial for the country to formulate a diverse energy strategy and increase the share of renewable energy resources.

Renewable energy resources are the fastest growing energy resources in the world [6, 7]. However, there is not much national effort in Pakistan for the exploitation of renewable energy resources despite their enormous potential. Country's 1100 km long coastline is ideal for the installation of wind farms and various studies indicate exploitable wind energy potential of more than 50,000 MW along the coastline alone [8]. If we consider the regional context, during the last 5 years India has installed many wind farms along the coast and Pakistan is sharing the same Indian Ocean coastline with India. Moreover, wind energy is a rapidly growing, mature and proven technology already contributing 10 percent or more power in the national energy transmission systems of several European countries [9]. International Energy Agency (IEA) estimates that the investment and operating cost of wind power is expected to further reduce in future [9]. According to a report from Renewable Energy Policy Network, during the last four years wind power capacity has increased 250 percent [10].

It is likely that that deployment of wind energy will significantly help the country to overcome the energy shortage crisis, improve living standards of the society, diversify national energy mix, contribute towards economic growth, improve rural economy, reduce energy import bill, and ensure environment sustainability.

Instructions:

You are requested to identify the factors that in your opinion will affect deployment of wind energy on large scale, in the form of a casual map. These factors (concepts) will be interconnected through causal links representing the cause and effect relationships among concepts. You can highlight the positive or negative causal link between these factors depending on the type of causality that exists. For example a positive value between concept 1 to concept 2 means that an increase in concept 1 causally increases concept 2; whereas, a negative value between concept 2 to concept 3 means that an increase in concept 2 causally decreases concept 3 as shown in the Figure A-1.

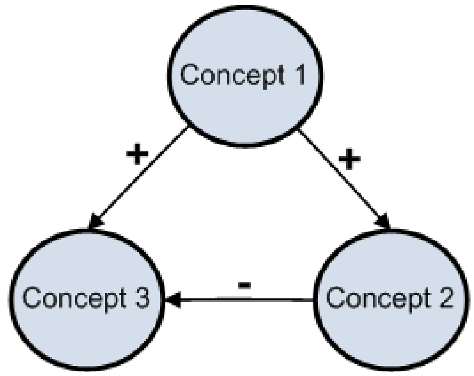

Figure A-1: A sample of causal cognitive map

Please take the following steps:

1. Identify and define the important factors
    a. Write down on Post-its with issues
    b. Cluster these issues as a map and discuss importance
2. Define the causal link between these factors
    a. Identify factors which are linked together
    b. Determine that the relationships is positive or negative
    c. Define relative strength of relationships by assigning causal weights using a 5-point Likert-type scale, with values that ranged from 1, representing a very weak causal link, to 5, representing a very strong causal link
3. Review the combined/integrated FCM
    a. Moderator will individually obtain the causal maps from every expert and combine them into an integrated FCM
4. Identify the most uncertain factors in the integrated FCM
    a. Please paste red dots on the most uncertain factors (5 red dots are provided to each participant in scenario workshop)
5. Identify plausible input vectors consisting of the most important factors from the integrated FCM.
    a. Moderator will provide a table of critical scenario drivers (factors) at the top of the each column and highlight number of conceivable development variations (at least two) of each scenario drivers
    b. Combine the development variations into plausible strands (input vectors) using markers of different colors

Examples:

Figure A-2 highlights an example from a case study, where three input vectors have been generated using morphological analysis. This process helps to ensure that there is no contradiction in these combinations shown in green, red and purple color. Morphological analysis is a useful tool and it helps to visually analyze combination of various conceivable development variations for all scenario drivers and ensure plausibility.

Variations	C 1 Economic growth	C 2 Growing energy demand	C 4 Increasing cost of energy	C 5 Design innovations	C 8 Favoring government policies
Variation A	1A: economic growth in country	2A: Increased energy demand	4A: Increase in energy cost	5A: Design innovations in wind turbine	8A: Favoring policies for wind by the government
Variation B	1B: No economic growth	2B: No increase in energy demand	4B: energy cost remains stable	5B: No design innovations takes place	8B: Favoring policies are not adopted

Input Vector 1
1B-2B-4B-5B-8A

Input Vector 2
1B-2A-4A-5A-8B

Input Vector 3
1A-2A-4B-5B-8B

Figure A-2: Morphological analysis to generate raw scenarios [11]

Figure A-3 highlights a causal map/FCM developed earlier as a pilot study for the deployment of wind energy in Pakistan. Every node of the combined causal map shown in the Figure A-3 indicates one concept (factor) and each arrow indicates a causal link from one concept to the other concept in the direction of arrow. In general each node in a FCM model may reflect a driver, trend, variable, event, action or goal of the system.

Please feel free to add more concepts (factors) or remove concepts which you think are not relevant, and change weights or direction of the causal links. Please ensure that your causal map should be plausible indicating a logical relationship among the identified concepts. Based on the integrated FCM multiple scenarios will be formulated.

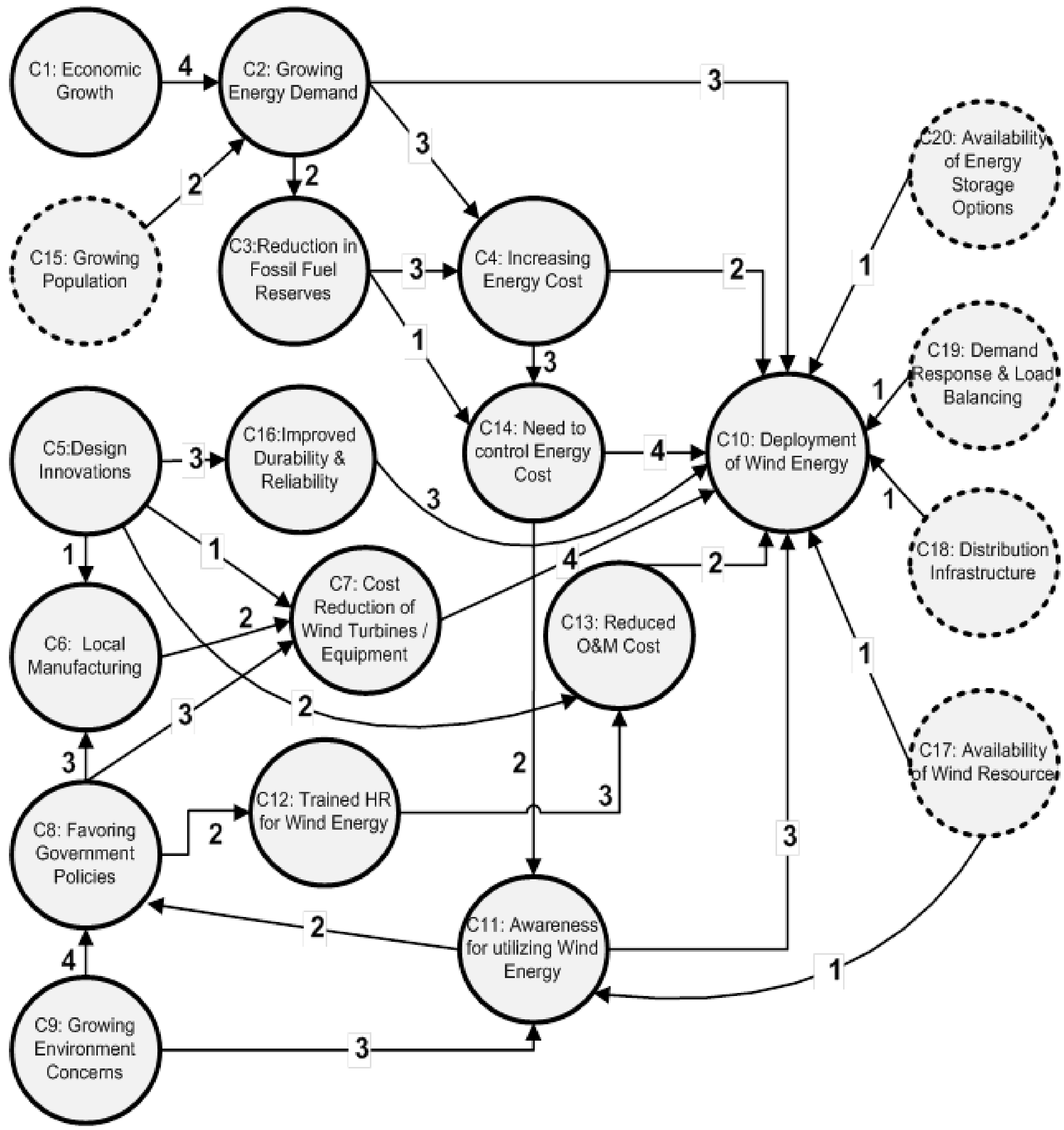

Figure A-3: Causal map/FCM for deployment of wind energy in a developing country [11]

References of Appendix A:

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Appendix B: Techniques for Combining Multiple FCMs

Finite number of Fuzzy Cognitive Maps (FCMs) can be combined together to produce the joint effect and capture opinion of multiple experts together in one map for the decision making process [1]. Integrated FCM represents information obtained from multiplicity of sources. FCM model integrates expert knowledge of multiple peoples who know the operation and behavior of an environment / system [2]. It is quite possible that experts will differ in content and weight of casual link when addressing the same problem or situation. Utility and usefulness of FCM model significantly depends upon the quality of underlying casual map, therefore selection of appropriate experts and combining their cognitive maps is very critical [3].

There are two methods presented in the literature to combine FCM of multiple experts. One method is proposed by Taber and Siegel and it is based upon assessing expert creditability by calculating creditability weights of each expert. The second method is commonly employed and it takes an average of the expert opinions expressed in all FCMs to generate combined FCM.

Expert Creditability Weights Method:

Taber and Siegel conducted a study to explore the estimation of expert weights in FCM and proposed a methodology for calculating weights of the experts [4, 5]. By this method we can assess creditability weight of an expert. This method is based upon calculating Hamming distance (bit difference) between inferences from various experts. The following two assumptions are made for developing this method:

a. Concurrence of an expert with the others implies a high level of expertise
b. The maps contain a sizeable measure of expertise

The combined FCM (CFCM) is calculated using the equation number 1 [4-6]:

$$\mathrm{CFCM} = \sum_{i=1}^{NE} FCM_i . W_i \qquad (1)$$

Where, NE represents no of experts, W_i is the credibility weight of expert i, and FCM_i is the FCM matrix of expert i.

The step by step procedure is described below [4, 5]:

i. Generate 500 hundred random stimuli i.e. input vectors, initial condition vectors. For n number of concepts, the input vector is *1 by n.*

ii. Excite each FCM matrix from these vectors and get inference. For n number of concepts, the input vector is *1 by n,* the FCM matrix is *n by n,* and the output vector is *1 by n.* The FCM adjacency matrix is excited through an input vector by multiplying input vector with the FCM matrix. The new output vector (first inference) is again multiplied with the FCM matrix to get the second inference vector. This process is further repeated until fourth inference is obtained.

iii. Hamming distance between the inferences generated by expert *i* and *k* is calculated and stored in a matrix. Hamming distance between two vectors is the number of bit difference, for example for the Hamming distance between two vectors (0101000) and (0111010) is 2. Hamming matrix ($H_{q,i,k}$) is symmetric with zero diagonal. One Hamming matrix is developed for each stimulus (input vector), therefore this process will generate 500 Hamming matrices. H will have 50,000 elements if we use 500 questions and input from 10 experts.

iv. Next step is to make a sum of these 500 Hamming matrices according to the equation 2:

$$M_{i,k} = \sum_{q=1}^{NQ} \frac{H_{q,i,k}}{NQ} \qquad (2)$$

Where *NQ* is the number of questions and $M_{i,k}$ indicates the average distance between expert *i* and *k* over all questions. This is also a symmetric matrix with zero diagonal.

v. Then calculate the total Hamming distance of each expert. Hamming distance of expert *i* can be obtained from the equation number 3:

$$h_i = \frac{\sum_{k=1} M_{i,k}}{(NE-1)} \quad \text{for } 1 \le i, k \le NE \qquad (3)$$

Where *NE* is the number of experts and h_i is the total Hamming distance of expert *i.* This is the sum of all columns of row *i* of the collapsed matrix. The smaller value of h_i indicates that response of expert *i* is closer to the mean response.

vi. Last step is to calculate credibility for each FCM. So the weight of expert *i* is calculated using equation number 4.

$$W_i \quad = 1 - \frac{h_i}{\sum_{i=1} h_i} \qquad \text{for } 1 \leq i \leq NE \quad (4)$$

Where W_i is the credibility for expert *i* or credibility for *FCMi* proposed by expert *i.* Then combined FCM is calculated using the equation number 1.

It is pertinent to mention that this method is based on the principle that the expert who differs and disagrees from the majority of experts will be given a lesser expert credibility weight while combining the judgment of several experts. So there is an important question that should we give a lesser weight to expert who disagrees from the majority, when combining the judgment of several experts?

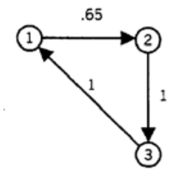
Scenario planning literature highlights the importance of identifying the weak signals and future surprises. If we apply this approach proposed by Taber and Siegel, it will further suppress any weak signals if highlighted by few experts. The expert credibility weight approach is suitable for healthcare sector where it is critical to achieve consensus, for example when developing a diagnostic criteria for a disease. However, it is not a suitable approach for combining multiple FCMs developed for scenario planning.

Averaging Multiple FCMs:

This method is more commonly used to combine FCM models of multiple experts [1, 6, 7] by taking average of their inputs. It is simple to use than the expert creditability weight method. To illustrate this method three fuzzy cognitive maps are shown in Figure B-1, highlighted as FCM_1, FCM_2, and FCM_3. The combined FCM is denoted as CFCM in Figure B-1. The each node in these FCMs represents unique concepts or variable and edges are directed and weighted relations between the nodes.

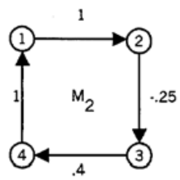
Fuzzy Cognitive Maps | FCM Matrix

FCM$_1$



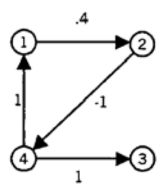
0	0.65	0	0
0	0	1	0
1	0	0	0
0	0	0	0

FCM$_2$



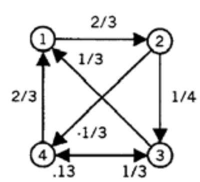
0	1	0	0
0	0	-1/4	0
0	0	0	0.4
1	0	0	0

FCM$_3$



0	0.4	0	0
0	0	0	-1
0	0	0	0
1	0	1	0

CFCM



0	2/3	0	0
0	0	1/4	-1/3
1/3	0	0	0.13
2/3	0	1/3	0

Figure B-1: Combining the FCMs by average method [6]

These different FCM matrices are summed and divided by number of experts to obtain the average edge weight [3, 8]. The combined FCM (CFCM) is a union set of nodes and average of the causal weights is taken. If one map is not showing a specific concept or edge weight, then in the FCM matrix 0 value is considered as the edge weight. For example in the map 1, concept 4 is not shown and there is also no link between concept 3 and concept 4. Therefore, we have considered 0 value of edge weight between concept 3 and concept 4 and value of edge weights from concept 4 to all other concepts is also zero in FCM$_1$. Thus multiple FCMs can be easily combined together to produce the combined FCM.

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Appendix C: Roadmap Objectives & Targets Workshop

Agenda

Purpose of Workshop Series:

- To develop a national level wind energy roadmap through Fuzzy Cognitive Map (FCM) based scenario planning

Purpose of TRM Workshop #1:

- Identify and discuss the strategic objective of the wind energy roadmap
- Identify and establish national targets of the wind energy roadmap for the next 20 years

Friday June 15, 2012

09:00 am	**Welcome, Introduction and Research Overview** **Muhammad Amer**, *Portland State University*
09:15 am	**Recap of FCM Workshop** Integrated Fuzzy Cognitive Map (FCM) Overview of FCM based Scenarios
09:30 am	**Strategic Objectives of the Wind Energy Roadmap** Participants identify and discuss the Strategic Objectives of the Wind Energy Roadmap in accordance with National Renewable Energy Policy of Pakistan
	FOCUS QUESTION #1: What are the strategic objectives for the national wind energy sector?
10.30 am	**Tea / Coffee Break**
10:45 am	**National Targets of the Wind Energy Roadmap** Participants identify, discuss and establish the National Targets of the Wind Energy Roadmap in accordance with National Renewable Energy Policy of Pakistan
	FOCUS QUESTION #2: Given the strategic objectives, what are national targets of the wind energy roadmap?
12:00 pm	**Review Results of Workshop** All Participants
12:30 pm	**Closing Comments and Adjourn**

Handout for Roadmap Objectives and Targets Workshop

Purpose:

- Identify and discuss strategic objective of the roadmap
- Identify and establish national targets of the wind energy roadmap for next 20 years

Focus Questions:

- What are the strategic objectives for the wind energy sector?
- What are the national targets of the wind energy roadmap?

Identification of Strategic Objectives and National Targets:

You are requested to identify the strategic objectives of the roadmap in accordance to the national renewable energy policy of Pakistan and establish the national targets of the wind energy roadmap for next 20 years. Please deliberate on the strategic objectives and the targets established in the national renewable energy policy.

The following strategic objectives are identified in the national renewable energy policy [1]:

- Energy Security
- Social Equity
- Economic Benefits
- Environmental Sustainability

In the second phase of the workshop, you are requested to establish the national targets for the wind energy sector for the next 20 years. The following targets have been proposed in the national RE policy [1]:

- Generation of 1700 MW of electricity from wind energy by 2015
- Generation of 9700 MW of electricity from wind energy by 2030
- Reduce national dependence on imported fossil fuel (oil)
- Develop local wind industry and establish domestic manufacturing base in the country

Reference of Appendix C:

[1] Government of Pakistan, (2006). "Policy for Development of Renewable Energy for Power Generation." Available: http://www.aedb.org/ [Jan 19, 2011].

Appendix D: Roadmap Barriers Workshop

Agenda

Purpose of Workshop Series:

- To develop a national level wind energy roadmap through Fuzzy Cognitive Map (FCM) based scenario planning

Purpose of TRM Workshop # 2:

- Identify, discuss and explore barriers and challenges towards deployment of the wind energy projects
- Prioritize the most important barriers on the basis of their impact on the roadmap targets for each scenario

Thursday July 5, 2012

09:00 am **Welcome, Introduction and Overview**

- **Muhammad Amer**, *Portland State University*

09:15 am **Recap of FCM and TRM # 1 Workshop**

- FCM based Scenarios
- Roadmap Objectives and Targets

09:30 am **Barriers and Challenges of the Wind Energy Roadmap**

- Participants identify and discuss the Barriers and Challenges of the Wind Energy Roadmap

FOCUS QUESTION #1: Given the roadmap targets, what barriers are standing in the way of deployment of the wind energy projects in Pakistan?

11.00 am **Tea / Coffee Break**

11:15 am **Importance of the Roadmap Barriers against Scenarios**

- Participants discuss the importance of Roadmap Barriers and Challenges for each Scenario on the basis of their impact on the Roadmap Targets

FOCUS QUESTION #2: Given the roadmap barriers, what is the importance of these barriers against the criteria (i.e. roadmap targets) for each scenario?

12:45 pm **Review Results of Workshop**

- All Participants

01:15 pm **Closing Comments and Adjourn**

Handout for Roadmap Barriers Workshop Handout

Purpose:

- Identify, discuss and explore barriers towards deployment of the wind energy projects
- Prioritize the most important barriers on the basis of their impact on the roadmap targets for each scenario

Focus Questions:

- Given the roadmap targets and integrated fuzzy cognitive map (FCM), what barriers are standing in the way of deployment of the wind energy projects in the country?
- Given the roadmap barriers, what is the importance of these barriers against the criteria (i.e. roadmap targets) for each scenario?

Identification of Roadmap Barriers:

You are requested to identify, discuss and explore barriers and challenges towards the deployment and implementation of wind energy projects against each scenario. A list of barriers has been made based on literature review and FCM model. You can also add more barriers and challenges if you think that some important barriers are not included in the handout. In the second phase of the workshop, we shall rank these barriers and challenges on the basis of their importance and impact on the roadmap targets.

Prioritization of Roadmap Barriers:

In order to prioritize and rank the roadmap barriers, you are requested to assess the impact of these barriers on the roadmap targets. As a first step, please rank the importance of the roadmap targets. In the second step, we will assess the impact of roadmap barriers on the targets. Please specify weights of the roadmap targets (criteria) on a Likert scale of 1 to 7 on the basis of their importance in impacting and hammering the roadmap targets. Assign value 1 if a criterion (TRM Target) is not at all important and assign value 7 if a criterion (TRM Target) is extremely important. Please use the following guidelines to specify level of importance [25]:

- 1 – Not at all important
- 2 – Low importance
- 3 – Slightly important
- 4 – Somewhat important

- 5 – Moderately important
- 6 – Very important
- 7 – Extremely important

Table D-1: Criteria for prioritization of roadmap barriers

Criteria for prioritization of roadmap barriers / challenges	**Weight (1-7)**
C1: Generation of 1700 MW of electricity from wind by 2015	
C2: Generation of 9700 MW of electricity from wind by 2030	
C3: Development of local wind industry and domestic manufacturing base in the country	
C4: Reduction of national dependence on imported fossil fuel by utilizing indigenous wind energy resources	

As a second step, you are requested to rank and prioritize the identified roadmap barriers and challenges. Please rank these barriers and challenges on the basis of their impact on the roadmap targets (criteria) and assign a score ranging from 1 to 5. Use the following guidelines to rank to each barrier [25].

- 1 – Not a barrier
- 2 – Somewhat of a barrier
- 3 – Moderate barrier
- 4 – Important barrier
- 5 – Extremely important barrier

Table D-2: Importance score of roadmap barriers against criteria

Roadmap Barrier	Importance score of roadmap barriers against criteria			
	C1	C2	C3	C4
Policy Barriers				
Institutional Barriers				
Financial Barriers				
Economic Barriers				
Technical Barriers				
Transmission Barriers				
Wind Resource Data Barriers				
Capacity Building Barriers				
Awareness Barriers				
Social Barriers				
Market Barriers				

The Weighted Sum Method (WSM) will be used to prioritize the roadmap barriers. WSM is a multi-criteria decision making method used for evaluating a number of alternatives against the decision criteria and it is the most commonly used approach in sustainable energy systems [1, 2].

Major barriers towards the deployment of wind energy:

There are various barriers impeding implementation of wind energy projects on large scale in Pakistan. It is vital to identify and rank these barriers and challenges, because without identifying the critical barriers, we cannot move towards addressing them. Based on literature review on wind energy and renewable energy sector of Pakistan, 11 critical barriers and challenges towards implementation of wind energy projects are identified. An overview of these barriers is presented below:

a. Policy Barriers [3-10]:

Lack of legislations, approved national energy policies and inconsistencies of the government policies is a major barrier. Policy barriers hinder development of wind energy projects and effective policies can significantly increase wind energy penetration in the country. Suitable policy instrument covers power purchase agreements, well-defined policies for private sector participation, guidelines for land allotments and clearance for wind project, subsidies and incentives for power generation from wind energy. Policy offering attractive incentives can nurture the wind industry.

b. Institutional Barriers [4-6, 11, 12]:

Institutional support plays a critical role for identification, promotion and implementation of wind energy technology in a country. There is a lack of institutional support and only a few institutes are working to promote to renewable energy technologies in Pakistan. Moreover, there is lack of coordination and cooperation within and between various ministries, agencies, institutes and other stakeholders. Absence of a central body for overall coordination of all activities in wind energy sector also results in duplication of efforts. These institutional barriers delay and restrict the progress in wind energy development and commercialization.

c. Financial Barriers [4-6]:

There are barriers in obtaining competitive forms of finance from local, national and international levels to implement wind energy projects in the country. There are many reasons for this barrier including lack of familiarity with wind technology, high risk perception, uncertainties regarding resource assessment, intermittent power generation from wind energy and site-specific nature of every project. Moreover, there is a lack of financial resources and proper lending facilities, particularly for small-scale projects.

d. Economic Barriers [5, 11, 13]:

The current power generation cost from wind energy is high, due to high capital cost (cost of wind turbines and supporting equipment), taxes and custom duty on equipment imports, low capacity factor and government subsidies given to conventional power plants. Energy prices also do not reflect environmental costs and damage, and mask the striking environmental advantages of the new and clean wind energy options. Subsidies give an unfair advantage to fossil fuel power plants over wind farms and these reasons make wind energy projects un-economical in the country.

e. Technical Barriers [4-6, 14]:

Technical barriers include limited R&D infrastructure in the country, availability of low quality products in the local market, and lack of standards in terms of durability, reliability, performance, etc. for wind energy products. These factors negatively affect commercialization of wind technology.

f. Transmission Barriers [4]:

Integration of wind energy with national grid is a challenge. Wind energy resources are often located in remote and dispersed locations, not connected with transmission and distribution networks. So it needs investments and modifications in the grid to integrate power generated from wind. Non-availability of distribution network at potential sites is a major challenge which leads to low exploitation of wind potential. Low reliability in grid operations also creates problems in integrating power from wind farms.

g. Wind Resource Assessment [7, 13, 15, 16]:

Lack of sufficient and reliable wind data and wind energy resource assessments is also an important barrier in exploitation of wind energy. Many suitable areas in remote locations have not been assessed properly for the implementation of wind energy projects. The development of wind power projects requires a detailed assessment of the wind regime of the area under consideration. Therefore, it is an important factor for making wind power projects bankable.

h. Capacity Building [4, 5, 7, 17]:

Shortage of maintenance infrastructure and skilled human resource to operate, maintain and support wind farms is also a challenge. Skilled manpower can provide the essential services such as, installation, operation and maintenance; troubleshooting of the equipment. Shortage of proper training facilities also increases this challenge. Inadequate servicing and maintenance infrastructure will lead to poor performance of the equipment installed in the field and ultimately result in limited market penetration of wind energy technology.

i. Awareness/ Information [5-7, 18]:

Lack of awareness and information regarding the usefulness of wind energy is also a challenge. There is very limited information regarding the practical problems in implementing and maintaining wind energy projects. Information regarding wind energy projects is not easily available which deters implementation of community level projects. So, there is a need for increasing the availability of technical information and education as a way of facilitating wind power projects.

j. Social Barriers [3-5]:

Lack of social acceptance and local participations in the wind energy projects also restricts deployment of decentralized wind energy projects. Community participation is restricted to just a few demonstration projects and it restricts deployment of wind energy projects on large scale. Moreover, access to land is sometimes difficult and it takes long negotiations with local community and significant compensation in order to acquire land for a wind energy project.

k. Market Barriers [4, 5, 7]:

Market barriers includes small size of the market, limited involvement of private sector, monopoly of the giant conventional power generation companies, lack of marketing infrastructure with promotion campaigns, low level of after-sales service and quality control measures. Absence of successful and replicable business models also hinders market penetration. These factors hinder market penetration of wind energy technology.

l. **Wind Speed Variation Challenges:**

Some studies support theories that climate change could affect surface wind speeds. Pryor et al. found that wind speeds across the United States have decreased since 1973 [19]. There are other scientific investigations that have reported a decline of surface wind speeds in many regions of the world [20-23]. Variations in the wind speed and wind energy density have great importance for the financial viability of wind farms [24]. Therefore, a decline in wind speed is a potential concern for wind energy sector and it may become a barrier in future and affect power output from wind farms.

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Appendix E: Follow-up Survey for Ranking of Roadmap Barriers

Purpose:

- Review the results of roadmap barriers workshop and prioritize the most important barriers against the criteria (i.e. roadmap targets) for each scenario.

Instructions:

You are requested to prioritize and rank the following roadmap barriers and challenges on the basis of their impact on the roadmap targets (criteria) and assign a score ranging from 1 to 5. Use the following guidelines to rank to each barrier.

- 1 – Not a barrier
- 2 – Somewhat of a barrier
- 3 – Moderate barrier
- 4 – Important barrier
- 5 – Extremely important barrier

Table E-1: Importance score of roadmap barriers for Scenario A

Roadmap Barrier	Importance score of roadmap barriers against criteria			
	C1	C2	C3	C4
Policy Barriers				
Lack of Competition with Conventional Power Plants				
Institutional Barriers				
Financial Barriers				
Circular Debt Barriers				
Economic Barriers				
Technical Barriers				
Capacity Building Barriers				
Transmission Barriers				
Wind Resource Assessment				
Wind Speed Variation				
Lack of Awareness				
Market Barriers				
Social Barriers				

Table E-2: Importance score of roadmap barriers for Scenario B

Roadmap Barrier	Importance score of roadmap barriers against criteria			
	C1	C2	C3	C4
Policy Barriers				
Lack of Competition with Conventional Power Plants				
Institutional Barriers				
Financial Barriers				
Circular Debt Barriers				
Economic Barriers				
Technical Barriers				
Capacity Building Barriers				
Transmission Barriers				
Wind Resource Assessment				
Wind Speed Variation				
Lack of Awareness				
Market Barriers				
Social Barriers				

Table E-3: Importance score of roadmap barriers for Scenario C

Roadmap Barrier	Importance score of roadmap barriers against criteria			
	C1	C2	C3	C4
Policy Barriers				
Lack of Competition with Conventional Power Plants				
Institutional Barriers				
Financial Barriers				
Circular Debt Barriers				
Economic Barriers				
Technical Barriers				
Capacity Building Barriers				
Transmission Barriers				
Wind Resource Assessment				
Wind Speed Variation				
Lack of Awareness				
Market Barriers				
Social Barriers				

Appendix F: Roadmap Action Items Workshop

Agenda

Purpose of Workshop Series:

- To develop a national level wind energy roadmap through Fuzzy Cognitive Map (FCM) based scenario planning

Purpose of TRM Workshop # 3:

- Propose and discuss various action items in the wind energy roadmap in order to overcome the roadmap barriers and translate roadmap targets into action items.

Friday July 20, 2012

09:00 am — **Welcome and Overview**
- **Muhammad Amer**, Portland State University

09:10 am — **Recap of the Roadmap Barriers Workshop / Follow-up Survey**
- Roadmap Barriers and Challenges
- Importance of Roadmap Barriers for each Scenario

09:20 am — **Barriers and Challenges of the Wind Energy Roadmap**
- Participants propose and discuss various Action Items required to overcome the Barriers and Challenges of the Wind Energy Roadmap and translate Roadmap Targets into the proposed action items.

FOCUS QUESTION #1: Given the roadmap barriers, what are the action items required to overcome these barriers?

11.00 am — **Tea / Coffee Break**

11:15 am — **Classification of the Propose Action Items**
- Participants classify the proposed Action Items of the Roadmap in categories as explained in the Action Items Workshop Handouts and Worksheet

TASK #1: Highlight and/or modify the action items already taken to address the roadmap barriers.
TASK #2: Propose new action items (gaps/needs) required in order to overcome roadmap barriers and achieve roadmap targets.
TASK #3: Assign the responsibility for each action item

12:30 pm — **Review Results of Workshop**
- All Participants

01:00 pm — **Closing Comments and Adjourn**

Handout for Roadmap Action Items Workshop

Purpose:

- Propose and discuss action items in the wind energy roadmap, required to overcome the roadmap barriers and translate roadmap targets into action items.

Focus Question:

- Given the roadmap barriers, what are the action items required to overcome these barriers against each scenario?

Tasks:

- Identify and propose action items required to be taken in order to overcome roadmap barriers for each scenario
  - Propose new action items (gaps/needs) required to overcome roadmap barriers and achieve roadmap targets
  - Action items already taken by the stakeholders (Government, regulators, private sector etc.) to address the roadmap barriers
  - Action items which are already taken by the stakeholders but requires significant modification, adjustments or reforms in order to impact roadmap barriers
- Assign the respective leading role and responsibility for each action item to the government, national electricity regulator / power distribution companies or wind industry.
- Specify the estimated time frame when these action items are required

Identification of Roadmap Action Items:

You are requested to propose and discuss various action items required to overcome the barriers and challenges towards the deployment and implementation of wind energy projects against each scenario and translate roadmap targets into these action items. Various barriers and challenges were identified and prioritized in the roadmap barriers workshop and follow-up surveys. In the first step, you are requested to identify and discuss the action items required to be taken in order to overcome roadmap barriers for each scenario. Then highlight that which action items have already been taken by the stakeholders (Government, regulators, private sector etc.) and mention if there is a need to modify these action items already taken to address the barriers and challenges. You are also requested to propose new action items (i.e. gaps/needs), which are not taken earlier but essentially required to overcome the roadmap barriers. In the end, assign the respective leading role and responsibility for each action item to government, regulator / power distribution companies or wind industry. You can also assign two or more actors responsible for some action items if deemed necessary. You are also requested to specify the estimated timeline for the proposed roadmap action items as given below:

- Short-term: To be taken immediately
- Medium-term: Between the year 2015 to 2020
- Long-term: After the year 2020

Example:

An example shown in Table F-1 highlights some action items proposed against roadmap barriers:

Table F-1: Identification and classification of roadmap action items

Roadmap Barrier	Roadmap Action Items (AI)		
	AI already taken	AI required improvements	New AI required (Gaps/Needs)
Policy Barriers			Tax Incentives and subsidies to wind energy sector by the Govt.
			Legislations to support wind energy projects, e.g. RPS for utilities etc.
			Govt. required to adopt a quick process to grant clearance to wind farms
			Govt. to ensure consistency in policies towards wind energy
			Finalize wind power purchase agreements within the stipulated time
	Tax benefits on import of wind turbines and related equipment in Pakistan	Removal of custom duty on import of wind turbines and related equipment	
	Policy for land allocation for wind farms	Standardize and simplify land allocation process	
Wind Resource Data Barriers			Establish benchmark wind speeds for all the potential locations
			Install sensors for on-site wind speed measurement
	Developed 50 m wind resource map of the country	Use advanced modeling techniques to produce detailed wind maps	

Appendix G: Stability Test between First and Second Round of Delphi

(All responses for scenario A and Policy Barriers for Target 1)

The individual stability test was conducted to measure consistency of responses between successive Delphi rounds. It has been recommended in the literature that stability is an appropriate criterion for terminating Delphi study [1, 2]. Stability refers to the consistency of responses between successive rounds and it is statistically verified through chi-square test using the following equation [1]:

$$\chi^2 = \sum_{k=1}^{n} \sum_{j=1}^{m} \frac{(O_{jk} - E_{jk})^2}{E_{jk}}$$

Where O_{jk} and E_{jk} are the observed and expected frequency indicating the number of respondents who voted for the j^{th} response interval in the i^{th} round but voted for the k^{th} response interval in round $i+1$.

m and n are number of non-zero response intervals in the round i and round $i+1$

In order to test individual stability, it is required to determine whether there is a significant difference between individual responses in different rounds using the chi-square test. The following two hypotheses are tested:

H_0: Individual responses of rounds i and $i+1$ are independent.

H_1: Individual responses of rounds i and $i+1$ are not independent.

If individual responses in the rounds are dependent, than it can be concluded that the same respondents who voted for a given response in the i^{th} round, would also have voted for the same response in round $i+1$. The responses from experts for round 1 and round 2 regarding the impact of Policy Barriers against roadmap Target 1 in Scenario A are shown in Table G-1.

Table G-1: Observed and expected individual frequencies of round 1 & 2 for policy barriers against roadmap Target 1 in scenario A

Observed Frequencies

Response Interval		First Round					Total
		1	**2**	**3**	**4**	**5**	
Second Round	**1**						
	2						
	3			2			2
	4				4		4
	5				1	8	9
Total				2	5	8	**15**

Expected Frequencies

Response Interval		First Round				
		1	**2**	**3**	**4**	**5**
Second Round	**1**					
	2					
	3			0.26	0.67	1.06
	4			0.53	1.33	2.13
	5			1.20	3	4.80

The calculated value of chi-square using observed and expected frequencies mentioned in Table G-1:

$$\chi^2 = 25.67$$

The above test has 4 degrees of freedom; it can be calculated as below:

$$\text{Degrees of freedom } (df) = (m - 1)(n - 1)$$
$$= (3 - 1)(3 - 1) = 4$$

The critical value Chi-square (χ^2) at 0.01 level of significance and 4 degree of freedom is 13.277. Since the Chi-square value (25.67) is greater than the critical value. Thus, the null hypothesis is rejected (H_0: Individual responses of rounds *i* and *i+ 1* are independent) and individual stability is verified.

References:

[1] W. W. Chaffin and W. K. Talley, "Individual stability in Delphi studies," *Technological Forecasting and Social Change,* vol. 16, pp. 67-73, 1980.

[2] J. S. Dajani, M. Z. Sincoff, and W. K. Talley, "Stability and agreement criteria for the termination of Delphi studies," *Technological Forecasting and Social Change,* vol. 13, pp. 83-90, 1979.

Appendix H: Cluster Analysis

(Clustering of the roadmap barriers for scenario A)

The scores assigned to the roadmap barriers by the experts were normalized. Then k-means clustering technique was used to group the roadmap barriers [1, 3, 6]. Cluster analysis is a generic name for a class of techniques used to classify cases into groups that are relatively homogeneous within themselves and heterogeneous between each other [7]. Thus, data clustering technique allows objects with similar characteristics to be grouped together for further analysis. Cluster analysis has been extensively used in numerous applications ranging from strategic management and marketing research to information technology and climatology [1-5, 7]. The k-means method aims to minimize the sum of squared distances between all points and the cluster center [6].The elbow method was used to define the number of clusters [4].

The roadmap barriers were grouped into three clusters. The elbow method was used to define the number of clusters and scree diagram was created for each scenario.

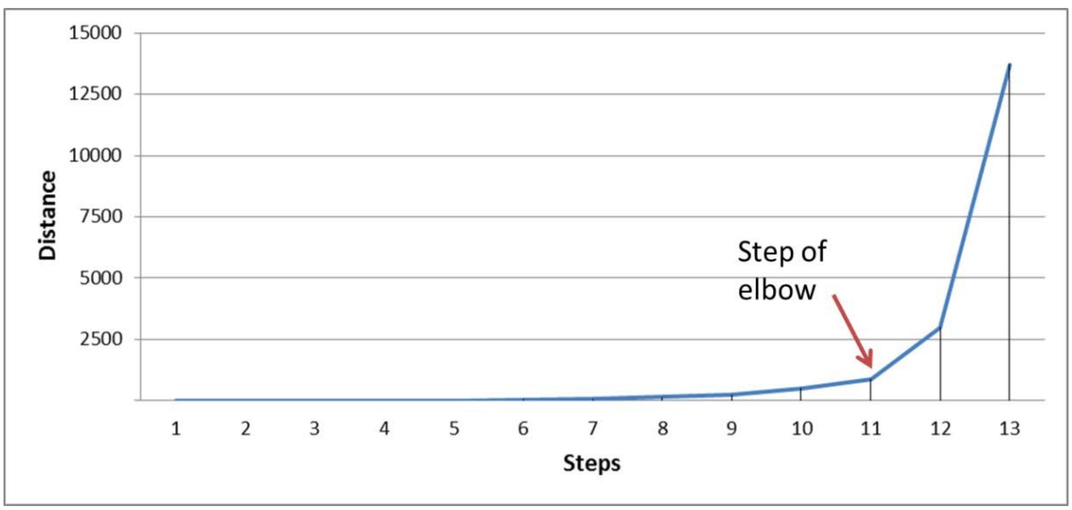

Figure H-1: The scree diagram for scenario A

The appropriate number of clusters for scenario A is calculated as given below:

- Number of Barriers 14
- Step of ‘elbow’ 11
- Number of clusters = (14 - 11) = 3

Policy barriers, lack of competition with conventional power plants, and intuitional barriers emerged as the most significant roadmap barriers for scenario A. The results of the cluster analysis performed for the roadmap barriers against each scenario are given in Table 31. The results of k-means cluster analysis performed for the scenario A are shown in the following tables.

Table H-1: Distance between the final cluster centers for scenario A

Distances between Final Cluster Centers			
Cluster	1	2	3
1		75.917	45.000
2	75.917		30.917
3	45.000	30.917	

Table H-2: Cluster membership of roadmap barriers for scenario A

Cluster Membership		
Roadmap Barriers	Cluster	Distance
Policy	1	10.333
Competitiveness	1	3.333
Institutional	1	13.667
Technical	3	7.333
Capacity	3	3.667
Awareness	3	3.667
Financial	2	10.250
Economic	2	1.250
Transmission	2	6.250
Wind Resource	2	4.750
Social	2	13.750
Market	2	10.250
Circular Debt	2	4.750
Speed Variation	2	4.750

Table H-3: ANOVA for scenario A

ANOVA						
	Cluster		Error			
	Mean Square	df	Mean Square	df	F	Sig.
Scenario_A	6410.190	2	81.167	11	78.976	.000

References for Appendix H:

[1] V. Estivill-Castro, "Why so many clustering algorithms: a position paper," *ACM SIGKDD Explorations Newsletter,* vol. 4, pp. 65-75, 2002.

[2] K. R. Harrigan, "An application of clustering for strategic group analysis," *Strategic Management Journal,* vol. 6, pp. 55-73, 2006.

[3] R. Huth*, et al.*, "Classifications of atmospheric circulation patterns," *Annals of the New York Academy of Sciences,* vol. 1146, pp. 105-152, 2008.

[4] D. J. Ketchen and C. L. Shook, "The application of cluster analysis in strategic management research: an analysis and critique," *Strategic Management Journal,* vol. 17, pp. 441-458, 1996.

[5] G. Punj and D. W. Stewart, "Cluster analysis in marketing research: review and suggestions for application," *Journal of Marketing Research,* pp. 134-148, 1983.

[6] S. Ray and R. H. Turi, "Determination of number of clusters in k-means clustering and application in colour image segmentation," in *Proceedings of the 4th international conference on advances in pattern recognition and digital techniques*, 1999, pp. 137-143.

[7] C. Romesburg, *Cluster Analysis for Researchers*. North Carolina Lulu Press, 2004.

Appendix I: FCM Simulation

Multiple input vectors are used to conduct the FCM simulation and generate scenarios. For this research, five input vectors were developed through the morphological analysis. Although, the most important scenario drivers are used to form the input vectors; but in the FCM simulation all of the scenario drivers (concepts) in the FCM model and their complex causal relationships are considered for generating scenarios. It happens because when a concept changes its state, it affects all concepts that are causally dependent on it, and this process depends on the direction and strength of the causal link [6]. The newly activated concepts may further influence other concepts which they causally affect and this activation spreads in a non-linear fashion in the FCM model until the system attains a stable state [6]. Due to the meta-rules, it is also possible that in some cases several input vectors may lead to the same final system state [7]. The FCM simulations can be used to experiment with different input vectors and compare their outcome [7]. Therefore, it helps to deal with a complex situation and holistically evaluate all concepts of interest. Moreover, despite using the input vectors consisting of the critical scenario drivers, all drivers/concepts and their causal links in the FCM model are considered during the development of FCM-based scenarios.

For or this research, individual FCMs were obtained from the experts and combined into an integrated FCM by the researcher. In the scenario workshop, the expert reviewed and validated the integrated FCM. Then Wilson matrix was used rank the scenario drivers. Finally, input vectors were created to conduct the FCM simulation and generate scenarios. The Adjacency Matrix (E) of the integrated FCM model is shown in Figure I-1. Figure I-2 provides an overview of the FCM-based scenario development process.

E=

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	26	27	28	29	30	31	32	33	34	35	36	37	38	39	41	42	
0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	3	3	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
0	0	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
0	0	0	0	0	0	0	0	0	0	3	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11
0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13
0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
0	0	0	0	0	0	0	0	0	0	0	2	3	0	0	2	0	0	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15
0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16
0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	19
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24
0	0	0	0	0	0	0	0	0	0	0	2	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	26
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	27
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	29
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	30
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	32
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	34
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37
0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39
0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41
0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42

Figure 1: Adjacency Matrix of the integrated FCM

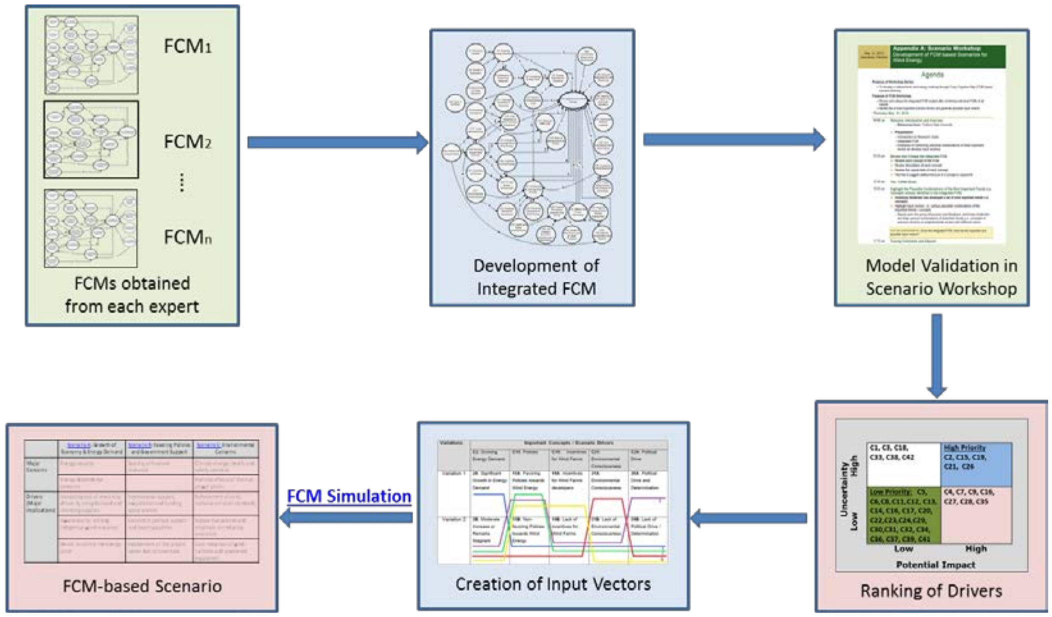

Figure I-2: FCM-based scenario development process

FCM Simulation with Binary Function

The integrated FCM model was tested against the input vectors. In the first scenario, the effects of economic growth and increase in energy demand were evaluated on the deployment of wind energy. In this study, the FCM model was run with a simple binary squashing function. For this squashing function, input and output values of concepts are either 0 or 1, which indicates that a concept has been turned "on" and "off". The simple binary function has been used for developing scenarios [2, 3, 6].

The FCM simulation is performed until the output vector is stabilized. It is performed by multiplying the input vector with the FCM adjacency matrix. A squashing function is applied after every multiplication as a threshold function to the output vector. A simple binary squashing function is used which squeezes the result of multiplication in the interval of (0, 1). For n number of concepts, the input vector is *1 by n*, the FCM adjacency matrix is *n by n*, and the output vector is *1 by n* [8]. The new output vector is again multiplied with the FCM adjacency matrix and this process is repeated until the multiplication results in equilibrium [5, 6, 8, 9]. As a result, the system is settled down and stabilized, then new matrix multiplications will result in the same output state vector. Implications of the FCM model are analyzed by clamping different concepts and the vector and adjacency matrix multiplication procedure, to assess the effects of these perturbations on the state of a model [1]. This vector – matrix multiplication is performed as:

$$S_i = I_j \times E$$

Where, S_i = the new state vector (output / inference vector)

I_j = the jth inference vector

E = the FCM Adjacency Matrix

Figure I-3 highlights the FCM simulation. The Adjacency Matrix obtained from the integrated FCM and input vectors are used to perform the simulation.

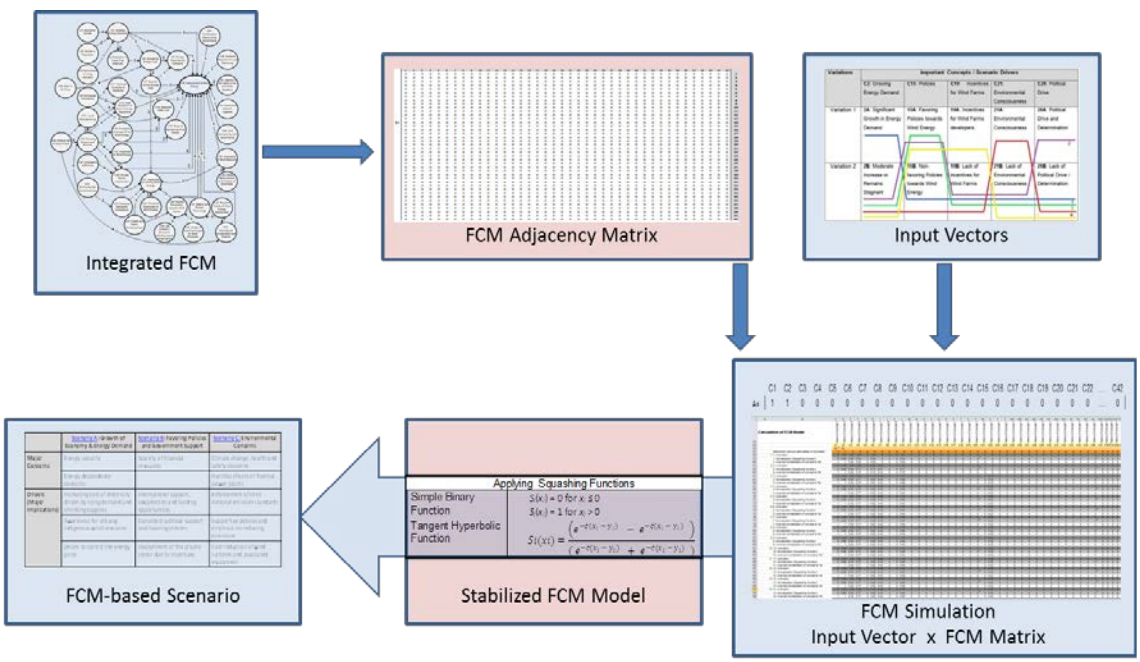

Figure I-3: FCM Simulation

For the first input vector, the integrated FCM model was evaluated against two factors: growth in energy demand and economic growth of the country. The effects of these concepts (variables) on the deployment of wind energy projects in Pakistan were examined. Therefore, the initial states of C1 and C2 are set as 1, whereas the initial states of all other concepts are 0. The states of C1 and C2 are clamped to always be on (1). The input vector (A) is shown below:

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	….	C42
A=	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	….	0

The input vector is multiplied with adjacency matrix (E) and simple binary squashing function (that converts output value of ≤ 0 to 0 and output value of > 0 to 1) is applied. Then we obtain the output vector, in which all elements greater than zero indicate that the concept does occur given the antecedents and a squashing function (threshold operation) is applied. This output vector is also called first order inference. The first inference vector (A') is shown below:

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	….	C42
A'=	1	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	….	0

The second order inference is obtained by multiplying the first inference vector with the FCM adjacency matrix (E) and again applying the simple binary squashing function. The second inference vector (A'') is shown below:

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	….	C42
A''=	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	….	0

Similarly, by repeating the same process again, we obtained the third order inference vector and subsequent vectors. The third (A''') and fourth (A'''') order inference vectors are shown below:

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	….	C42
A'''=	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	….	0

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	….	C42
A''''=	1	1	1	1	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	….	0

The FCM simulation is continued until the output vector is stabilized. The result has been stabilized and settled down after fourth multiplication. The third (A''') and fourth (A'''') inference vectors are similar. If the results are not stabilized at this level, then we would have generated further higher order inference vectors as well. The fourth inference vectors (A'''') indicates that besides concept 1 and 2; now concepts 3, 4, 6, 7, 10, and 22 are also turned on in the output vector.

A customized worksheet in MS Excel was made to conduct the FCM simulations. The results of the FCM simulation were also verified by using another worksheet developed by Jetter [6]. The results of the FCM simulation performed for the first input vector are summarized in Table I-1. The concepts which are turned on (1) in the subsequent inference vectors are mentioned in Table I-1.

Table I-1: The results of FCM simulation for the first input vector
*States of C1 and C2 are clamped to always be 1 (on).

The results of FCM Simulation for the First Input Vector	
Input Vector	C1*, C2*
First Inference Vector	C1*, C2*, C3, C4, C6, C10
Second Inference Vector	C1*, C2*, C3, C4, C6, C7, C10
Third Inference Vector	C1*, C2*, C3, C4, C6, C7, C10, C22
Fourth Inference Vector	C1*, C2*, C3, C4, C6, C7, C10, C22

FCM Simulation with Tangent Hyperbolic Function

After conducting the FCM simulation with the simple binary squashing function and developing the FCM-based scenarios, it was observed that all three scenarios have indicated an increase in the deployment of wind energy in the country. Thus, all the scenarios indicate widespread deployment of wind technology, but the barriers, challenges, and the wind energy deployment paths were different against each scenario. In order to check the behavior and robustness of the integrated FCM model, it was further analyzed by applying a different squashing function to generate some heterogeneous scenarios. Thus, the hyperbolic tangent function was applied to the model as a squashing function. Mathematical expressions of the simple binary and tangent hyperbolic functions are given in Table I-2.

Table 2: Different squashing function [6]
S_i is the new state vector

Applying Squashing Functions	
Simple Binary Function	$S_i(x_i) = 0$ for $x_i \leq 0$ $S_i(x_i) = 1$ for $x_i > 0$
Tangent Hyperbolic Function	$Si(xi) = \frac{\left(e^{-c(x_i - y_i)} - e^{-c(x_i - y_i)}\right)}{\left(e^{-c(x_i - y_i)} + e^{-c(x_i - y_i)}\right)}$

The FCM simulation was conducted again with a different squashing function to examine the behavior of the integrated FCM model. The hyperbolic tangent function (*tanhx*) is a bipolar sigmoid function and it has been also recommended in the literature for conducting the FCM simulations [4, 6]. A hyperbolic tangent function drawn for values between -1 to 1 is shown in Figure 3.

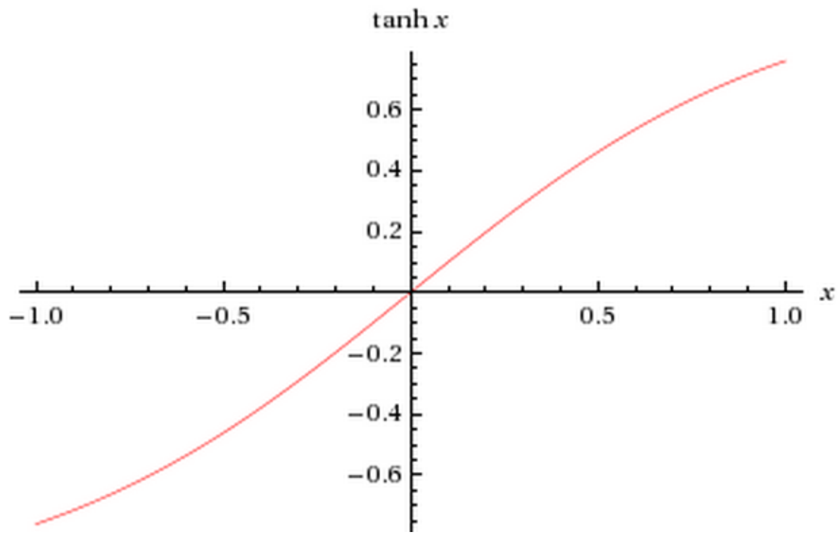

Figure 4: Adjacency Matrix of the integrated FCM

Table I-3 provides a summary of the FCM simulation results with simple binary function (SBF) and tangent hyperbolic function (THF) for all three scenarios. It can be observed that there are similarities and some differences among the simulation outcome obtained from different squashing functions. However, all the simulation results have indicated a positive trend towards the deployment of wind energy projects on a large scale in the country (concept 10 is on). The purpose of applying the hyperbolic tangent function was to examine the behavior of the FCM model against a different squashing function. However, it has also shown a positive trend towards deployment of wind farms in the country and concept 10 is turned on in each case, as highlighted in Table I-3.

Scenarios and Squashing Functions		Results of the FCM Simulation with different squashing functions (SBF and THF)																					
		C1: Economic Growth	C2: Growing Energy Demand	C3: Reduction in Fossil-Fuel	C4: Increasing Energy Cost	C6: Dependence Concerns	C7: Control energy cost	**C10: Deployment of WE**	C12: Local Manufacturing	C13: Reduced Turbine Cost	C14: Reduced O&M Cost	C15: Favoring Policies	C16: Trained HR for Wind	C17: Ease of Maintaining	C19: Incentives for Industry	C20: Private Sector	C21: Environmental Concerns	C22: Awareness to use WE	C23: Emission Standards	C26: Government Support	C27: Health & Safety Concerns	C28: Positive Perception	C33: International Cooperation
Scenario A	SBF	✓	✓	✓	✓	✓	✓	✓										✓					
	THF	✓	✓	✓	✓	✓		✓															
Scenario B	SBF							✓	✓	✓	✓	✓	✓	✓	✓	✓				✓			✓
	THF							✓	✓	✓		✓			✓	✓				✓			✓
Scenario C	SBF							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	
	THF							✓				✓			✓	✓	✓	✓			✓	✓	

Table 5: The results of the FCM simulation with simple binary and tangent hyperbolic functions

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